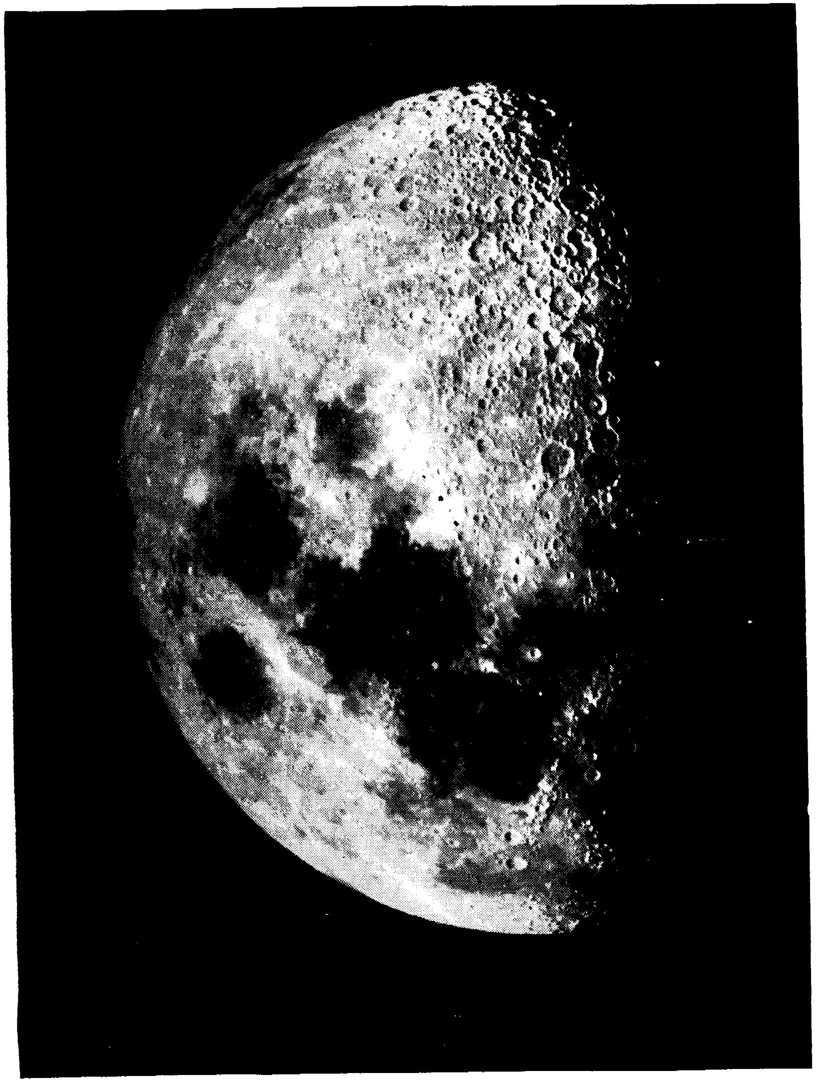


The moon at eight days' age, photographed by Henry Paul at the focus of a 10-inch. f/9 reflecting telescope using fine grain copy film. Image 0.8-inch in diameter enlarged 20 times to 16-inch diameter and reduced for reproduction.

AMATEUR TELESCOPE MAKING

(BOOK THREE)

A sequel to AMATEUR TELESCOPE MAKING
(BOOK ONE)
and to AMATEUR TELESCOPE MAKING ADVANCED
(BOOK TWO)

ALBERT G. INGALLS, Editor
Contributing Editor, Scientific American

Contributions to amateur precision optics by advanced amateurs and professionals

SCIENTIFIC AMERICAN, INC.

1953

First Edition, first printing, 1953

PRINTED IN THE UNITED STATES OF AMERICA
KINGSPORT PRESS, INC. KINGSPORT, TENNESSEE

TO THE MEMORY OF

Russell W. Porter

Preface

The amateur telescope making pursuit began with the simple aim of making telescopes, but in next to no time the nimble-minded people to whom it appealed were running all over the field of precision optics in search of other instruments they could build, while some delved into physical optics to understand its theory, and all to some extent did both. The old demarcation between amateur and professional optics receded, became blurred, or vanished. Neither can that demarcation be found in the present volume, which is for all who are interested in optics, though essentially for amateurs. Some of its authors are amateurs, some are professionals who began as amateurs and have remained so in their spirit of enthusiasm, and a few are professionals who never were amateurs but nevertheless have fun with optics.

Some of the chapters describe projects and procedures, others technics, others tests, others professional methods adaptable to amateur use, still others the design of telescope lenses by professional methods including ray tracing made lucid by sympathetic writers who have striven not to "keep 'em mystified." There are chapters on the selection of lenses, plates and films for astronomical photography, and on the construction of lens systems for the same purpose. Others are on the construction of spectrographs, a spherometer, a precise photoelectric photometer for variable star work, a monochromator for solar observation, and on the mechanical understanding, complete overhaul and accurate adjustment of binoculars. A chapter explains the design considerations for eyepieces, describes 91 eyepiece types and includes the specifications for 39 eyepieces. Another is on the understanding of diffraction. Others are on the Barlow lens, optical flat making, Schmidt camera making and making elementary camera lenses, lens production on a small professional scale, coating of lenses and aluminizing of telescope mirrors, building and using an optical testing bench, preparing scratchless optical abrasives, a null test and an ultra-precise test for mirrors, and a procedure for designing a Maksutov Herschelian telescope. An innovation is a brief, intimate biography of each contributor, from which the reader may discover human interest that should increase his enjoyment of the book, its authors being human beings, not remote abstractions. This homey feeling is further enhanced by the reproduction of their own drawings instead of reduction to uniformity.

ATM, Book One of this series, has been described by the humorist "Red" Herring as "an incomparable paragon of reverse sequence" (the result of many additions and internal operations down through the years). Nor is "ATMA Book Two," in a logical sequence; how could such a varied assemblage be made so? There is logic, however—that of the alphabet—in the sequence of the running heads at the tops of the pages of the present volume.

A. G. I.

CONTENTS

CONTENTS

Optical Systems for Astronomical Photography

By James G. Baker

Research Associate of Harvard College Observatory and of the
Lick Observatory of the University of California.
Consultant to the Perkin-Elmer Corporation

Many kinds of optical systems of actual or potential use in astronomical research have been developed in recent years. An adequate discussion of these systems would prove to be both voluminous and technical. For the purpose at hand, which is to provide the skilled amateur telescope maker with several optical systems that he can construct and use for astronomical photography, the author has selected two types of more than ordinary value.

The first such optical system consists of an interchangeable optical corrector for the usual paraboloidal mirror telescope that converts the instrument into a wide field photographic telescope of excellent quality. The second type satisfies a need of the skilled amateur who cannot often put his hands on a detailed, reliable formula for a photographic lens of moderate clear aperture and focal length suitable for astronomical photography. This second type consists of a related pair of Cooke triplet lenses, designed expressly for use on the stars, one for violet and one for visual light.

Both forms of equipment come within the time and budget possibilities of the skilled amateur. Astronomers should also take note that these designs are well adapted to use in professional research work of the highest caliber, and that nothing essential has been sacrificed in making these designs available to amateur needs.

PART I. The Reflector-Corrector

Observational astronomy is making an ever increasing use of the large reflecting telescope not only as a collector of light for photoelectric and spectrographic attachments but for a photographic instrument as well. Technological improvements made possible by the enhanced budgets and activities of recent years are now being applied with much success, particularly to auxiliary equipment for the reflector. Among these improvements one can cite advances in sensitivity and stability of photoelectric photometers, interference filters of many kinds, permanent reflecting films for mirror surfaces, hard anti-reflection coatings of improved efficiency, infrared detectors, faster photographic materials of finer grain, and a variety of special devices.

Astronomers have known since the 17th Century that the front surface paraboloidal mirror is the simplest form of telescope. Although many modifications have been proposed and are in use, the need for efficiency in handling starlight exerts a decisive influence over what one may dare to attempt in the line of mathematical improvements. However, at present the criterion of efficiency is more important in the cases of photoelectric photometry and spectrographic observation than in direct photography, for in the latter case, exposures are cut short by sky fog anyway. Hence, where direct photography is considered, we are privileged to give priority to image quality and field coverage over efficiency.

In this discussion we shall demonstrate that there exists a correcting means for the standard paraboloidal reflector that converts the telescope into a photographic instrument comparable in quality to the Schmidt camera, such that when the corrector is removed, the paraboloid may continue to be used in full efficiency for photometric and spectrographic observations.

It is assumed in this writing that the reader is familiar with the terms relating to the use and construction of the paraboloidal telescope, and that readers interested in making up the attachment to be described have made at least one successful paraboloidal mirror. Both preceding ATM books contain all that is necessary to clarify anything in this discussion left undefined in the reader's mind.

The well-made paraboloidal mirror is capable of forming an image at its prime focus limited in sharpness only by the nature of light itself in relation to the adopted aperture and focal length. The image of a star on the optical axis of the mirror can then be directed into a photoelectric photometer for measurement of the quantity of light, or into a spectrograph for analytical studies. For observations of one object at a time in such wise the simple paraboloidal telescope is completely sufficient and need not be improved.

Star images formed off the optical axis of the paraboloid suffer from an aberration known as coma. The oncoming parallel bundle of light from a single star, when inclined to the optical axis, is not converged accurately by the paraboloidal shape into a sharp point image, but instead strikes the focal plane in the form of a small fan-shape pattern. The apex of the fan is directed toward the optical axis or center of the field of view. The size of the comatic flare may be measured by the total radial extent of the flare of light from the apex to the outermost ray. The coma is of such a nature that the size of the flare is closely proportional to the off-axis angle. Coma is therefore absent at the very center of the field but grows ever larger as one departs from the optical axis of the mirror.

For visual purposes the paraboloidal mirror contributes a field of view within the grasp of the usual eyepiece, sensibly free of coma. If the coma is observable at all at the edge of the field, owing to choice of a low focal ratio and wide angle eyepiece, the residual flare can be eliminated by opposite aberration introduced in the design of the eyepiece. Thus, for visual purposes the paraboloidal telescope remains the most efficient form of reflector, particularly in the Herschelian form.

Because of the perfect achromatism and possible size of the reflector, the paraboloidal mirror has been used for many decades as a photographic instrument. Some photographic work has been accomplished at the Cassegrainian focus but, for the most part, the Newtonian or prime focus has been used. Most large reflecting telescopes have a focal ratio in the neighborhood of $f/3$ to $f/6$. It is of considerable concern to the astronomer making use of such an instrument year after year as to whether his photographs have the overall

desired precision and sufficient field. In these respects the ordinary paraboloidal telescope is sadly deficient.

The photographic emulsion examines all stars focused upon it with admirable objectivity. The size of the photographic plate to be used is largely a matter of choice and may depend on the nature of the particular research in progress. For photographic work on celestial objects of small angular size, such as the fainter external galaxies, the ordinary paraboloidal telescope may continue to be all that is needed and the photographic plate used can be of convenient dimensions such as 2 by 3 inches. For other kinds of research the astronomer may wish to have photographic plates as large as 14 by 14 inches with star images sharp to the corner. Of course, the maximum plate size must be kept quite appreciably smaller than the clear aperture of the telescope where the reflector is of moderate size.

We can assume that the photographic plate will be placed perpendicular to the optical axis of the mirror and that the optical axis will strike the glass plate near its center of symmetry. Even after careful focusing for the center of the field, the observer will find a growing deficiency in the quality of the star image furnished by the paraboloid according to the distance off axis.

A paraboloidal mirror whose focal length is about five times its aperture (focal ratio $f/5$) will have a field of view on the photographic plate approximating one inch in diameter. Outside of this somewhat arbitrary circle the comatic flare becomes of such a size as to be apparent over the graininess of the emulsion or larger than the seeing disk.

The size of the comatic flare varies directly with the field angle off axis and more or less inversely as the square of the focal ratio of the telescope. For example at a given linear distance off the optical axis the coma given by an $f/3$ telescope will be reduced to one fourth its size if the telescope is stopped down to $f/6$. In turn, the usable field of the $f/6$ telescope is approximately four times in diameter and 16 times in area that of the $f/3$ telescope.

If we compare the coma of two $f/5$ telescopes, one of twice the focal length and hence aperture of the other, we see that both have the same usable field of about one-inch diameter. The one of greater focal length will form an image of a star twice as far off axis in terms of inches, as compared to the other. The coma, being an angular error, is then doubled in size on the photographic plate. At half the given field angle the coma is reduced to half. Consequently, the $f/5$ telescopes have the same linear field, as limited by the first appearance of comatic flare. The field of the 100-inch $f/5$ telescope is therefore of the order of one-inch diameter. The field of a 6-inch $f/5$ telescope would also be of the order of one-inch diameter. The useful field of the 200-inch telescope is of the order of 0.4-inch diameter. Faint star images may still appear to be point images on the photograph outside of this circle, but it is evident that much light is lost from the image with damage to the limiting magnitude.

It is for such reasons that the large telescopes suffer seriously from restricted angular field. The focal length may be very large, but with the linear size of the field fixed, the angular field becomes very small. The useful field of the 100-inch $f/5$ telescope approximates only 1 percent of a square degree on the sky, or from another point of view, it would take well over a million photographs to cover the accessible sky once without overlap. The limits imposed in this discussion may be doubled or halved according to the criterion of performance based on seeing, emulsion graininess, and opinion of the observer. The fact remains, however, that the coma of a large reflecting telescope is a serious matter.

The paraboloidal reflecting telescope suffers likewise from the aberrations of curvature of field and astigmatism. Most reflecting telescopes are built at relatively small focal ratios, from $f/3$ to $f/6$. For these the defect of coma is so large as to conceal or render unimportant the added defects of astigmatism and curvature of field.

Field curvature and astigmatism are closely related aberrations. A telescope afflicted by pure astigmatism forms an image of a star as one or the other of two short lines at right angles to one another and slightly displaced in focus along the line of sight. With respect to the optical axis the astigmatic lines are either radial or tangential line-segments of length proportional to the square of the off-axis angle. The radial lines for various stars over the field lie in one focal surface and the tangential lines in another. For the paraboloidal reflector the radial lines lie on a flat surface and the tangential lines on a spherical surface curved about the center of the mirror surface. The mean focal surface is curved and lies about halfway between the radical and tangential surfaces, all of which coincide at the optical axis.

Photographic plates used with the reflector are always flat. Star images far off axis will show both coma and radial lines. For an $f/10$ reflector on a flat photographic plate the astigmatism overtakes the coma at about 1° off axis, and predominates at greater angles. However, at 1° off axis the coma is already so large as to inhibit the usefulness of the photograph. (For a 30-inch $f/10$ the flare is already 0.25 mm in maximum length.) At $f/3$ the coma even at 1° off axis is so large that one does not even get around to wondering what the astigmatism may be.

Bernhard Schmidt made a most basic addition to photographic astronomy in 1930 when he introduced a coma-free type of telescope that now bears his name. There have been other and varied optical developments before and since, but none that reaches so directly to the heart of the problem as Schmidt's contribution. Other portions of ATM3 describe the nature and construction of the now world famous Schmidt telescope with its spherical primary mirror and correcting plate at the center of curvature of the mirror. Many amateurs have built Schmidt telescopes of fine quality and performance. Professional astronomers are turning more and more to the Schmidt telescope as the standard of quality desired in astronomical photography, and there would be a good many more such telescopes if wishes could be materialized.

The largest existing Schmidt telescope is the Palomar Schmidt with its 48-inch clear aperture (actually 50 inches are usable), 72-inch spherical primary mirror, and 14 by 14 curved photographic plate. The photographs made with this instrument leave little to be desired. The 48-inch clear aperture still places this Schmidt well behind the largest paraboloids in point of light grasp

on individual objects on axis. However, the most pertinent need now is not so much a larger Schmidt instrument as a duplicate of the Palomar Schmidt for the southern hemisphere. This need is now approximated by Harvard's conversion of its southern 24-inch Bruce telescope into a two-mirror modified Schmidt with flat field (the ADH telescope).

Without detracting from the remarkable and successful performance of the Schmidt telescopes, we can mention that the optical system has two pronounced inconveniences that lead to enhanced costs, and hence fewer and smaller Schmidt telescopes. The first difficulty is that the length of telescope tube is approximately twice the focal length, whereby the dome contains perhaps eightfold more material and design. To overcome this trouble, most Schmidt telescopes have low focal ratios, and are deemed "fast" instruments. While one gains in angular field, at least for large Schmidt telescopes where the photographic plate is but a fraction of the clear aperture, one loses in terms of "limiting magnitude." The slightly luminous night sky background photographs according to the "speed" of the telescope. An $f/2.5$ Schmidt telescope will produce pronounced sky fog in a matter of perhaps 30 minutes' exposure on a fast plate, whereas an $f/5$ Schmidt can well go on exposing for two hours or more to fainter magnitudes. For nebulosities there is little to choose, save where the fine details of nebulosity are better resolved at the larger scale. On the other hand, the star images with a Schmidt telescope are so sharp that remarkable penetration can be obtained even with short exposures.

The second inconvenience occasioned by the Schmidt telescope is that of curvature of field. The photosensitive emulsion must be caused to lie in a spherical focal surface whose radius of curvature is very accurately equal to the focal length. The curved field causes no insuperable trouble except for the smaller Schmidt telescopes, and glass plates can be made to bend to moderate curvatures without breaking. In the case of the Palomar Schmidt telescope, glass plates measuring 14 by 14 are used successfully by the expedient of coating the sensitive emulsion on an unusually thin and hence flexible glass base. Many small Schmidt cameras employ cut film.

There is a great deal of literature on the Schmidt telescope. The reader will find a sufficiently complete account in both ATMA, ATM3 and in the Harvard book on "Telescopes and Accessories." While discussion of the Schmidt very properly belongs in a chapter of this kind as a most effective instrument for photographic astronomy, we seek only to describe an alternate type of instrument adapted to the needs of those who already own the standard type of paraboloidal reflector.

It will be seen that the Schmidt instrument with its primary spherical mirror and correcting plate offers the simplest possible improvement over the paraboloidal telescope. Astronomy might get along very well with only these two forms of instrument. However, there are other considerations. Many observatories cannot afford to obtain and operate both a large Schmidt and a large paraboloidal telescope. It would be somewhat of a shame for a Schmidt telescope to be used as a light collector for photoelectric and spectrographic instruments, although such use is not out of the question. Yet it would be fine if a paraboloidal telescope could deliver Schmidt performance for photographic applications and maintain its economy of light for photoelectric and spectrographic work.

The manufacture of a large telescope is a major enterprise. If the budget is so limited as to afford a choice of but one instrument, the astronomer is naturally eager to obtain the largest clear aperture telescope that can successfully be made for the money. If one chooses the regular Schmidt form, he loses some efficiency, which in itself is not too unfortunate but, what is more important, may find that his limited funds will necessitate a decisive trimming of clear aperture. Thus, one might obtain a 60-inch $f/5$ paraboloidal telescope for the cost of a 30-inch Schmidt with 50-inch spherical mirror, or possibly a 40–40 Schmidt employed with central stop. If the 30-inch Schmidt has a focal ratio of $f/3$, then the mirror will have a focal ratio of $f/1.8$. No doubt one could design a correcting lens in the converging beam that would transform the $f/1.8$ beam into a spherically corrected $f/4$ beam for spectrographic and photoelectric work, but the perfect achromatism of the image might be partially destroyed. If, on the other hand, one chooses the simple and efficient paraboloidal mirror, one is faced with loss of photographic field and quality.

The question has been raised a number of times as to whether there are other systems that can serve all demands. Schwarzschild investigated the properties of two-mirror systems and arrived at results of varying and doubtful usefulness. Similarly, many two- and even three-mirror forms have been studied by several investigators with adequate success for certain phases of the overall problem. The addition of a second mirror is attended with loss of light both from silhouetting and second-surface reflection. A two-mirror and correcting plate system can meet photographic needs quite well, but is deficient for photoelectric and spectrographic studies because of inefficiency.

F. E. Ross has long since studied the problem of adding small lenses in the converging beam from the standard paraboloidal mirror for the purpose of eliminating comatic aberration, which for the 200-inch telescope reaches devastating proportions. Yet the comatic aberration of an $f/5$ paraboloid or even of an $f/3$ paraboloid is not large, when considered as an intermediate aberration of a compound optical system. Many all-refracting systems have prodigious amounts of coma and other aberrations at intermediate image planes but are adequately corrected at the final image plane. For the paraboloid it is simply that the coma is altogether uncorrected and hence appreciable in its effect at the prime focus. Where a correcting means can be found, the residual aberrations are likely to be negligible.

Ross stipulated that a doublet form of corrector of weak or zero optical power should be used, located near the focal plane in the converging beam from the primary. Such a lens must maintain achromatic quality, and introduce no marked astigmatism, while eliminating coma. An investigation was made of an entire gamut of these so-called zero correctors. Inevitably, elimination of coma is accompanied in a thin system of doublet form by a reappearance of spherical aberration. Ross selected a compromise form of lens,

which is limited in effectiveness for low focal ratios. Ross points out that the lens form was intended to improve the uniformity of the star images over the field for photometric purposes, and that one cannot expect overall star images as small as obtained on axis by the uncorrected paraboloid. In practice, the Ross lenses have indeed achieved the required uniformity of image, and have the inevitable softness of focus associated with removal of coma in such wise. In later years Ross has successfully developed other such lenses in connection with the 200-inch telescope. Some of these lenses succeed in reduction of coma and spherical aberration within the lens system while at the same time the speed of the 200-inch is changed from $f/3.3$ to about $f/5$ or so. The increase in scale and reduction of sky fog are desirable for certain applications.

The writer had occasion to consider these several points during the summer of 1946 in connection with a possible modification of the $f/3.5$ Schmidt telescope at Harvard's Agassiz Station. Although the modification proved financially inadvisable in the end, the computations made at the time led to a novel form of corrected telescope reported to the American Astronomical Society in December, 1947. Afterward this new type of telescope was studied in England by C. G. Wynne, who has investigated the subject of field correctors for paraboloidal mirrors in detail. His findings appeared in the *Proceedings of the Physical Society*, Volume 62, pages 772–787 (December 1949), to which the reader is referred.

It is well known that the field curvature of a positive mirror is opposite in sense to that of a positive lens system. It is likewise well known that a positive simple or compound lens can be added to an ordinary Schmidt system for the purpose of achieving a flattened focal surface. It is also well known that a positive lens located in a strongly converging beam can be caused to contribute negative astigmatism to the combined optical system. Finally, it was clear that a correcting plate added to the paraboloidal mirror with Ross correcting lens, all with redesign, would serve to eliminate the small but objectionable spherical aberration of the lens. There was no evident reason why all these benefits could not be put together to achieve a flat field photographic telescope, free of spherical aberration, coma, astigmatism, longitudinal and lateral color.

Investigations of the pertinent optical considerations were carried out in September of 1946 but, because of numerous other optical enterprises afoot, were placed aside for a time. These investigations showed that there exists a family of highly corrected telescopes feasible for practical use. Figure 1a, under the title of "reflector-corrector," shows such a system.

The optical system of the paraboloid plus the Reflector-Corrector necessarily works as an integrated unit. However, one can point out special functions of each part, even though intermingled with intermediate overlapping properties. Thus, the positive achromat has such lens power as to provide flatness of field. The same lens has such a shape as to eliminate astigmatism. The same lens is located at a certain distance in front of the focal plane in order to eliminate the coma left over from the adopted positioning of the correcting plate. Finally, the correcting plate is figured aspherically to eliminate spherical aberration.

If one intends to build a complete system for photographic purposes alone, one can choose a form for the primary mirror anywhere from an oblate spheroid to a sphere to a paraboloid and beyond. If the oblate spheroid is used, the system in the limit resembles the Wright-Väisälä form of Schmidt reflector, but is fully corrected for astigmatism and flatness of field. The oblate spheroidal primary means that the coma compensation required of the correcting lens is held to a minimum. The elimination of coma can be exact for only a chosen color for the Reflector-Corrector, owing to the nature of the simple achromat. Therefore, where the oblate spheroidal primary is used, the variation of coma with color is more or less minimized. In any case, the chromatic coma is very small compared to the original uncorrected coma of the mirror. The consideration is not sufficient to justify selection of an oblate primary over a spherical primary.

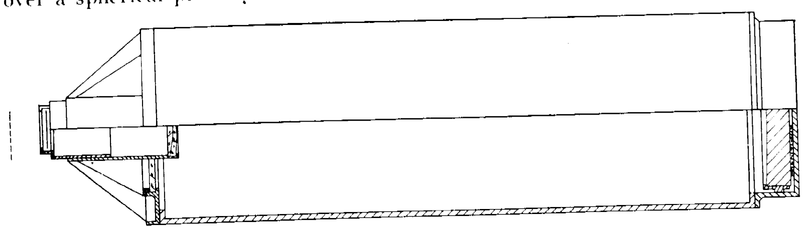


FIGURE 1a THE REFLECTOR - CORRECTOR

Drawings by the author

It would appear that the use of a spherical primary represents the easiest solution for the Reflector-Corrector type of instrument. The overall result is comparable to the ordinary Schmidt with added field flattener, except that the tube length is cut in half. It is also a convenience that the plateholder of the Reflector-Corrector system is external to the telescope and in an accessible position for loading and guiding. (*Cf.* Figure 1a). For instruments where tube length is of no importance the Schmidt form with field flattener is to be preferred over the Reflector-Corrector system with spherical mirror. For larger telescopes the reduction of tube length is a real factor. Also, the primary mirror tends toward a smaller diameter for the same vignetting present in the comparable Schmidt, or toward less vignetting of the field for the same primary mirror size.

A photographic system built up of spherical primary and Reflector-Corrector will not be as efficient for photoelectric and spectrographic purposes unless again when the corrector is removed one can employ a lens in the converging beam from the spherical mirror for use of the telescope as a light collector. In this respect, we should consider the most important question of all: can the ordinary reflecting telescope with paraboloidal primary mirror be changed over into a Schmidt-quality flat-field anastigmat by the addition of a suitable Reflector-Corrector? The answer is yes.

Figure 1a is meant to be such a system in schematic view. The focal ratio may be chosen within the range from $f/3$ to $f/6$ with satisfactory results. For the purposes of this chapter, we adopt a primary mirror of 20 inches clear aperture and 100 inches focal length which then is for an ordinary 20-inch $f/5$ prime focus telescope. As we have already mentioned, most of the important existing reflectors have focal ratios between $f/3$ and $f/6$. Any one of these can be converted into a high quality photographic instrument by the design and construction of this Reflector-Corrector type of interchangeable attachment.

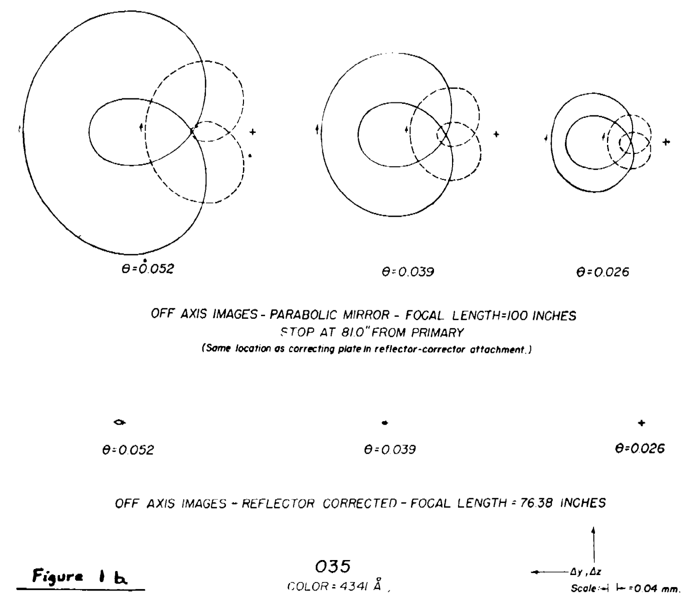


Figure 1b.

An enlarged view of the trace of a star image in the focal plane of the ordinary paraboloid before correction and for the reflector-corrector system after correction. The full line which goes through a double loop is the trace of the circular outer edge of the entrance pupil. The dashed line is the similar trace of a 0.7 zone of the entrance pupil.

Although the layout in Figure 1a is only schematic, it will be noted that the correcting plate, achromat, and photographic plateholder assembly are meant to be mounted in one rigid unit to be attached to the telescope in some convenient way. The idea is to remove the photographic attachment during the time that the primary $f/5$ mirror is in use as a light collector for photoelectric or spectrographic instruments, or for small field photographic work requiring utmost efficiency or great spectral range. Unless the tube of the telescope is unusually flexible, it is likely that the adjustment of the Reflector-Corrector will not be found critical. One has the usual tolerance on depth of focus for a precision $f/4$ beam to meet, which for good seeing is of the order of plus or minus 0.004 inch. A guiding telescope can readily be designed that will enable an observer at the side of the tube to guide on a selected field star off the side or sides of the photographic plateholder. In this way the observer has nearly the full aperture of the telescope at his disposal for selecting a bright guide star at high magnification.

Figure 2 shows a dashed line at the far left, which represents the position of the prime focus of the mirror. The addition of the positive lens not only reduces the overall distance from the mirror to the focal plane but also lessens the focal length. Figure 1b shows the state of correction of a star image at the designated radian angle off axis (approximately 1.°5, 2.°2, and 3.°0 off axis). The upper large image outlines are for the uncorrected paraboloid, a 20-inch $f/5$, with the full line from the rim of the entrance pupil or stop, and with the dashed line from the 0.7 zone of the aperture. The small lower image outlines are for the corrected star images.

Figures 2, 3, 4, and 5 provide the optical data for the particular case of the cited 20-inch $f/5$ primary. The primary mirror then has a focal length of 100 inches and a radius of curvature of 200 inches. For this system the recommended photographic plate measures 4 by 5 inches. The system is designed for blue photography with optimum results at 4341 angstroms. The compound system has a new focal ratio of approximately $f/4.5$ for an adopted correcting plate aperture of 17.0 inches. It is to be noted, therefore, that the angular field of view is somewhat larger than that obtained on a 4 by 5-inch area with a focal length of 100 inches, inasmuch as one must evaluate it from the new focal length of 76.38 inches. The 4 by 5-inch plate covers an area of about 11 square degrees on the sky.

We should note particularly how other versions of the Reflector-Corrector are to be scaled from the numerical data of this chapter. Very few amateurs or professionals will build Reflector-Correctors for 20-inch $f/5$ telescopes, and it is even more unlikely that any existing 20-inch mirror will have a focal length of 100 inches plus or minus 0.5 inch. Therefore, if the data in the accompanying figures are to apply, it will be necessary for the builder of a unit to use a scaling factor.

The important unit length of the system is the focal length of the primary. It is for this reason that a focal length of 100 inches has been chosen for the particular system presented here. Let us suppose that we have a primary paraboloid of 60 inches focal length and of an aperture between 11 and 13 inches. The scaling factor is precisely 0.60, or 60 percent. All dimensions relating to radii of curvature, thickness, and separation are then to be scaled down to 60 percent of the values given in the Figures 2–5. The diameters might also be scaled down by exactly 60 percent, but such scaling is of secondary importance. For example, Figure 3 shows that the radius of the outer surface of the flint component is 36.45 inches. Scaled down by 60 percent, the radius for the smaller system would become 21.87 inches. The thickness of the

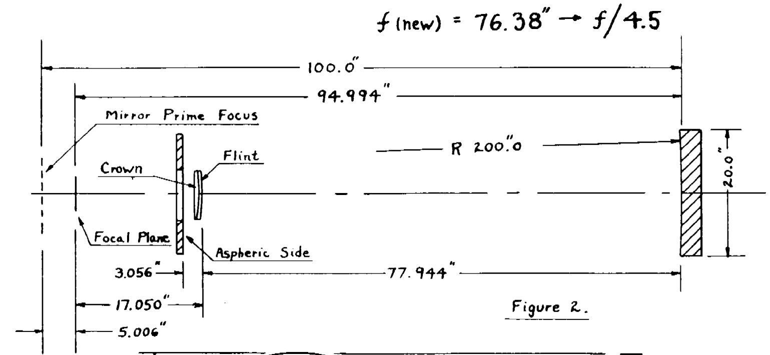


Figure 2.

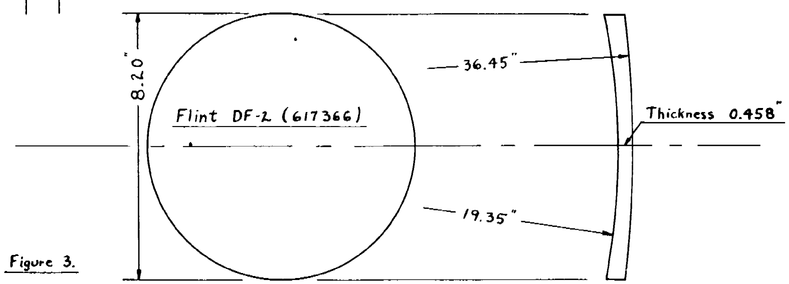


Figure 3.

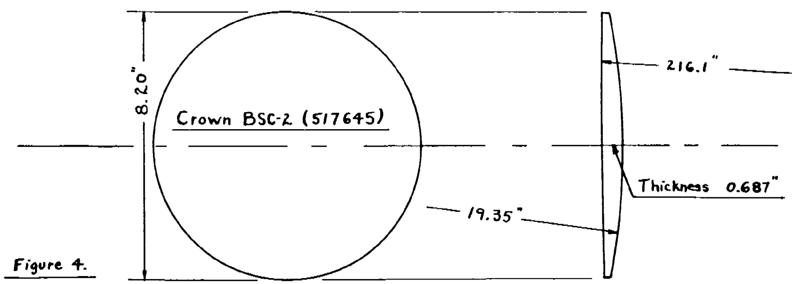


Figure 4.

lens would be reduced from 0.458 inch to 0.275 inch, etc. Lens thicknesses might safely be held within 5 percent of assigned value. Similarly, a reasonable tolerance on the radii of curvature for the cemented achromat is 0.5 percent of value, though it is easy for one to do better work.

The dimensions given in Figure 5 for the clear aperture of the correcting plate indicate a reduction from the clear aperture of the mirror. The purpose in the reduction is to accomplish uniformity of illumination over the field.

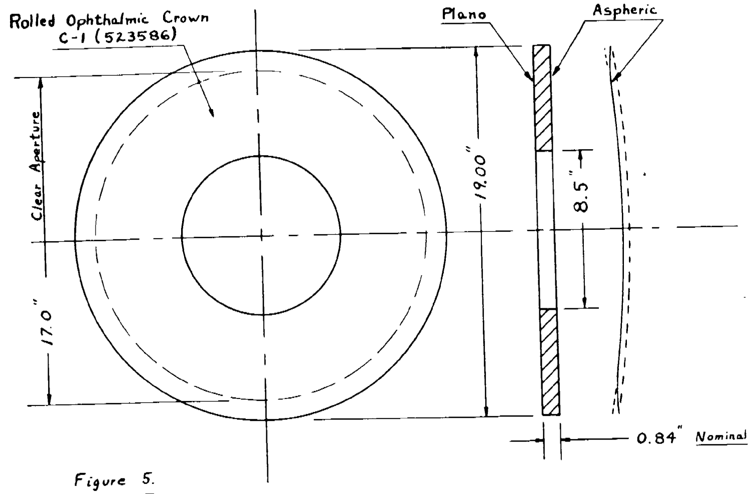


Figure 5.

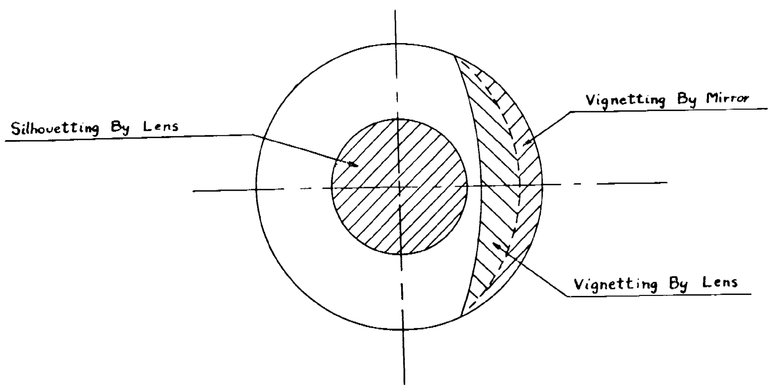


Figure 6.

One might complain at the loss of aperture, but the loss is not as great as would be required for the usual Schmidt. Thus, the 72-inch primary mirror of the Palomar Schmidt telescope takes a drastic loss in light-gathering power because it is used with a 48-inch aperture correcting plate, if we are to look at the problem in such a reversed way. Similarly, the presence of the achromatic lens of the Reflector-Corrector causes a shadow in the oncoming bundles

of starlight and a further loss in light-gathering power. The photographic plate is concealed within the same shadow, however, so that the loss is held to a minimum.

The indicated loss of light is not serious for photographic applications. Modern blue emulsions like 103a-O are so fast that an exposure of 2 hours at $f/4.5$ is all one can expect to obtain before sky fog becomes heavy. Generally, a one hour exposure is sufficient. While one might obtain the sky fog limit in 30 percent less exposure if the efficiency of the system were not so reduced, it is pointed out that the prolonged exposure recovers the lost light. Remember that the inefficiency applies to the sky illumination as well as to starlight, and it is the relative light that determines how faint one can go. All we are saying is that the observer can recover the penetrating power of his telescope simply by exposing longer. The limiting magnitude of the compound system will not be quite as good as that of the primary paraboloid used on axis, owing to the reduction of the focal length and the somewhat increased speed. On the other hand, the useful field will be increased by a factor depending on the size of the telescope. The factor approximates 40-fold for the 20-inch system described in the figures to as much as 400-fold for a 60-inch $f/5$ telescope.

The nature of a Reflector-Corrector leads to another choice that will help diminish the loss of light. Here one makes a *full-size* correcting plate with respect to the primary mirror. The diameter of the achromatic lens is increased to approximately half the adopted clear aperture of the correcting plate. A system of this kind will have more light concentrated on the photographic emulsion relative to that given by the smaller correcting plate, but the percentage of vignetting will be greater. If the vignetting is regarded as important, then an aperture stop in the form of a sheet metal diaphram can be placed halfway along the axis between the correcting plate and mirror. For the 20-inch $f/5$ primary telescope serving as the example, one might assign a clear aperture of 18 inches to this aperture stop, and 9 inches to the diameter of the achromatic lens. The vignetting would then be much reduced for photometric applications, and yet the stop can be removed for purposes that benefit from the 20-inch aperture. The particular case can be left to the maker's discretion.

In making the correcting plate one can drill out the central hole at the start. The glass plate can be brought to approximate plane-parallelism through medium Carbo stage on both sides. The plano front face can then be carried to completion even to the final figuring against a test flat. The surface figure should be smooth and spherical to within half a wave. The departure from flatness can be considerable, but it seems best to work against a master flat.

The aspheric face of the correcting plate is to be finished only after everything else has been completed. The aspheric departure from the nearest sphere is very small, and can readily be accomplished by knife-edge testing alone. As in the case of the correcting plate for the ordinary Schmidt telescope, one can place the zone of zero deviation at 70 percent of the way from axis to the edge of the aperture, or howsoever one prefers. The thing to be noted is that final figuring should follow test results carried out in blue or violet light. One can obtain a suitable filter from the Eastman Kodak Company through any of the retail outlets. Wratten 34A, called the Fluorescence Process Filter, will suffice for the violet, or Wratten 47A, called Stage Blue, for the blue-violet. Good results will be obtained even with tests made in ordinary white light, but in such case the figure might be left slightly undercorrected. The chromatic aberration of the compound system is relatively small.

Exact calculations indicate that the aspheric side of the correcting plate can profit slightly from having a general very slight convexity with the aspheric correction superimposed. The ordinary Schmidt plate makes use of such a central convexity for the purpose of minimizing chromatic aberration. While the similar purpose is served for the correcting plate of the reflector-corrector, there is also a very slight need for improving the residual chromatic aberration of the lens achromat. The matter is relatively unimportant, but nevertheless it is easy to impart such a figure to the correcting plate. Moreover, the central convexity makes it possible for one tabulation to serve for a run of focal ratios from $f/2.5$ to $f/5$.

Figure 5 at right shows the general shape of the correcting plate. The solid line represents the aspheric curve very much exaggerated. A "negative" aspheric trend is superimposed on a "positive" general spherical convexity. The coordinates for the correcting plate curve are given in Table 1. Column 1 gives the zone height, called r, in terms of inches off the optical axis. Although the correcting plate of our particular example has a nominal clear aperture of 17.0 inches, as given in Figure 5, the clear aperture can be extended as needed, either to lower focal ratios than $f/4.5$ or toward equality with the mirror aperture as described above, or both. In the limit Column 2 provides data for a system with correcting plate aperture of 40 inches for a primary mirror focal length of 100 inches. The new speed rating at full aperture is then $f/2.5$ but, as mentioned earlier, a stop placed halfway between the correcting plate and mirror can be used to advantage. A primary paraboloid at $f/2.5$ is not useful for other applications, and hence part of the purpose of the reflector-corrector is defeated. If so fast a system is desired, it would be preferable to use the ordinary Schmidt type, or the ordinary Schmidt with field flattener.

Let us suppose that a system is to be made up for a 12-inch $f/4$ telescope. The focal length is then to be 48 inches. For this purpose we must apply the scaling factor in reverse. The focal length of the compound system in Figures 2–5 is 76.38 inches. The focal length of the primary of the same example is 100.00 inches. Therefore, the focal length of the primary in the case of the 12-inch $f/4$ is $100/76.38 \times 48.0$ or 62.84 inches. If the clear aperture of the correcting plate is to be 12 inches, we can adopt an aperture of 16 inches for the primary mirror which then will become a 16-inch $f/3.93$ paraboloid. The scaling factor of 62.84 percent is now to be used on all radii of curvature, thicknesses and separations. The diameter of the achromat can be kept to approximately half that of the correcting plate, or 6 inches for the 12-inch $f/4$ camera. The useful size of photographic plate will then be 3 by 3 inches or so. The unaided $f/3.93$ paraboloid will have a useful field of about 0.6 by 0.6 inch. The added Reflector-Corrector will therefore increase the field by 25-fold in area.

For making up the correcting plate, one should apply the scaling factor of 62.84 percent to the tabulation of Columns 2 and 3, and to r of Column 1. For example, r equal to 8 inches zone height in Column 1 becomes r equal to 5.0 inches for the 12-inch $f/4$ system. The depth of curve in Column 2 for this new r then becomes −0.000 91 inch, and in Column 3, −0.000 05 inch, etc.

TABLE 1

Column 1 (inches) r	Column 2 (inches) Total Depth	Column 3 (inches) Aspheric Depth
0	0.000 00	0.000 00
1	−0.000 03	−0.000 01
2	−0.000 11	−0.000 02
3	−0.000 24	−0.000 05
4	−0.000 42	−0.000 08
5	−0.000 63	−0.000 09
6	−0.000 89	−0.000 12
7	−0.001 16	−0.000 11
8	−0.001 45	−0.000 08
9	−0.001 74	−0.000 00
10	−0.002 01	
11	−0.002 25	
12	−0.002 44	
13	−0.002 57	
14	−0.002 60	
15	−0.002 53	
16	−0.002 31	
17	−0.001 93	
18	−0.001 37	
19	−0.000 57	
20	0.000 47	

Column 2 of Table 1 gives the departure of the curve on the correcting plate from flatness. Evidently, the convexity strongly predominates unless one adopts the extreme focal ratio of $f/2.5$ or so. Column 3 of Table 1 gives the departure of the superimposed aspheric figure from the nearest sphere which has been fitted to a limiting clear aperture of 18 inches, and which will serve nicely for actual work to be accomplished on a clear aperture of 17 inches in our specific example. One notes that the aspheric figuring for this $f/4.5$ system is very slight and amounts to 6 waves of green light at the intermediate zone height of 6 inches. The sagitta of the spherical convexity at zone height of 9 inches amounts to −0.001 74 inch. One notes also that at $f/2.5$ the maximum depth of correcting plate is still only 0.002 53 inch, in terms of departure from a plane surface.

If one adopts the data of Column 2 to govern the shape of the correcting plate for the 20-inch $f/5$ primary and 17-inch clear aperture, he should first grind in a spherical convex curve leading to a sagitta of about −0.0018 inch at 9.5 inches zone height. One can then proceed to figure according to knife-edge testing. Column 3 again shows that the figuring is relatively slight.

The slight spherical convexity of the second face is occasioned in the optical design by the need to bring both the axial and corner images to best color balance for 4341 angstroms. The color residual is so slight, however, that the convexity can be ignored if convenience is to be served. The convexity is about equivalent to the addition of a weak plano-convex lens to the optical system, of focal length nearly one mile. It is easy to see that omission of such a lens would hardly affect the performance after a slight refocusing has been accomplished.

Figure 6 shows the nature of the vignetting pattern at the edge of the field. For the 20-inch $f/5$ primary converted with the Reflector-Corrector, we have adopted a photographic plate size of 4 by 5 inches. The vignetting pattern in Figure 6 is for the side of the plate. The corners of the plate are somewhat more vignetted but have relatively little utility other than one's convenience in handling and storing rectangular plates.

It is evident that the vignetting arises from both inadequate size of primary and too small an achromatic lens. A compromise is necessary, more or less as given here. Vignetting will be reduced for the same size of photographic field if one adopts a lower focal ratio and therefore larger correcting plate and correcting lens. Some compromise is necessary also for the ordinary Schmidt telescope unless the mirror reaches a diameter considerably greater than that of the correcting plate. Thus, the Harvard 24–36 inch Schmidt telescope yields an unvignetted field of 6 inches diameter, although the photographic plate used with the instrument is 8 by 8 inches. For the same amount of vignetting a Reflector-Corrector system could get by with even a 30-inch mirror for a 24-inch correcting plate.

Few things in optics are perfect, and it is necessary to examine the limitations of the Reflector-Corrector system. As long as the focal ratio is kept within bounds and the best overall performance obtained by slight axial adjustments of the achromatic lens, it appears that the most pronounced residual error is that of lateral color. This color aberration is such that a star image becomes a short spectrum directly radially outward from the optical axis. In the case of the Reflector-Corrector the lateral color arises from the so-called secondary spectrum of the achromatic lens.

Even though the star image in any one color formed at a given off-axis point may be perfectly sharp, the images of varying color lie at slightly different distances from the optical axis. Some chosen color has its image closest to the optical axis with respect to the images of other colors. In the case of the optical data of Figures 2–5 the achromatic lens has been designed

for optimum results at 4341 angstroms in the violet. Accordingly, at a point, say, 2.7 inches off the optical axis in the focal plane, the star image formed of 4341 rays focuses slightly nearer the axis than the blue or ultraviolet rays. Calculations show that the total length of the radial streak between 4000 and 5000 angstroms amounts to 0.010 mm at 2.7 inches off axis. Star images lying closer to the optical axis have proportionately smaller radial extensions. For most photographic purposes we can consider that a lateral color error as small as 0.010 mm is entirely negligible. Astrometrically, one should anticipate that blue and red stars will be slightly shifted with respect to a star of mean color, and that this shift will increase linearly from a value of zero at the optical axis to perhaps 0.002 mm at the side of the field.

The Reflector-Corrector system transmits a good deal of ultraviolet light. Bright stars may show a tendency toward formation of radial streaks, owing to the more pronounced lateral color error in these short wavelengths. Should the defect be objectionable, one can make use of a Corning glass filter, such as Corning 3850, called Greenish Nultra. Corning filters are procurable in the form of molded squares up to 6.5 by 6.5 inches. Interposition of the filter just in front of the photographic plate will displace the focal plane outward away from the mirror by approximately one third the thickness of the filter glass. Very likely, such a filter will be found unnecessary.

The residual lateral color is caused by the inability of ordinary crown and flint glass to be perfectly achromatized. The error is directly related to the color aberration of refracting telescopes, but here shows up as a defect in the lateral position of the star image rather than as a colored halo around the image point. There seems to be little possibility that the color error can be eliminated altogether. A combination of fluorite and light crown glass would suffice for photographic plates up to 3 by 3 inches, but fluorite is expensive. Optical glasses available differ too slightly to provide any noticeable improvement in color correction. Optical plastics have something to offer in this respect, and it may prove feasible to employ an achromat of CHM and light flint glass.

The longitudinal color error is very nearly negligible in this compound system. Thus, ultraviolet, violet and blue focus practically at the same point on the optical axis, and the central part of the field will show sharp, color-free star images. In the design given in Figures 2–5, wavelengths 4047 and 4861 have been combined accurately even within the small secondary spectrum remaining. The departure of the minimum focus of 4341 from the focal point for 4047 and 4861 amounts to only 0.000 022 of the focal length of the compound system, in this case 0.043 mm along the optical axis. One cannot detect any change in quality of star images on a photograph within a range of plus or minus 0.100 mm at $f/4.5$. Hence, it is clear that the entire violet-blue spectral region will be in simultaneous focus when the Reflector-Corrector is used.

If the compound system is used for photo-visual photography with 103a-G emulsion and Wratten Minus-Blue No. 12 filter, or Corning 3385 Noviol Shade C glass filter, there may exist a slight need for refocusing by 0.1 mm or so.

Ideally, because of the lateral color, one should have another interchangeable achromat redesigned for green light. For all amateur use, however, the one violet-blue achromat will suffice. The residual lateral color necessarily increases in green light but the spectral range is short.

Similar considerations hold true where the system is to be used in red light with 103a-E emulsion and Wratten 25A gelatin filter, or Corning 2418 H.R. Traffic Red. The professional astronomer might wish to have two interchangeable achromats, one figured for violet light at 4341, and the other a compromise lens for yellow and red work with optimum design for 5800 angstroms. The amateur can get along quite well enough with but one achromat according to the design of this chapter. Again, the lateral color increases rather rapidly in red light but the spectral range is so short as to minify the error. In any case, the improvement over the unaided paraboloid is drastic.

With respect to the monochromatic aberrations, calculations (Figure 1b) indicate that there may remain a slight comatic flare at the edge of the field of the order of 0.035 mm total extent. So small an error may not appear on the photographs and will be partly eliminated anyway by the vignetting of the upper rays of the aperture. However, one can experiment with small axial adjustments of the achromatic lens, or correcting plate, or both together, for the purpose of obtaining the best sharpness of image over the field. For this purpose one should design a spacer ring or rings in the mounting of the optical parts to facilitate such adjustment. Movement of the correcting plate along the optical axis is likely to be insensitive as a means of adjustment and it is recommended that such adjustment be carried out with either the lens alone or with lens and correcting plate together. The data given in Figure 2 may indicate need for precision construction, which is not the case. Measurement with an ordinary steel rule or tape should suffice.

Residual astigmatism and field curvature are entirely negligible for angular fields within the grasp of the Reflector-Corrector. The initial error in the images formed by the primary paraboloid is small, and yet in principle this error can be compensated completely by the Reflector-Corrector. Any residual astigmatism that appears may arise from slight maladjustment of the Reflector-Corrector or slightly imperfect curves.

The distortion is given by the displacement of the star image at a given off-axis point from where it should be for perfect reproduction of projection of a sphere onto a plane through a point of perspective. The distortion varies closely as the cube of the field angle. For the 20-inch $f/5$ system the calculated distortion at 2.5 inches off axis amounts to only 0.012 mm. The error is of no consequence except to astrometric work where its effect would normally be removed by proper reduction. For the amateur distortion in this sense means nothing at all.

If possible, the design for the plateholder assembly should call for a slightly tapering light-tight sleeve between photographic plate and correcting lens. Otherwise, off-axis bundles of light are sufficiently inclined to the optical axis to cause increased shadowing by a cylindrical sleeve. The taper required is not considerable, amounting to only 0.6 inch in 17 inches of length.

One might build up a light welded cage of tubing with a sheet metal surround. Similarly, supporting fins indicated in the schematic arrangement of Figure 1a should be streamlined to prevent excessive shadowing of starlight. The design of the reflector-corrector at start was chosen to locate the correcting plate at the approximate center of gravity of the over-all attachment. The correcting plate itself can be used to support the main weight of the lens and plateholder assembly by means of some form of clamping ring and shoulder. The inclined fins can be used, then, to prevent twist and pivot of the assembly.

The Reflector-Corrector unit described in this chapter reaches its most effective form for telescopes of intermediate size. It is unlikely that correcting plates larger than 60 inches will be made in the foreseeable future. Moreover, for telescopes as small as 10 inches clear aperture, one can equally well use a Schmidt with field flattener, and a separate paraboloid in a dual mount. The Reflector-Corrector will then be most useful for telescopes having primaries ranging from 20 inches to 60 inches in diameter. Many telescopes of such size are in existence and hence can be converted into photographic instruments of approximate Schmidt quality. Where the primary mirror is 60 inches, the photographic plate can well measure 14 by 14 inches. In turn, removal of the Reflector-Corrector will make the telescope available for photoelectric and spectrographic work in its fullest efficiency.

Amateurs will be interested in smaller instruments with primary mirrors of 12 or 16 inches diameter. If the telescope has an adopted clear aperture of 12 inches for the correcting plate, the amateur can expect to photograph stars as faint as the 18th magnitude.

Part II. Two Photographic Lens Designs

Telescope making as a hobby seems to grow with the years, and there is an ever increasing interest in phases of optics that go beyond the construction of the simple paraboloidal reflector. In recent years amateurs have made successful refracting telescopes and Schmidt cameras. During World War II amateurs contributed in a number of ways to the national effort, and many became professional opticians during the period.

The average amateur must always work within a very limited budget and do the best he can with simple materials. This is one reason why the reflecting telescope has been so popular. For a few dollars the amateur can make up a sizeable telescope. The author remembers that his 8-inch reflector of college days would have cost no more than $35 even now.

Because there have been many queries by amateurs concerning compound lens designs for use in astronomical photography, the author believed it would be useful to contribute several designs within the budget possibilities and equipment of the amateur, while at the same time keeping astronomical needs foremost. The Reflector-Corrector described in Part I of this chapter can serve as a means of obtaining a relatively large clear aperture for photographic uses over limited angular fields but to faint limiting magnitudes. For photographic work covering a wide angular field with less penetration, the amateur must resort to photographic lenses. Elsewhere in this volume, one can obtain full information on application of existing commercial lens types to astronomical photography, as well as designs for making up relatively small lenses to cover wide angular fields. It is the purpose of the author to provide here a lens type within the needs of the amateur that at the same time will yield high resolution and light-gathering power over moderate angular fields.

There are many hundreds of lens designs made possible by combinations of a number of positive and negative lens elements of many types of optical glass into an integrated grouping. One can well ask, why so many designs and what do they accomplish?

Compound lens systems differ among themselves according to the specific application to be served. A wide angle lens system of speed $f/11$ may require entirely different treatment from the design of a lens of speed $f/1.5$ covering but a few degrees of field. Commercial lenses compete among themselves according to speed, field, and economy. Performance is generally expected to be satisfactory, and there have indeed been pronounced gains in the overall image quality. However, a commercial lens is designed to be as simple as possible for the results gained, and wide margins of image imperfections are often allowed. For example, no commercial designer worries overly much about the color residuals that plague the astronomer.

The astronomical applications of photography cover a very large spectral range. As a result, the residual color errors of an all-refracting lens system reach marked size. The reader may have read elsewhere in these volumes of the secondary spectrum that limits the perfection of the refracting telescope. The same color error is present in the photographic lens but much enhanced by longer spectral range and lower focal ratios. The aberration appears as a dependency of focal position along the optical axis on color. A lens normally termed "achromatic" has been corrected to a good first approximation for the longitudinal color. The "secondary spectrum" is the color error left over, and appears as a quadratic variation of focal position with color. Some chosen color generally lies at a minimum distance from the lens system. Colors of the spectrum on either the shorter or longer wavelength side of the mean color will then focus farther from the lens system. Visually, the adopted minimum focus lies in the yellow-green part of the spectrum, with red and blue focusing farther from the lens, and violet and infrared still farther from the lens. The progression of colors is continuous. Hence, a star image formed by a visually corrected refracting system will show a central sharply focused disk formed principally of yellow-green light, surrounded by a color halo of blue and red.

The position of the minimum focus along the spectrum can be assigned by the designer. Moreover, the effective performance of the lens is determined approximately by the position of focus of the 70 percent zone of the clear aperture. Commercial lenses are often designed such that the D and G′ lines of the spectrum (5893 and 4341, respectively) are brought to a common focus for the 70 percent zone of the aperture with minimum focus in the blue or

blue-green. On the other hand, lenses designed specifically for aerial photography with yellow or red filters have a minimum focus in orange light.

The residual color error of the average lens is so large that star images suffer badly. The observer of course will focus the lens to go with the particular emulsion and filter combination, but the rate of change of focus with color is pronounced. The importance of the residual defect depends also upon the focal ratio of the lens.

If a lens has been designed for optimum performance in green light, it is quite normal for the error in focal position to amount to 1 percent of the focal length in the near ultraviolet. A lens of 21 inches focal length will then produce an error in focus of the order of 0.21 inch, or about 5 mm. If the aperture ratio is $f/4.5$, then the image diameter for the extreme color is about 1 mm, which is a very bad error. Normally, one would focus for best results in blue-violet and the out-of-focus error would be cut in half, but the error is still bad. Even a 12-inch $f/4.5$ lens designed for panchromatic use will yield an average image error diameter of perhaps 0.25 mm in the blue-violet where 0.025 mm is to be desired.

Nevertheless, lenses have been used in this way, and often seem to give pretty good results. What is the rub? The point is that, for star photographs, the lens serves as its own filter. The out-of-focus ultraviolet light is so reduced in surface brightness as to be recorded only for the brightest star images. The fainter star images show as good points, but only because the out-of-focus halos are too weak to record. The strong color error therefore does not show up to the disadvantage of the appearance of the star photograph, except where the user becomes critical and wonders where all the starlight is going. The limiting magnitude is directly affected. A Schmidt photograph for the same aperture and focal ratio will show much fainter stars than will a photograph taken by an ordinary lens system.

A star field photographed with a lens may, then, appear to be very satisfactory and redound to the pride of the owner. However, the owner should ask himself which part of the lens aperture he is using to form star images. Moreover, the owner should examine the structure of the brightest star images before becoming too pleased with the faint images. Aberrations that leave a sharp central peak of brightness in the star image will behave much as the color error. Fainter star images will look like good points, but the brighter images may show a large and varied structure. The limiting magnitude is the give-away. The speed rating of a lens is often a poor criterion of its light-gathering power for stars, and the limiting magnitude may vary over the field. Even a simple $f/2$ condenser lens will show passable star photographs, although only a few percent of the entering light is used to form an image.

There are other considerations relating to aperture and focal ratio. The effective speed of an astronomical lens system is not necessarily indicated by the focal ratio except for luminous surfaces. The reader should examine Table 2, which relates limiting magnitude to focal ratio and aperture. It will be seen that the $f/7$ lens can photograph fainter stars than the $f/3$ lens of the same diameter. This gain is achieved solely by increase in exposure time. The $f/7$ lens is slower in speed for photographing the luminous night sky background than the $f/3$ lens. The light-gathering power for stars, on the other hand, depends on the clear aperture, at least for systems of moderate focal length. Consequently, the $f/7$ lens permits a long exposure before sky fog becomes serious, and fainter stars are thereby recorded over what the $f/3$ lens can do.

TABLE 2 *

Aperture		$f/3$		$f/5$		$f/7$	
Cms	Inches	Image Diam. mms.	Lim. mag.	Image Diam. mms.	Lim. mag.	Image Diam. mms.	Lim. mag.
1	0.4	0.023	10.20	0.026	11.18	0.028	11.84
2.5	1.0	.024	12.15	.027	13.12	.030	13.74
5.0	2.0	.025	13.61	.029	14.55	.032	15.18
7.5	3.0	.026	14.44	.031	15.36	.035	15.96
10.0	3.9	.027	15.03	.032	15.96	.037	16.51
15.0	5.9	.030	15.80	.036	16.71	.042	17.27
20.0	7.9	.032	16.35	.040	17.21	.047	17.77
25.0	9.8	.034	16.77	.043	17.62	.052	18.15
30.0	11.8	.036	17.10	.047	17.92	.058	18.42
40.0	15.7	.041	17.58	.054	18.39	.068	18.88
50.0	19.7	.045	17.96	.061	18.75	.078	19.21
60.0	23.6	.049	18.28	.069	19.01	.088	19.48
75.0	29.5	.056	18.61	.080	19.33	.103	19.79
90.0	35.4	.062	18.90	.091	19.59	.119	20.04
100.0	39.4	.067	19.05	.098	19.74	.129	20.17

* Table from Whipple and Rubenstein, *Popular Astronomy*, 1942, by permission.

An $f/7$ lens can be used for two hours or more with 103a-O emulsion before sky fog becomes objectionable. An $f/5$ lens would show a fairly black plate in a two hour exposure. An $f/3$ lens can be exposed for perhaps half an hour or so. Now, if we examine the table and compare the performance of a 6-inch lens at $f/7$ and at $f/3$, we see that the $f/7$ lens can reach stars of 17.27 magnitude, whereas the $f/3$ lens can reach only 15.80. From another point of view a 6-inch $f/7$ lens can do as well in limiting magnitude as a 12-inch $f/3$ lens, namely, about 17.3.

The personal preference of the author is for lens systems from $f/4.5$ to $f/7$ for the purpose of increasing the penetrating power of the photographic telescope. As we shall see shortly, there are other cogent reasons why focal ratios up to $f/7$ are to be preferred. Professional astronomers in general will also prefer greater penetration over the wider angular fields and smaller scale of the "faster" lens systems.

Schmidt systems are often of the order of $f/3$ or so, partly because of the need to conserve tube length and partly to provide an increased angular field. The best all-around speed for Schmidt telescopes of large size is probably $f/3.5$. For lens systems, the best all-around speed will depend on the application. The author feels that the color errors of lenses of focal ratio smaller than $f/7$ rule against adopting these lower focal ratios, and that the fast modern blue plates make $f/7$ an acceptable focal ratio for precision lenses. Even in the absence of color aberration, an $f/7$ rating makes it possible for a small lens to do the work of a larger $f/3$ lens, and in practice the $f/3$ lens wastes still more light relatively because of aberrations.

The color aberration of lenses of small focal length is of lesser importance. The focal ratios of such lenses can then be reduced to $f/4.5$ or even to $f/3.5$ if we overlook sky fog as a consideration. Lenses of 50 inches focal length or more had best stay close to $f/7$. The Petzval lens with field flattener is an exception to the rule. For Petzval lenses the secondary spectrum is approximately two thirds normal and a focal ratio of $f/4.5$ is not unreasonable. The Harvard 16-inch has such a doublet construction but employs a curved field instead of a field flattener. The focal ratio of this lens is $f/5$, but the secondary spectrum is no greater than that of a 12-inch $f/5$ symmetrical lens. On the other hand, so-called telephoto lenses have pronounced secondary spectrum, and except for short spectral regions or small focal length the use of such lenses is not to be recommended. Aerial photographic lenses of telephoto construction are particularly bad for astronomical blue photography, though usable in red and yellow light with proper filters.

Various types of lens designs have been used for astronomical photography. The two forms that have been more or less standard through the years are the Cooke triplet and the F. E. Ross four element lens. In Europe some use has been made of a four element Tessar construction, which resembles a Cooke triplet with a cemented doublet as the rear component, and of a four element form which resembles a Cooke triplet with its front element divided into two positive elements.

There are many specific forms of Cooke triplet and the quality of image correction varies over a wide range. The residual errors will depend on glass types chosen, on distribution of powers, on the adopted focal ratio, the color correction, etc. In general, it is advantageous to employ glass types with high indices of refraction. A properly designed Cooke triplet will exhibit negligible lateral color, and the mean focal surface can be made quite flat. Usually, there are appreciable residuals of zonal aberration (residual spherical aberration), coma, astigmatism, distortion, oblique spherical aberration (reappearance of spherical aberration in the outer part of the field), chromatic spherical aberration (variation of the spherical aberration with color), and of course the inevitable secondary spectrum.

The Ross lens form has added much to the photographic equipment of astronomers and can be made superior to the triplet in one or more respects. The usual Ross lens does have some chromatic spherical aberration which is concealed on star photographs by the above-mentioned failure of the emulsion to record out-of-focus halos, except for bright stars. If the chromatic spherical aberration is eliminated by the expedient of employing a relatively long lens barrel with respect to the focal length, then the astigmatism residuals become comparable to those of the Cooke triplet of similar length. In such case the Ross form offers no real advantage over the simpler triplet form.

There exists a more elaborate form of Cooke triplet which in the limit is to be preferred over the ordinary triplet or Ross type. This lens form is related to the triplet, but the first and third components are cemented doublets (Pentac or Dynar basic form). By proper design it is possible to eliminate spherical aberration not only on axis but also at a chosen off-axis angle. The same off-axis angle can be used as the node for the intersection of the radial and tangential focal surfaces. Consequently, such a lens is capable of showing sharp star images in an annulus quite far off axis of a degree of purity normally obtainable only on the axis. Intermediate field angles show images not far from desired perfection, and the field need not be extended much beyond the annulus of good definition.

More elaborate lens forms can be corrected for all these things. One can obtain essential freedom from such aberrations as longitudinal color (except for secondary spectrum), lateral color, spherical aberration, coma, astigmatism, field curvature, distortion, chromatic spherical aberration, chromatic coma, chromatic astigmatism, chromatic distortion, zonal spherical aberration, zonal coma, oblique spherical aberration, oblique coma and balancing of all of these foregoing aberrations in the form of small residuals against uncorrected hybrid higher-order aberrations. Such lenses are necessarily expensive, and out of the reach of an amateur's time, budget, and interest. Moreover, such lens forms may be very useful for ordinary photographic applications of limited spectral range, but not necessarily for astronomical photography. These lenses still have the usual magnitude of secondary spectrum, which then remains the chief disadvantage to the astronomical user. As long as it is necessary to design and build lenses for specific spectral regions, it would appear that emphasis should be placed on simplicity of construction, good transmission, and quality of monochromatic image formation.

There are a few forms of apochromatic astronomical lenses that may sooner or later become of interest to amateurs. The word apochromatic in its strictest sense goes far beyond ordinary achromatism. An apochromatic lens should have not only three widely separated colors brought to a common focus, but should also be corrected for spherical aberration and coma at two widely separated colors. There is little purpose in replacing a colored blur by a white one. Hence, an apochromatic lens should at least match the monochromatic performance of the ordinary lens.

It is feasible to design an apochromatic flat-field anastigmat based on the Cooke triplet form, wherein the negative central element is made up of two negative crown elements cemented around a central fluorite element. In this way one might design an apochromatic lens at $f/7$ up to 8 inches clear aperture that would cover the spectrum adequately for blue, yellow and red photography. The cost of fluorite is very high, however, and only a major project could finance such a lens.

The author debated the question of designing for this chapter some four- or five-element lens form, but came to the conclusion that for a start the amateur will be better off with a satisfactory triplet lens. In this way the glass costs are moderate, the transmission high, and the amount of work limited.

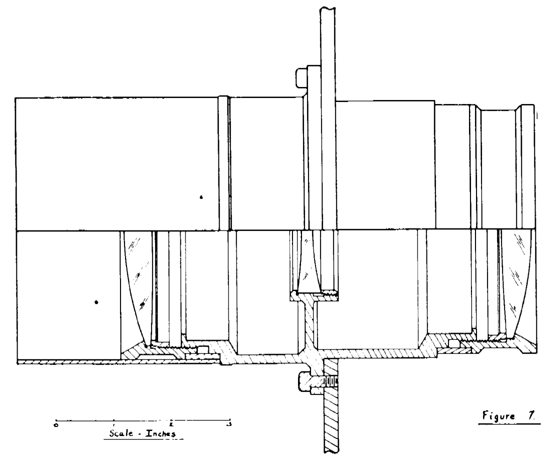


Figure 7

Two designs of Cooke triplets are provided below, one for blue-violet photography with 103a-O or similar blue-sensitive emulsion, and the other for photo-visual work. The design work was based on the supposition that the focal length could be scaled according to the wishes of the individual maker, and that $f/7$ lenses up to 6 inches clear aperture might be desired. The plate size for the 6-inch $f/7$ lens is normally 8 by 10 for most types of research where precision takes precedence over field angle and more expensive plates. Both of the specific designs given in the accompanying figures are for 3-inch $f/7$ lenses. The recommended plate size therefore becomes 4 by 5 inches, which will be well within the average amateur's needs. A readjustment of curves would permit extension of the field for the 3-inch lens to the 8 by 10 plate, but in so doing, the average quality of image would suffer. Those who can afford the effort will get the most satisfaction out of making up the 6-inch $f/7$ lens for 8 by 10 plate, but even a 3-inch lens is a useful thing.

Examination of Figure 7 shows the reader that the clear aperture of the front element is 4 inches, for a lens system which we call a 3-inch. The purpose here is to eliminate most of the vignetting that would result if too small outer elements were employed. One can trim down the clear apertures of the first and third elements if he so desires, but some degree of vignetting will be introduced. As it stands, the vignetting does not begin until a point 2.5 inches off axis is reached, and even in the corner amounts to only a few percent.

Two separate lens designs are given. The first, given in Figures 8, 9, 10, 11, 12, 13, and 14, is designed for optimum performance at 4341 angstroms in

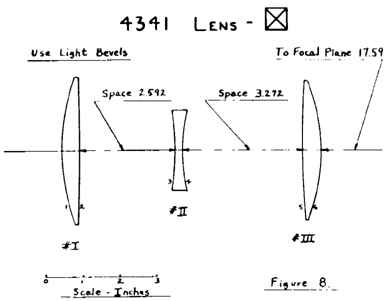


Figure 8.

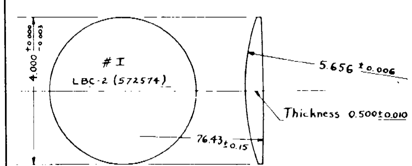


Figure 9.

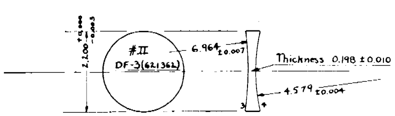


Figure 10.

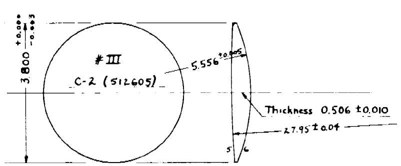


Figure 11.

the violet. The second, given in Figures 15, 16, 17, 18, 19, 20, and 21, is designed for optimum performance at 5461 angstroms in the green. The first lens is intended for use with blue-sensitive plates. The second lens is to be used with a yellow-sensitive emulsion such as 103a-G, together with a minus-blue filter, such as Wratten No. 12, or Corning No. 3385. The second lens may also be used successfully with a red-sensitive emulsion and red filter and focused for the new combination. For professional use, there should be a third lens designed for optimum results at 6300 angstroms in the red. For the time being, the second lens form will serve.

The accompanying figures are intended to give all the necessary information for fabrication of either or both of the triplets. However, almost everyone has his own ideas and in any case may have to adapt machine designs to his

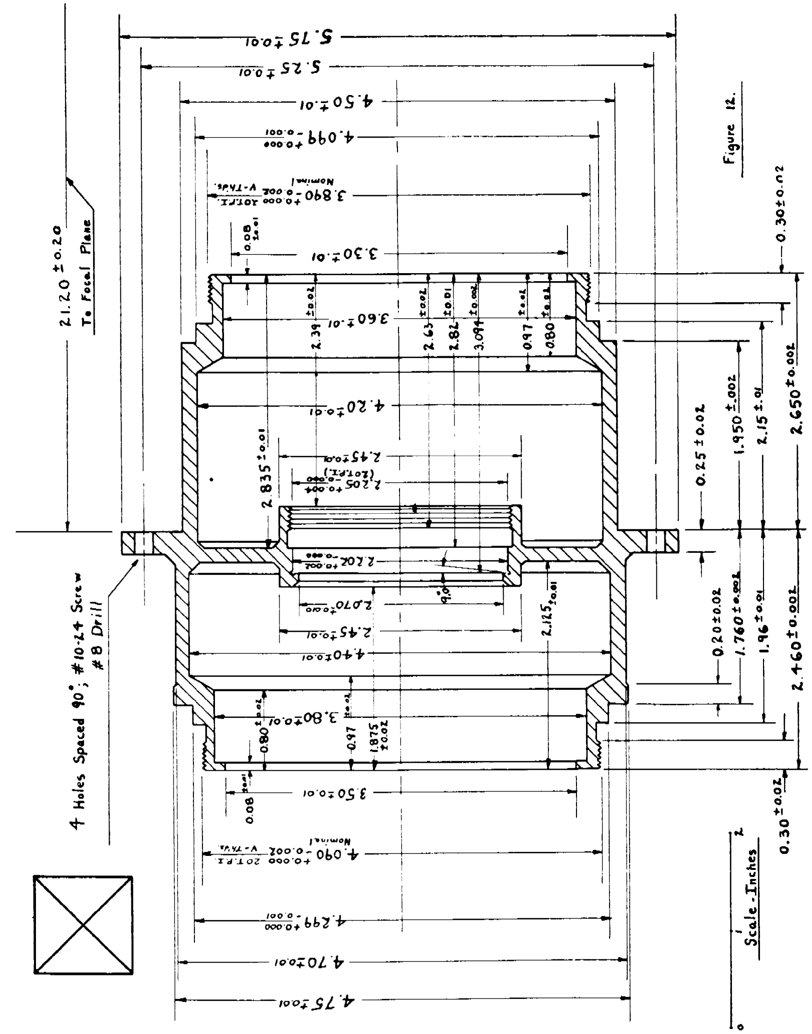
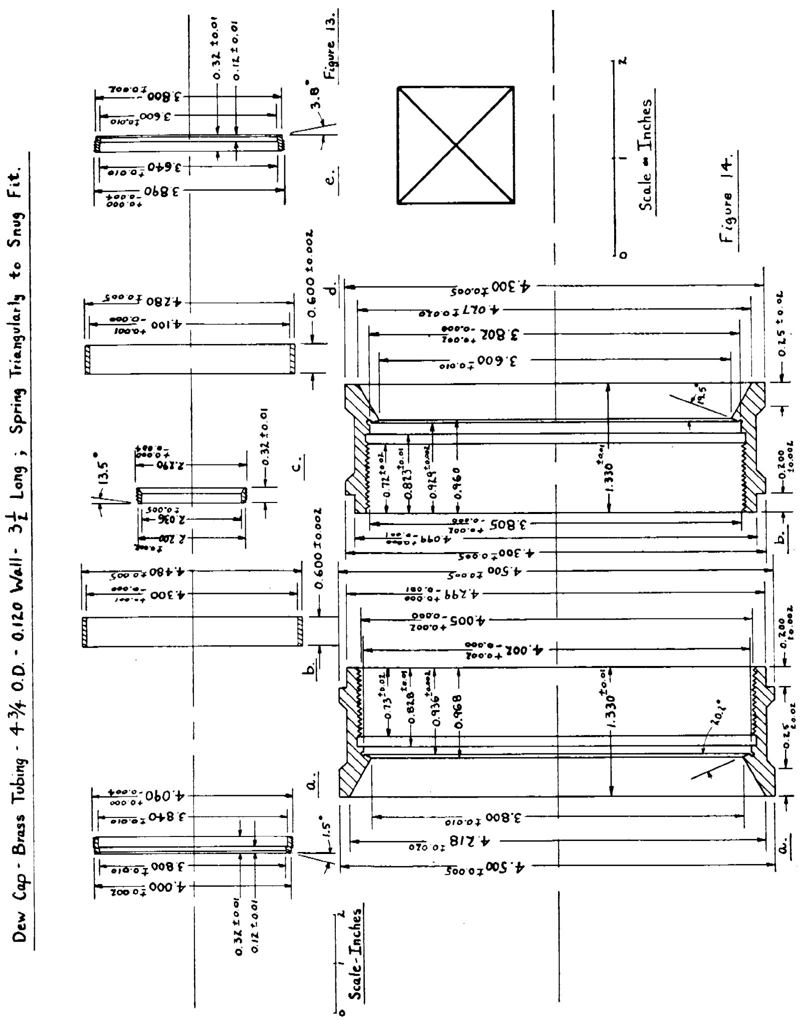


Figure 12.



equipment. The drawings can be used to establish fundamental dimensions for anyone undertaking a redesign of the metal mount. The mounting is essentially the same for both designs, and differs mostly in the width of the spacer rings and in several of the clear apertures.

The tolerances reproduced in the figures are possibly too small to decipher. Lens elements should fit into their cells with reasonable snugness and be held by the retainer rings with something between a light and a firm pressure. The several dimensions that relate to the airspacing of the elements are to be held to individual tolerances of plus or minus 0.002 inch. In the end the axial positions of the lens surfaces should be within plus or minus 0.015 inch of the assigned values.

The pertinent portions of ATM and ATMA referring to lens making ought to be studied by the amateur interested in making up one of the triplets. At $f/7$ the lens elements are not sensitive to adjustment. However, good workmanship should apply, if only a matter of pride. The only extra word of warning to be given here is not to hold the lens cells in a three- or four-jaw chuck, if it can be avoided. In any case the turned parts should be under no appreciable stress.

The mounting design incorporates spacer rings, as shown in Figure 13b and 13d. Variations in melts of optical glass will cause slight changes in image quality which can be eliminated by proper adjustment of the airspaces. The adjustment can be accomplished with the spacer rings omitted from the assembly, and the screw threads used as a micrometer. Thereafter, the exact value for each spacer ring thickness can be measured and the proper rings inserted.

Both of the triplet designs are safely within the Rayleigh diffraction limit at $f/7$ for a 3-inch aperture. Under the knife-edge, however, the observer will see a zone of undercorrection in the axial image. There is no real purpose in correcting this zone by hand figuring, but many amateurs may wish to add this bit of finesse to their work. The slight figuring is best done on the front surface of the central element. Foucault testing is best carried out in the color of light for which the lens is designed. The first lens should be tested in violet light, and the second lens in green light. (*Cf.* recommended filters for similar application in Part I.)

In the outer part of the field a knife-edge test will show some overcorrection of the outer rim of the aperture, but only in the shape of lunes to the right and left with respect to horizontal off-axis tilt. Figuring comes easy to the amateur, and hence it is recommended that this slight overcorrection be figured out of the lens at an image point 2.25 inches off axis. Even without the figuring work, the star field will show sharp images in the outer field, but with the figuring, the light grasp of the lens will be slightly improved. The aspheric work is of the nature of a turned down edge and is easy to do.

In order to clarify the testing set-up, let us consider for the moment that we are looking down on the test bench. We are to test the lens in parallel light produced by a paraboloidal mirror and light source at its focus. Now we rotate the lens off axis clockwise as seen from above by a tilt of 6°.

Now as the observer sits down at the end of the bench to carry out a knife-edge test, the optical axis of the lens will be on his left.

The clear aperture of the front element is 4 inches, whereas the central bundle of light from a single star is but 3 inches in diameter, as limited by the clear aperture of the negative central element. It is evident that the outer half-inch annulus plays no role in forming the axial image. Hence, the figuring of a turned down edge on the outer half-inch annulus of the back

5461 Lens - ⊕

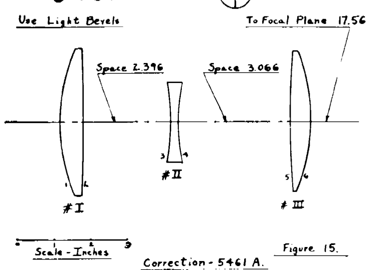


Figure 15.

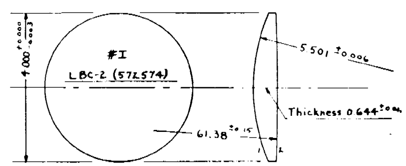


Figure 16

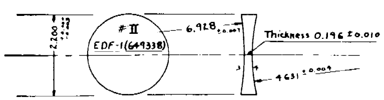


Figure 17.

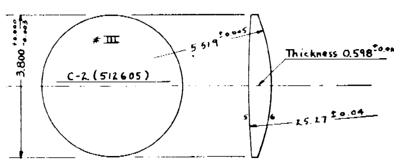


Figure 18.

surface of the front element will serve to reduce or eliminate the slight over-correction present in the image 6° off axis, without affecting the quality of the axial image. Similarly, the outer 0.65-inch annulus on the inside surface of the rear element can be figured to a turned down edge. Figuring of the front element removes the overcorrection apparent in the left-hand lune as seen in the Foucault test, and figuring of the rear element eliminates the over-correction in the right-hand lune. The figuring should not encroach on the central 3-inch clear aperture of the front element or on the central 2.5 inches of the rear element. The Foucault testing should not be overdone, and should be supplemented regularly by eyepiece testing. The idea is to obtain as round an image as figuring will permit. Too close figuring by knife-edge may instead produce a slightly astigmatic image.

Although the author believes that these two triplet designs are about the

most satisfactory that can be accomplished with such standard glass types, where both distortion and chromatic spherical aberration have been removed, nevertheless the amateur can hardly expect images that compare with the quality obtained with his on-axis paraboloid. A certain amount of judgment is required in assessing the best overall image quality, and it should be remembered that the faster photographic plates are unable to distinguish appreciable difference between a diffraction image or a slightly imperfect image.

The removal of the chromatic spherical aberration means that the secondary color is about the same over the entire aperture of the lens. Hence, the minimum focus for the first lens is about the same in wavelength for central rays of the aperture as for the 70 percent zone, and placed at 4341 angstroms. From another point of view, the central image is free of spherical aberration over a considerable spectral range and it is only the secondary spectrum that prevents a perfect image. The calculated secondary spectrum is of normal magnitude for symmetrical anastigmats. At the F-line, 4861, the focal shift amounts to 0.000 829 of the focal length with respect to 4341. For a 3-inch $f/7$ lens the shift is then 0.442 mm. The corresponding error on the ultraviolet side of 4341 occurs at about 3900 angstroms. Now an $f/7$ lens will have a depth of focus for sharp images of the order of plus or minus 0.15 mm or 0.30 mm in all, to be compared to 0.442 mm for the color spread of the 3-inch $f/7$ lens. It is clear that the 4861 and 3900 radiation will lie outside the mean focus and produce enlarged images for the brighter stars. For these outlying colors the central portion of the lens aperture is still contributing to the mean central image, but a portion of the aperture is wasted.

As pointed out earlier in detail, these harsh facts are characteristic of lens systems of ordinary optical glasses. Consider the difficulties of the 20-inch $f/7$ astrographic lens of the Lick Observatory, which has nearly 7 times the above-described focal error. Evidently quite an appreciable amount of light is lost from the star images in outlying colors with consequent effect on the limiting magnitude. The star photographs are nevertheless of pleasing appearance, and have the desired astrometric qualities.

The two triplet designs given here are somewhat unusual in being well corrected for distortion, and are therefore well suited to astrometric measurements. The calculated distortion for the 3-inch $f/7$ lens in the outer part of the field amounts to only one or two microns (0.001 mm) in terms of the shift in the lateral position of the star image from where it ought to be. The lateral color error is nearly as small, and amounts to only a couple of microns between 4000 and 5000 angstroms, except in the very corner of the plate. The mean field for both lens designs is essentially flat. A slight amount of astigmatism will be discernible monochromatically in the intermediate part of the field, but photographically will be concealed by the secondary spectrum. That is, the photographic plate is of approximate uniform sensitivity along the spectrum surrounding 4341 and the emulsion will select those colors most nearly in focus. Field curvature and astigmatism when small simply cause a slight shift in the color or colors in focus at a given off-axis point. Therefore, one can anticipate quite sharp star images to the very corner.

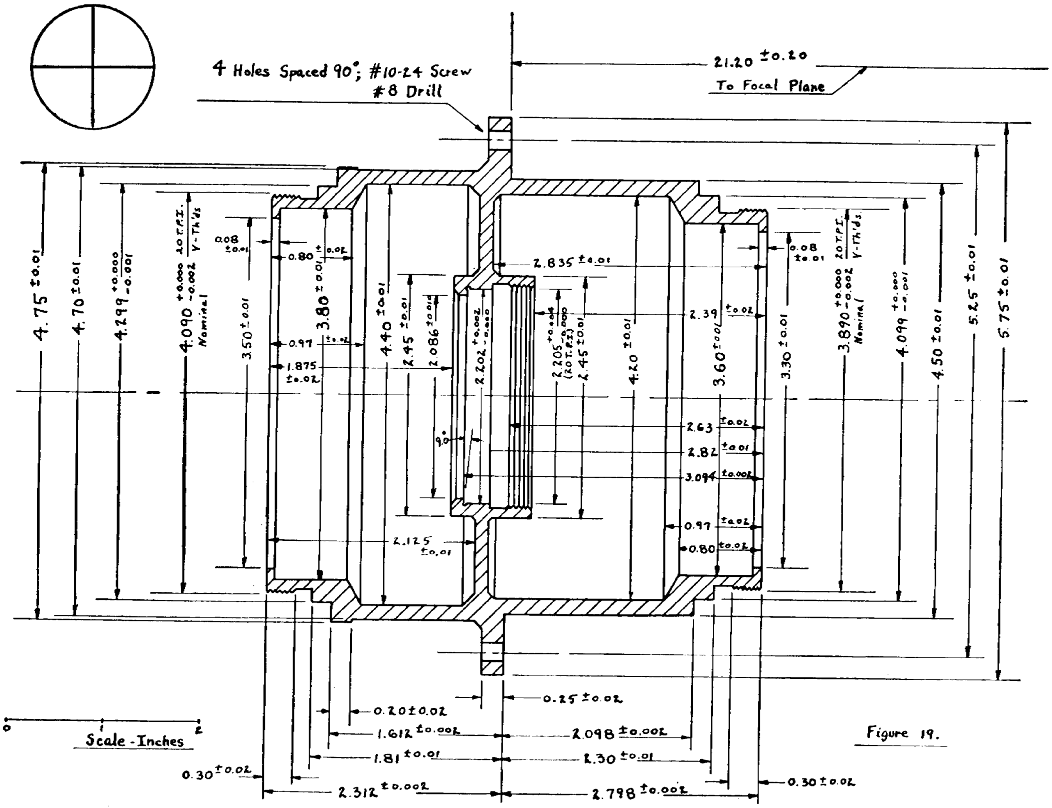


Figure 19.

Dew Cap - Brass Tubing - 4 3/4 O.D. - 0.120 Wall - 3 1/2 Long ; Spring Triangularly to Snug Fit.

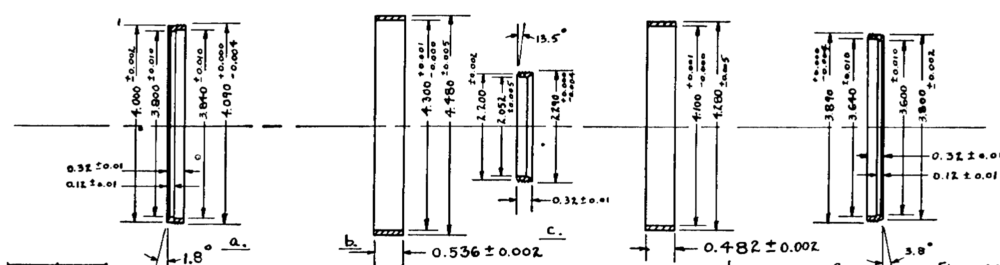


Figure 20.

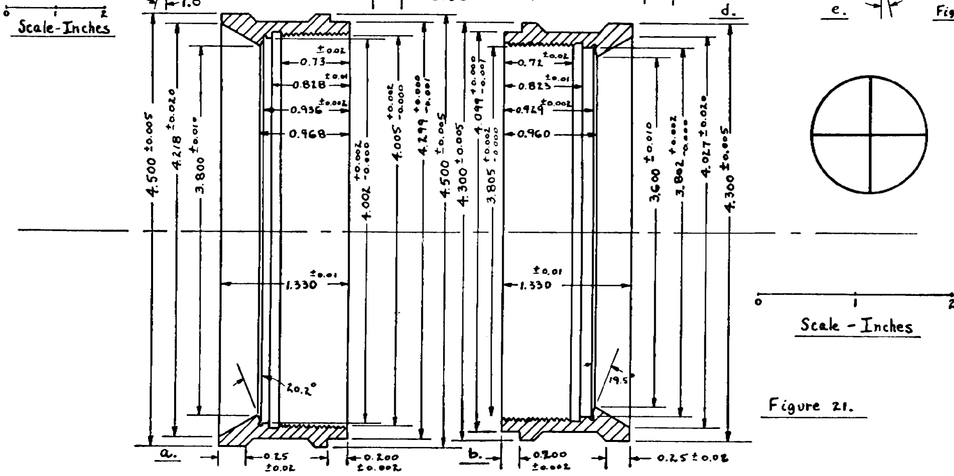


Figure 21.

As lens designs go, the two triplets may be considered to have somewhat sharper images than usual for the special astronomical application. The limiting magnitude will quite likely be improved over the values given in Table 2. A 3-inch $f/7$ lens can be expected to reach 16.3 magnitude. A 6-inch $f/7$ lens can be expected to reach 17.6. A 6-inch $f/7$ paraboloidal telescope used on axis should be capable of photographing stars down to magnitude 17.8.

It is hardly worthwhile for an amateur to make up a photographic lens unless he has some form of equatorial clock-controlled telescope at hand. One will have a very nice multiple-duty telescope if he combines a paraboloidal mirror with Reflector-Corrector on the same mount with one or both of the $f/7$ photographic lenses. In this way the guiding arrangement of the mirror telescope can be used profitably for taking critical photographs with either the Reflector-Corrector or the $f/7$ lenses, or possibly all together.

High Vacuum Equipment

By Earle B. Brown
Farrand Optical Company, Inc.*

Every TN has probably had the desire to aluminize his own mirrors and anti-reflection coat his own lenses, but has felt that the equipment for doing this work was so complicated and expensive that it was not worth while for the small amount of work required by an individual or even by a small group. Coating lenses and aluminizing mirrors, however, is only a small part of the work which can be performed by high vacuum equipment, and the processes of which it is capable offer a fascinating field for the TN, with his mechanical ingenuity and intellectual curiosity. The field has limitless horizons, and is only now being explored by various types of industry. The optical processes possible with high vacuum include, as well as aluminizing and lens coating, the production of interference filters, beam splitters, photo-electric cells, aspheric reflecting and refracting surfaces, and many others. There are numerous applications in chemical, physical and electrical fields in which the interested hobbyist may find much interest. High vacuum is a vast, largely unexplored territory. The properties of materials subjected to vacuum is a new world for discovery and adventure. There are fifty articles a month in technical journals on high vacuum and associated fields.

Not the least of the appeal of high vacuum to the TN is its natural perversity. Compared to a high vacuum system, the most recalcitrant optical surface is a paragon of meek submissiveness. This sort of thing makes raving maniacs of most people, but TN's are of the peculiar breed of cat which thrive on frustrations.

We shall attempt here to describe the usual form of high vacuum unit from the point of view of the individual who intends to construct one for himself, and briefly describe some of the operational procedures and technics.

I. General Description and Component Parts

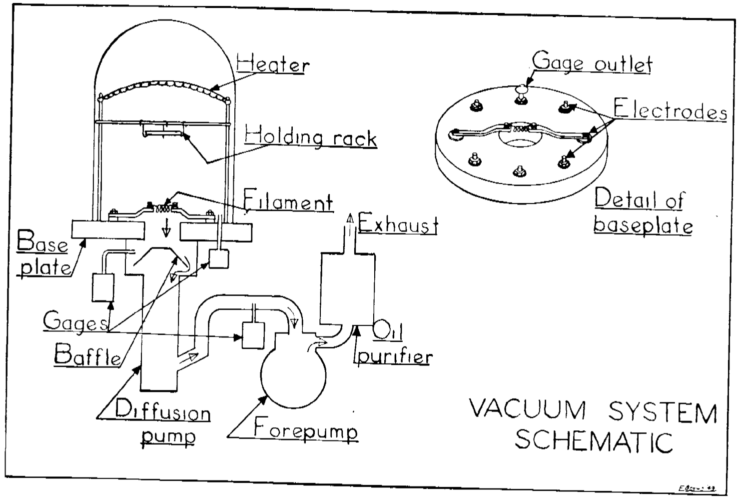
Figure 1 shows the principal parts of a typical modern laboratory and industrial high vacuum unit for general work. Some industrial processes which require high vacuum have developed their own specialized equipment but, for a unit which is to be used interchangeably on many different applications, no one has yet come forward with any arrangement fundamentally different from the old-fashioned bell-jar, which you may remember from chemistry and physics laboratories.

The vacuum chamber itself is the inside of a bell-jar of glass or metal, cylindrical in form and with domed top. This is open at the bottom and sits on a metal base plate. Inside the chamber are the outlets to the pumping and gaging systems, electrical terminals for filaments, heaters, high voltage discharge, etc., racks for holding objects to be processed, etc. The pumping

* 4401 Bronx Boulevard, New York 66, N. Y.

system consists of two types of pumps, mechanical pump (forepump) and diffusion pump. A gage system is included, usually consisting of two separate gages, a low-vacuum gage and a high-vacuum gage. A hoist for the bell-jar is usually included.

In operating the system, the items to be worked on are placed inside, the bell-jar is lowered and the pumps started. The two pumps are connected in series, with a cutoff directly from the chamber to the mechanical pump if



Drawings by the author

FIGURE 1

desired for more rapid operation. The diffusion pump is not started until the mechanical pump has brought the system down to a relatively low pressure. When the diffusion pump has brought the pressure down to the required value, the operations within the chamber are begun. Usually, it is desired to have as high a vacuum as possible, although in certain cases, which will be mentioned below, it is necessary to work at specific pressures higher than those which prevail if the pumps are allowed to operate unhindered as is generally the case.

A typical operating cycle for evacuation might be as follows:

1. Start mechanical pump.
2. Place work inside and arrange filaments, etc.
3. Close chamber.
4. Open valve to mechanical pump. Open slowly to avoid cloud chamber effect.
5. Start lens heaters if they are being used.
6. When pressure is below 50 microns, start the diffusion pump.

7. When low vacuum gage indicates 1 micron, switch on high vacuum gage.
8. Proceed with coating or other operation when pressure is sufficiently low.
9. If heated lenses are in chamber, do not open too soon—shut off heaters and allow to cool.
10. If diffusion pump is not valved off, allow to cool before opening chamber.

II. Functional Characteristics

In high vacuum it is customary to discuss the degree of vacuum in terms of the absolute pressure of the residual gases in the system; that is, we talk not of how much vacuum we have, but of how much actual pressure remains. Thus, a perfect vacuum would have zero pressure; with no vacuum at all we have atmospheric pressure, or 760 millimeters of mercury, mm of Hg being the customary units of measurement in this work.

"High" vacuum is generally considered to prevail when the residual pressure is less than 1 micron (10^{-3} mm) of Hg. This is about one millionth of atmospheric pressure. It is customary, in the sort of vacuum unit being described, to work in the neighborhood of 10^{-5} mm. Electronic vacuum tubes are often maintained at a pressure of the order of 10^{-8} mm. Gages are available to measure to about 10^{-10} mm. Lower pressures than 10^{-7} mm are not generally achieved.

Vacuum systems may be classified as "static" and "kinetic." A static system is one in which every precaution is taken to seal the system absolutely against all leaks, to cleanse everything within the system thoroughly, to "outgas" all components, etc. After the pumps have removed all the gases possible, they are sealed off, and recourse is had to technics for absorbing some of the gases remaining in the chamber by means of "getters," that is, materials, such as barium, calcium, magnesium, etc., which absorb large volumes of gas under certain conditions. A kinetic system is one in which the pumps remain connected and in operation throughout the cycle, the theory being that small leaks may be present, because the system is sealed with gaskets and rubber seals instead of with wax and cement, but, the pumps being very fast, will remove air faster than the leaks permit it to seep in.

The type of system we describe is a kinetic system; the static system, while capable of higher degrees of vacuum, is not adapted to processes where it is necessary to open the chamber frequently. Modern developments in pump design have resulted in pumps of such high pumping rates that kinetic systems are readily capable of working at pressures as low as 10^{-6} mm, which is sufficiently low for anything but the most refined types of experiment.

III. Mechanical Pumps

It is not recommended that the amateur try to construct a mechanical vacuum pump. Figure 2 shows a typical rotary mechanical pump used on high vacuum systems. These pumps are available from the Central Scientific

Co., W. M. Welch Scientific Co., Kinney Manufacturing Co., and others. Prices depend, of course, on size, and run from $50 up. The pumping speeds of mechanical pumps run from about ½ cu. ft. per min. for the Cenco Hyvac pump to about 25 cu. ft. per min. for one of the Kinney pumps. Larger sizes are available, of course, but are not likely to be considered for small vacuum units. The ultimate pressures attainable with mechanical pumps on kinetic systems run as low as 10 microns. Manufacturers' literature will list ultimate vacuum as 1 micron or even lower, but this is measured under ideal conditions, with the pump operating out of a vacuum chamber of practically no volume, and is not to be expected under any practical application. A mechanical

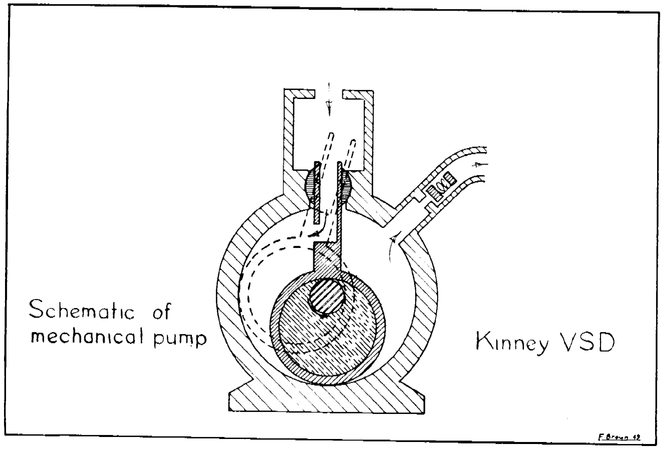


FIGURE 2

pump is useful if it will pull 100 microns, but any pressure greater than this is too much for diffusion pump efficiency.

Mechanical pumps depend upon their supply of lubricating oil to maintain a vacuum seal, and consequently this oil must be of good quality, and clean. Special oils are sold by the pump manufacturers and these are, of course, the best. However, they are rather expensive, and it will often be found that automobile oil of about SAE 10 or 20 will serve quite satisfactorily. It would be wise to obtain data as to the vapor pressure of the particular oil in question, and choose the lowest vapor pressure possible. The oil will become contaminated by the gases being pumped out, and should be changed rather frequently. It is possible for a mechanical pump to become so contaminated that it must be disassembled and thoroughly cleaned. This will be especially true, if any work is being done on plastics in the vacuum chamber.

The chamber, piston and vanes of a mechanical pump should never be

cleaned with anything coarser than very fine emery cloth. When these working surfaces become pitted and scored, the pump has lost most of its effectiveness. Do not disassemble the mechanical pump unless it is absolutely necessary, as continual disassembly and reassembly will reduce its efficiency.

When loss of efficiency has indicated the necessity of an overhaul, clean all the working parts with kerosene, and follow with a cleaning in acetone to remove the kerosene. Reassemble the pump dry, placing a light film of shellac between metal surfaces which are bolted together. Be sure no shellac gets into the pump chamber. Turn the pump over slowly by hand a few revolutions to lubricate the parts before starting the motor.

In some types of mechanical pumps, it is possible to reassemble some of the parts backward, in which case the pump will not work effectively, hence mark all parts upon removal to assure their being replaced in the proper orientation. Pumps are designed to operate at an optimum speed, so if you obtain the motor separately, be sure that the speed ratio is correct.

The pumping speed and limiting pressure of a mechanical pump depend upon the effectiveness of the seal, which in turn is a function of the mechanical tolerances between the working parts, and also upon the ratios of chamber volume, rotor speed and intake area.

To avoid the wearing out of a good mechanical pump too rapidly, it is a useful practice to use an old pump for "roughing out" the chamber, and cut in the good pump only after the old pump has reduced the pressure as far as it is capable.

The time necessary to create a high vacuum in the system and the degree of vacuum attainable are dependent perhaps principally upon the efficiency of the mechanical pump, since the efficiency of the diffusion pump increases as the pressure at its output is reduced. Hence a good mechanical pump is one of the first requisites for an effective vacuum system. Within reason, the larger the mechanical pump, the more effective the system. Larger pumps usually have a lower ultimate pressure.

IV. Diffusion Pumps

Mercury diffusion pumps were first used, and are still used to some extent, principally upon laboratory systems. **Caution: Mercury fumes are poisonous.** The oil diffusion pump (Figure 3) has become the standard for most vacuum systems. The diffusion pump may be made of glass or of metal, the metal being, of course, free from the danger of breakage, which is always a problem with glass pumps. Glass, however, is a better material, vacuum-wise.

In the diffusion pump, a high velocity stream of oil or mercury vapor is provided by vaporizing the pump fluid, and shooting it through jets. The residual gases at the intake of the pump diffuse into the vapor stream, which is directed toward the output of the pump, where sufficient pressure is built up to make the mechanical pump effective. A good diffusion pump can maintain a pressure differential between intake and output of about a million to one.

The speeds of diffusion pumps are usually stated in liters per second. This is a function of the area of the intake as well as of the efficiency of the pump itself. If an opening one square centimeter in area existed between a chamber at pressure *P* and one at a perfect vacuum, the rate of air flow across this area would be 11.7 liters per second. This rate of flow is independent of the pressure *P*. Obviously, no pump can remove air faster than this, which represents the maximum rate at which the air will flow into the pump chamber. The speed factor of a pump is the ratio of its pumping speed to this maximum value. For a good oil diffusion pump this speed factor is about 0.5 or 0.6.

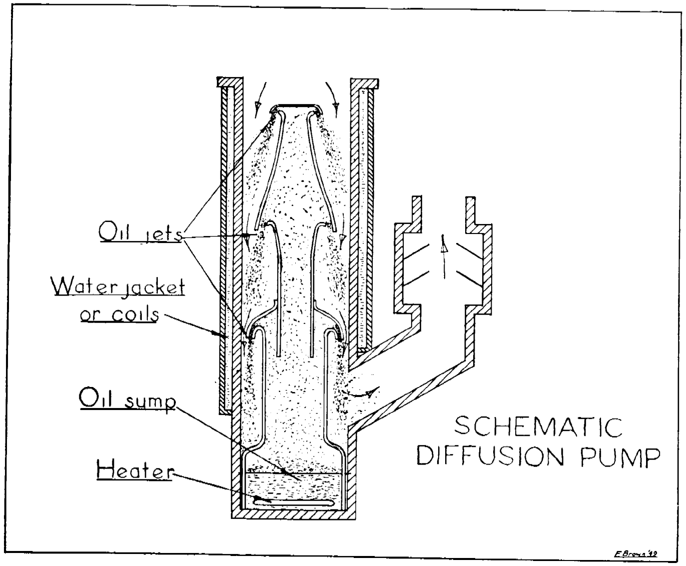


FIGURE 3

An oil diffusion pump with a throat aperture of about 4 inches has a pumping speed of about 250 liters per second.

The metal oil diffusion pump is merely a long section of metal tubing, closed at the bottom. An electrical immersion heater is placed in the bottom and a chimney, or jet, is placed over the heater. Copper coils surround the upper portion of the tube, through which water is circulated to cool the walls. The design features of the pump are the exact contours of the jets and the chimney, and the spacing of the cooling coils.

Cooling coils are also provided around the heater section of the tube, to accelerate the cooling of the hot oil after the pump is shut off, since the system cannot be opened to the atmosphere until the oil in the diffusion pump

is cool. This is not necessary, of course, if a valve is provided between the diffusion pump and the vacuum chamber.

Some operators *never* open the diffusion pump to the atmosphere but fill it with dry nitrogen when it is not in use.

It is quite feasible to make one's own diffusion pump, although the exact dimensions of the chimney may be rather troublesome. Many details are available in the literature on diffusion pump design.

It is usually advisable to have some sort of control on the heater of the diffusion pump, although it is quite possible to operate it satisfactorily without a control. A variable transformer is the usual type of control provided. The pump will operate faster at the higher pressures with the heater on full, but is more effective at the lowest pressures and will attain a somewhat lower vacuum at about 60–70 percent of full voltage. It is necessary to provide a control on the circulating water for the cooling coils. Usually, the pump will operate most efficiently when the top of the pump is about 20° below room temperature and the lowermost cooling coil is slightly above room temperature. Some diffusion pumps are made with water jackets instead of coils.

Diffusion pumps are sometimes made with an ordinary heater coil *outside* the housing. Effective temperature control can then be attained by merely moving the heater toward or away from the pump. Cooling at the end of a cycle is also accelerated.

The oil in the diffusion pump is of special type. Manufacturers offer various types of oils, the principal difference being the limiting pressure attainable, which becomes lower, as might be expected, as the price of the oil goes up.

Fortunately, this oil will last indefinitely if carefully treated. It must be occasionally drained and cleaned by allowing it to settle or by straining through chamois. When the oil is drained, the chimney of the pump is removed and cleaned of varnish.

Air must *never* be allowed to contact hot diffusion pump oil, or it will oxidize, resulting in not only the loss of valuable oil, but a messy cleaning job.

Of the diffusion pump oils available, Octoil-S, procurable from Distillation Products, Inc., is one of the best (and most expensive). Butyl phthalate is an effective pump fluid, and relatively inexpensive. It is capable of a vacuum of about 10^{-4} mm. For better vacua, better oils are necessary. Silicone fluids have been offered for diffusion pumps, and serve very satisfactorily. One advantage claimed is freedom from danger of oxidation, it being stated that silicone fluids may be exposed to atmospheric pressure when hot without danger.

V. Valves and Manifolding

If suitable valves (Figure 4) are provided at strategic points in the system, the time required per operation cycle will be materially reduced, and the location of leaks is considerably simplified. A valve at the intake of the mechanical pump is almost a necessity; other valves may or may not be provided, depending upon the individual constructing the system. A separate line from the roughing pump directly to the chamber, together with a valve at the diffusion pump intake, will make it possible to keep the diffusion pump operating between two vacuum cycles, thus saving at least a half hour or more. When the work in the chamber is completed, the diffusion pump intake valve is closed, and the chamber opened to the atmosphere. At the beginning of the next cycle, the diffusion pump is cut off from the roughing pump, and the latter opened directly to the chamber; when the chamber has reached forepressure, the roughing pump is cut off from it, the valve between

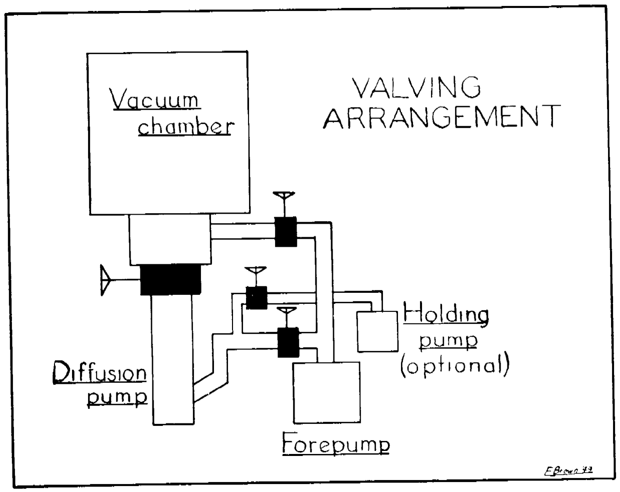


FIGURE 4

the roughing pump and diffusion pump is opened, and, finally, the valve between the chamber and the diffusion pump. The heater in the diffusion pump remains on throughout all the above, since, by proper valving, we have eliminated any opening of the diffusion pump to the atmosphere.

Some back-streaming occurs in the diffusion pump when it is cut off from its forepressure during the time the roughing pump is working directly on the chamber, but, since this is usually a matter of only about ten minutes with a good mechanical pump, it is not too important. It would be better, of course, to provide a small mechanical pump to maintain forepressure at the diffusion pump output during this period, but this is a refinement that is of interest principally when it is required to make as many operating cycles as possible in a working day.

The Kinney Mfg. Co. offers vacuum valves suitable for the roughing pump

intake valves, or the amateur may construct his own by modifying a steam valve of proper type. Metal bellows (Figure 5) is the customary type of seal for vacuum valves; packing will not suffice for high vacuum. Some operators report having made satisfactory vacuum valves from ordinary steam valves by merely replacing the packing with Neoprene washers and using a Neoprene seat.

A valve for the diffusion pump intake, where the aperture is of the order

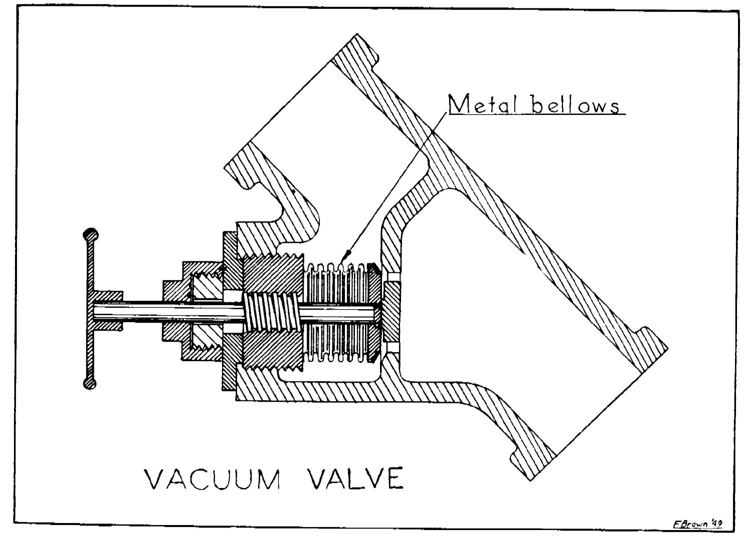


FIGURE 5

of 4 inches, will probably be found too expensive for purchase; it is quite feasible to make one. A suggested type is shown in Figure 6.

For the relief valve in the base plate Figure 7 shows the customary type.

Regarding piping and connections in the system, the guiding principle is that the pipes should be as short and as large as possible; any sharp bends or constrictions will inhibit the flow of gases through the system and thus cut down the overall pumping speed.

VI. Baffles and Cold Traps

Baffles and cold traps are often provided in vacuum systems to prevent substances such as diffusion pump oil from entering the vacuum chamber by providing a low temperature region where they are condensed upon the walls. In the usual vacuum system, a small, water-cooled chamber just above the diffusion pump, fitted with a flat baffle plate somewhat larger in diameter than the diffusion pump throat and placed some distance above it, is sufficient. It is possible to construct complicated baffle assemblies, which usually result in a cutting down of the pumping speed. When mercury is used in the pump or in any gages, a full-fledged cold trap is necessary. This usually consists of a U-bend in the connecting pipe, around which is placed a cooling mixture, such as liquid air, or dry ice and alcohol or acetone.

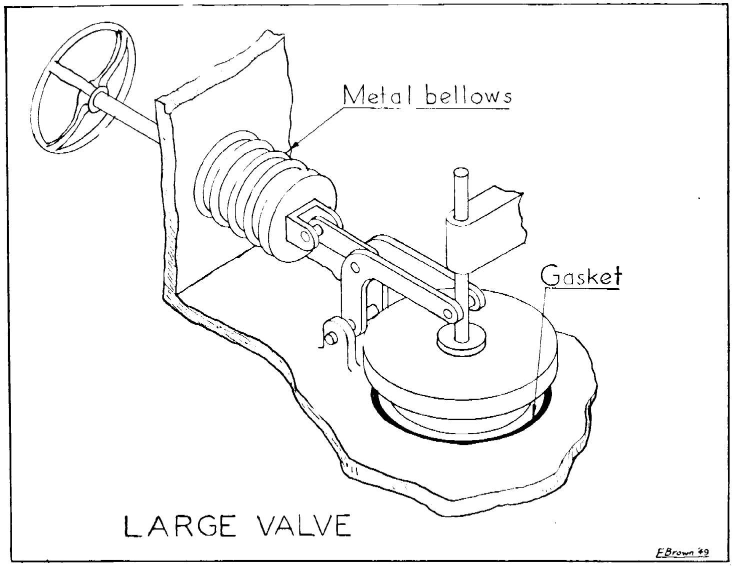


FIGURE 6

As a precaution the cold trap should not be operated until the pressure in the system has reached a relatively low value. Operating the cold trap when the system is at high pressure will result in condensing a great deal of water vapor in the trap. When the pressure is reduced, the condensed water vapor will begin to evaporate, and will have all the symptoms of a leak. It may take a long time to sublimate the ice which will gather in a cold trap if it is operated at high pressure.

VII. GAGES

There is no really satisfactory substitute for a suitable and reliable gage system. An expert can usually make a rather close estimate of pressure by

such intangibles as the sound of the pumps, the appearance of filaments, etc., but this is unreliable to say the least. The neophyte may be advised that gages are not necessary. For one unfamiliar with high vacuum, however, gages are considered essential by the author. When the operator can guess the gage reading without looking at it, he is permitted to throw it away.

Two different gages will be necessary; one in the region of mechanical pump pressures (above 1 micron), and one for the lower pressure region (down to 10^{-5} or below). There is no one gage which will operate satisfac-

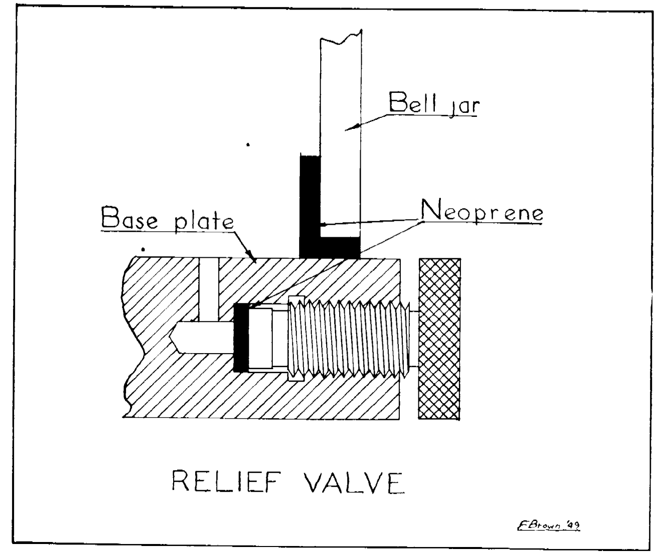


FIGURE 7

torily over the entire range. We will describe here only the operating principles of some of the gages; detailed descriptions will be found in the literature.

The standard vacuum gage is the McLeod gage; this is a mercury gage, by means of which a sample of the gas in the chamber is compressed into a small capillary; its consequent pressure against a column of mercury is a measure of the pressure in the chamber. The standard McLeod gage is a large and cumbersome instrument; modifications have been made which are relatively inexpensive and convenient; it is a very handy instrument to have because, with only a few exceptions, it is the only vacuum gage which does not have to be calibrated. Because of its two disadvantages, it is not quite suitable for a kinetic vacuum system; but it is extremely useful as a calibration tool for the gages which may be used on the system. The two disadvantages are that it cannot be used without a cold trap, due to the mercury it contains; and it measures only the partial pressures of *non-condensible* gases. The sample of gas which is measured by the McLeod is compressed, and in this compression process, condensible gases are eliminated from the sample. Since water vapor is often a significant component of the residual gas in a kinetic vacuum system, the McLeod will not give a reliable pressure reading.

For the low-vacuum region (above 1 micron) two general types of gage seem most suitable and most widely used; these are the Pirani gage and the thermocouple gage. In the Pirani gage, two heated filaments, one sealed off in a high vacuum, the other exposed to the chamber, are connected in a bridge circuit. Residual gases in the chamber cool the filament exposed to them, changing its resistance, and unbalancing the bridge. The degree of unbalance is read on a meter. This gage is useful in the region 1 micron to about 50 mm. It would be advisable to purchase the actual gage elements, which are not very expensive; the electrical circuit can be home-made; circuit diagrams will be found in the literature. Remember that the gage must be calibrated against some gage such as the McLeod.

The thermocouple gage is useful in the same region as the Pirani, and in some respects it is more sturdy. A thermocouple element is placed close to a heated filament; the heating effect of the filament upon the thermocouple is read on a suitable meter; the higher the pressure in the chamber, the lower the reading, because of the cooling effect of the residual gases. As in the case of the Pirani gage, the gage elements can be purchased and the circuits constructed at home.

For the high vacuum region, an ionization gage is customarily used. This gage is essentially a three-element radio tube, connected to the vacuum chamber; it consists of a hot cathode, a *positive* grid and a *negative* plate. The electron current flows from cathode to grid. The electron stream creates positive ions in the residual gases of the chamber, which are collected by the plate, and the resulting current, which is a measure of the pressure, is read on a meter. As in the above cases, the gage elements can be purchased and the circuits built.

All the above gages are supplied with a tubular glass neck; this may be passed through a perforated rubber stopper, which is in turn clamped into a hole in a wall of the vacuum system, or it may be connected to the system by means of a section of heavy-walled rubber tubing.

More recently, the Phillips gage has come into rather wide usage. It consists essentially of a two-element radio tube, in which an electronic discharge is produced. Measurement of the electron flow by a suitable circuit indicates the pressure. The Phillips gage as currently produced has a very wide range; it will cover the range of both the ionization and Pirani gages for most vacuum systems.

In all these gages, two or more gage units may be used with a single electrical circuit; it is often convenient to have gages in more than one place in the system. A separate low-vacuum gage at the roughing pump intake will provide a measure of the operation of this pump independent of the rest of the system; the high-vacuum gage should enter the system *below* the base-plate, preferably in the baffle chamber; if this is done, the search for leaks is simplified; when a leak occurs which cannot readily be found, the opening in the base plate which leads to the diffusion pump is closed up with a pressure plate and the system operated; if the system can create the desired vacuum in the baffle chamber, then the leak is obviously somewhere above the base plate. The difference in pressure between the chamber itself and the baffle chamber is not usually significant during operation.

It is advisable to provide baffles over the gage openings, especially in the case of the ionization gage, to prevent possibility of contamination of the filament with diffusion pump oil or other contaminant; this will cause the gage to give incorrect readings.

Under no circumstances should the ionization gage be turned on when the pressure is higher than 1 micron; to do so will cause the filament to burn out very rapidly.

There are innumerable other vacuum gages; the Knudsen gage, the Langmuir gage, the Miller gage, and many, many others. Descriptions of these will be found in the literature; the five types described above, however, are most commonly used today.

VIII. The Vacuum Chamber

Certain apparatus must be provided in the vacuum chamber: holding devices for the items to be worked on, a heater if anti-reflection coating is to be done, holders for the heating filaments, electrical connections through the base plate for filament, heater, glow discharge (if used) and possibly other items. An arrangement permitting the simultaneous use of two or more filaments will be found desirable for multiple coatings.

As to general arrangement, it is customary to provide a circular, horizontal base plate, and a cylindrical, domed-top bell-jar, glass or metal. A metal jar is more expensive, but there is no danger of breakage. If a glass jar is used, cover it with a heavy wire screen for protection in case of breakage; jars do not often break, but when they do, it is a very dangerous accident. Pyrex bell jars are available in 12- and 18-inch diameters; or a large glass jar may be utilized by cutting off the bottom and sealing the neck. Don't cut off the neck end—the domed shape is essential.

The base plate should be sufficiently thick to obviate any bending under a 15 lb/sq. in. pressure—for an 18-inch jar, the base plate should be not less than ¾ inch thick, preferably more. Stainless steel is the best material, but cold-rolled steel, brass, or even cast iron is serviceable. If cast iron is used, it should be thoroughly buffed to fill the pores and then nickel plated. A thorough coating with Glyptal on the outside will be helpful, as cast iron tends to be porous.

The bell-jar is sealed to the plate with a Neoprene gasket (Neoprene is better than natural rubber in a vacuum system; other synthetic rubbers are also quite satisfactory). The base plate must, of course, be ground smooth on top, although a high polish is not necessary.

a. *Geometry of the Vacuum Chamber:* The home builder is completely free to arrange the vacuum chamber as he will. The usual arrangement is with the diffusion pump outlet in the center of the base plate, with holders for items to be coated overhead. The heater may be either overhead (resistance type) or on the base plate (infrared lamps). The writer favors an off-center location for the diffusion pump, in order to avoid any unnecessary restriction of the opening to it and consequent decrease in pumping speed. Some operators prefer to evaporate downward when metals such as aluminum are being used; in this case there is always the danger of hot droplets of metal falling on the items being coated and damaging them. Most non-metals must be evaporated upward; metals can usually be evaporated in any direction.

b. *Heaters:* For anti-reflection coatings, and certain other operations, the items being coated must be heated to rather high temperatures; both infrared lamps and resistance heaters are used. Some sort of voltage control should be provided. Since the heating, even by a resistance heater, is almost wholly by radiation (being in vacuum), the heater should be backed up by a reflector. The heater should never be allowed to become bright red, but should be wound with a sufficiently heavy wire to furnish the required heat at a color temperature not higher than dull red. If the wire is too hot, it will evaporate onto the items being heated. Nichrome wire is usually used.

After a coating operation, heater wires should be burned off in low vacuum before the next cycle.

c. *Electrical Terminals:* A sufficient number of electrical leads must be provided through the base plate for all the equipment required. There is usually a heater, two or more filaments, and perhaps a glow discharge. The terminals for the filaments must be able to carry upward of 150 amperes. A common type of electrode is shown in Figure 8. This is not adequate for high voltage; in this case, the electrode shown in Figure 9 is suggested. Use glass or quartz (not rubber) as insulation in the vacuum chamber.

d. *Optics Holders:* The type of holding devices provided depends entirely upon the work being done. A metal ring supported upon three or four posts about 12 inches above the base plate makes a good support for whatever type of holder is desired. Some advantages are gained if the holders do not permit any of the evaporated material to pass the surface being coated; with some metals, back-coating is common, and in any case, confining of the evaporated materials saves a great deal of bell-jar cleaning.

e. *Source Shields—Mechanical Motions:* It is usually desirable to provide some sort of shield above the evaporating source which may be moved aside at the proper time after evaporation has begun. Usually, when the material begins to evaporate, impurities are given off, and a clean-up period with the shield in place is desirable. These shields can be made to operate magnetically, or by motion introduced through the base plate by means of a metal bellows. A venetian blind type of shield has been used very effectively.

f. *Glow Discharge—Electronic Bombardment:* A high voltage discharge between a high potential cathode and a suitable anode has been found very effective as a final cleaning operation before coating. It is believed that the ionic bombardment set up is effective in removing the adsorbed moisture layer (two or three molecules thick) which is always present on surfaces exposed to atmospheric pressure.

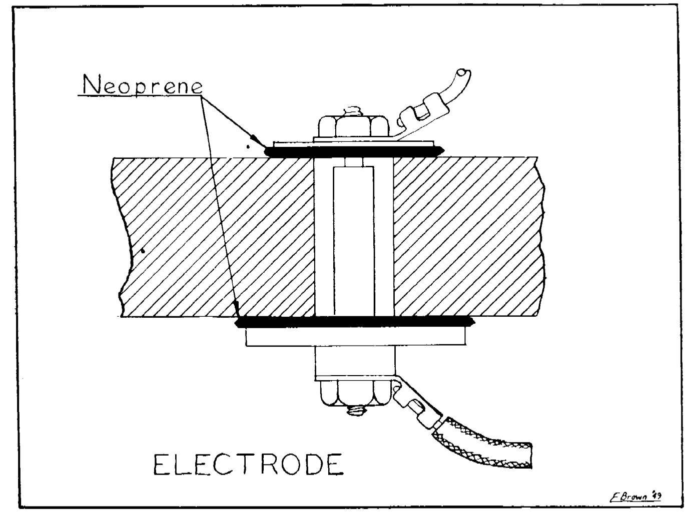


FIGURE 8

We avoid making any specific recommendations here regarding high voltage discharges in vacuum. The technic is quite complicated, many dangers are involved and, for effective use, the pressure in the chamber must be at the optimum value (in the 10 micron vicinity). The reader is referred to the literature for discussions of this particular field.

Glow discharges may lead to a lot of trouble. The phenomena are not well understood, and anything which is done is at the operator's own risk. One source of trouble is dirty electrodes, which may give off contaminating material when used.

g. *Filaments:* Both metals and non-metals are evaporated by means of electrically heated filaments. In industrial applications, induction heating has proved very effective, but the equipment is quite expensive. There are four principal types of filaments which are used.

1. Wire filaments: Metals which will wet a filament, and which can be electroplated onto the filament wire, are usually evaporated from wire of suitable material—usually tungsten, which is available in wire form. Coils are easily made by winding the wire around a ½ or ¾ inch bolt or the wire may be bent into an "accordion-pleated" flat filament. Tungsten wire forms very easily when heated to a dull red, although it is quite brittle when cold. It may be heated with a small alcohol torch while forming. Avoid overheating,

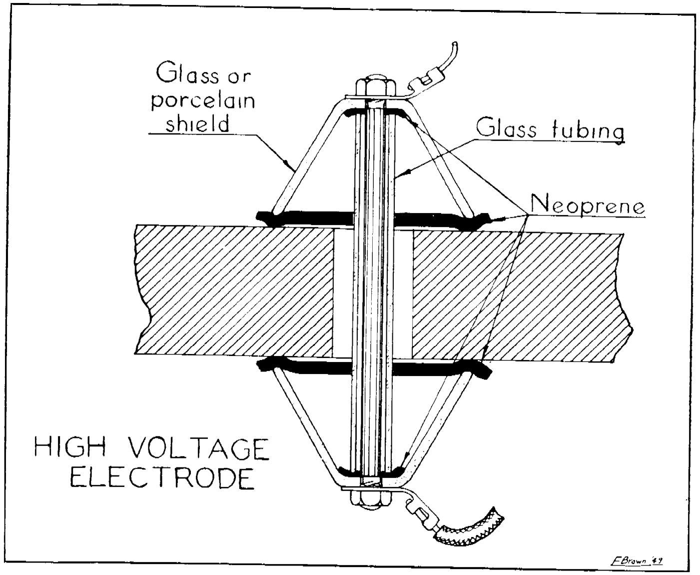


FIGURE 9

which will result in sharp bends and subsequent breakage at these points.

2. Crucibles: non-metals, such as magnesium fluoride for anti-reflection coatings, are usually evaporated from porcelain crucibles. The crucible is filled with fluoride, and a flat coil of tungsten is suspended a few millimeters above the surface of the fluoride. These flat filaments may be wound upon a suitable mandrel as described above.

3. Refractory crucibles: Refractory crucibles may be built up by first winding a conical filament of tungsten or other wire, and then dipping this filament repeatedly in a suspension of refractory material, such as Alundum. Baking out of the crucible in a low vacuum (1 micron) is necessary before using. These crucibles are useful for metals which will not wet filaments, and for non-metals.

4. The fourth form of evaporating device is the so-called "boat," which is merely a flat strip of tungsten or other heater material bent into a V form in a vise, to form a sort of trough, in which evaporating materials may be vaporized. Tungsten is not very suitable for boats, but molybdenum and tantalum are very useful for this form of heater.

h. *Assembly:* The entire system is assembled with Neoprene gaskets, coated with a film of vacuum grease (Plicene, Celvacene, etc.) and bolted tightly together. Glyptal is used as an exterior paint over joints, and (as a temporary expedient) to plug small leaks.

IX. Electrical Supply

There will be four items in the vacuum system requiring electrical power supply: the filaments, the heater, the diffusion pump, and the gage system. The filaments will each require at least a kilowatt for effective work, and this supply should be available at a voltage of about 5–15. This means a sizeable transformer—one from a welding outfit will be ideal. If more than one filament is provided for, as is recommended, there should be sufficient power to operate simultaneously at least two of them—preferably more. The electrical leads to the filaments should have a capacity of at least 200 amperes.

The heater will require 1000 watts or more—for really hard anti-reflection coatings, the more the better; the diffusion pump will require from 200–300 watts. As has been pointed out, a voltage control on both of these devices is desirable—especially on the heater.

The gage system will require only a few watts—and a d-c power supply, which is part of the gage electrical system—a copper oxide or selenium rectifier is adequate for the Pirani gage—an ionization gage will require a vacuum-tube rectifier with smoothing inductances—the reader is referred to the bibliography for detailed information on gage circuits.

If a glow discharge is to be used, a high-voltage transformer will be required—from one to several amperes capacity. Neon sign transformers are useful here.

X. Notes on Processes and Operations

General: a. Outgassing: Outgassing is the term used to describe the giving off of absorbed and adsorbed gases by materials when subjected to vacuum. All materials absorb gases (air) to a certain degree, depending upon their porosity and other characteristics. The amount absorbed will depend upon the air pressure to which they are subjected. When materials which have been exposed to atmospheric pressure are subjected to a vacuum, these gases will be given off, and given off rather slowly, so that the chamber is continually being subjected to a "virtual leak" until this outgassing ceases. In addition, most materials exposed to the atmosphere have a surface layer a few molecules thick consisting of water vapor and other gases, which are termed "adsorbed."

Outgassing is accelerated by heating the parts concerned. In addition to absorbed and adsorbed gases, most materials will evaporate to a finite extent even at low temperatures; some materials, of course, are highly undesirable from this viewpoint, especially certain plastics, the "fillers" of which tend to outgas continuously and voluminously over a long period of time, and organic materials in general.

The products of outgassing of such materials as plastics are likely to be very damaging to the pump oils, both in the diffusion pump and in the mechanical pump. The diffusion pump oil has an opportunity to clean itself to some extent because of its constant distillation, but the mechanical pump oil may become contaminated very rapidly, resulting in a significant rise in the forepressure. This oil must be changed from time to time in any event, due to contamination, principally from water vapor.

The entire inside of the vacuum chamber, of course, gets a coating of whatever is being evaporated at the same time as the objects within it, and must be frequently cleaned. A dirty chamber will rapidly become more and more difficult to evacuate to the required pressure, because of outgassing from the contaminants—evaporated metals especially are powerful absorbers. Steel wool, soap and water, followed by acetone to remove the water film, are about the most effective general agents for cleaning the inside of the bell-jar. Certain specific contaminents yield to specific agents—lye for aluminum, nitric acid for most other metals, etc. For small parts, such as electrodes, periodic disassembly and treatment with a buffing wheel is effective.

XI. Evaporation of Metals

a. *Aluminum Mirrors:* One of the most frequent jobs for a vacuum system is the production of evaporated aluminum front-surface mirrors for telescopes or other purposes. Aluminum is one of the simplest metals to evaporate, but there are several important considerations in its use.

A helical tungsten filament is the most generally used type. Aluminum and tungsten form a very brittle alloy which makes it impossible to use a tungsten filament more than once for aluminum.

Do not use a fine tungsten wire for aluminum; the aluminum will dissolve it and it will burn up. Use wire about .050″ diameter.

The following are the usual steps in evaporating aluminum, as for coating telescope mirrors:

1. Prepare the filament and the aluminum strips (aluminum wire or aluminum foil, prepared in small strips about 3 by 6 mm and bent into a U-shape).
2. Preheat the filament for about 30 seconds in low vacuum.
3. Open the chamber and hang the aluminum strips on the separate turns of the filament coil. Evacuate to about 1 micron and then operate the filament until the aluminum strips have melted and firmly adhered to the coils.
4. Open the chamber and place the object to be coated in position. If it is a telescope mirror, it must be placed perpendicular to the filament, and as far away as is practicable, considering the degree of vacuum achieved. Placing the mirror at an angle or too close will result in a change in its figure upon metallizing.

Evacuate to the highest vacuum attainable and coat. All metals should be evaporated as rapidly as possible to assure an even, adherent film. If heated too rapidly, however, metals may spatter. Once evaporation has begun, it will require only 15–30 seconds to complete a mirror. Telescope mirrors should not be coated too thickly, else the figure will be altered. A coating which is barely short of complete opacity is usually best. This usually results in a certain number of pinholes, which are not objectionable if not too numerous. The usual practice in aluminizing is to observe the hot filament through the surface being coated; thus it will be possible to determine just when opacity is attained. Be sure you are watching the true filament; not a reflection of it off the back surface of the mirror.

b. *Other Metals:* Silver mirrors are superior to aluminum in reflectivity in the visible spectrum; they are, of course, subject to tarnish, but are very satisfactory when furnished with a protective coating, such as magnesium fluoride. Hard protective coatings for mirrors offer a fertile field for experimentation. Silver is perhaps the easiest metal to evaporate—a tantalum or molybdenum boat is the most satisfactory means.

Gold, copper, nickel, etc., are readily evaporated onto mirrors which may be desired for special purposes—gold for infrared, for example, or Nichrome or stainless steel for neutral filters.

Table 1 is taken by permission from W. C. Caldwell, *Jrl. Appl. Physics*, Vol. 12, p. 779, 1941, and will be found very valuable.

c. *Filament materials:* Tungsten and tantalum are the most common filament materials; these two metals, together with molybdenum, will suffice to evaporate practically all metals (Table 2). A few words may not be amiss in the use of these materials.

Molybdenum, or "moly," is usually used in the form of a boat; it is the cheapest of the three filament materials, and is readily available in sheet form, (.010 to .020-inch thickness will be satisfactory) from which ¼-inch strips may be cut with shears and bent lengthwise into a V-shape. It is quite easily worked, and not especially subject to work-hardening. It becomes somewhat brittle after heating in vacuum, but may still be handled. It is a bright, silvery metal, not subject to oxidation in air. Tungsten is used more often than any other filament material, its greatest advantage being its very high melting point; it is somewhat more expensive than moly, but is readily available in wire of any desired diameter. (.025 to .050 inch will be found most useful). Tungsten is quite brittle, and must be heated to be worked; heating to a low red heat is best. Tungsten oxidizes quite readily in air, especially when heated; normally it is a dull silvery color, becoming darkened when exposed to air, and when heated too much in working, becomes covered with a greenish film of oxide. After winding, it must be cleaned by heating in low vacuum. Tungsten sheet is available, but is prepared in laminated form and does not readily form boats.

Tantalum is the most expensive of the three materials, and in some ways the most desirable; it is dark gray in color, quite ductile and readily formed into coils or boats; it is available in wire, sheet and ribbon; the ribbon form

Table 1—*EVAPORATION OF METALS FROM FILAMENTS*

(Melting and boiling points in degrees Fahrenheit)

METAL EVAPORATED

Filament Material	Aluminum 659–1800	Antimony 630–1380	Barium 850–1140	Beryllium 1350–1530	Bismuth 281–1470	Cadmium 321–767	Cobalt 1480–2900	Columbium 1950–2900	Copper 1083–2310	Germanium 959–2700	Gold 1063–2600	Iron 1535–3000	Lead 327–1613
Tungsten 3370–5900	W_1 E_1 R_2	W_3 1 R_1	W_1 E_1 R_1	W_1 E_1 R_2	W_2 E_1 R_1	W_3 E_3 R_1	M_3 E_3 R_3	M_3 E_3 R_3	W_3 E_3 R_1		W_2 E_1 R_1	W_1 3 R_2	W_3 E_3 R_1
Tantalum 2850–4100	W_1 E_1 R_2	W_2 E_2 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_2 E_1 R_1	W_3 1 R_1	W_3 E_3 R_3	M_3 E_3 R_1	W_2 E_1 R_1	W_1 E_1 R_1	W_1 E_2 R_2	M_3 E_3 R_3	W_3 1 R_1
Molybdenum 2620–3700	W_1 E_1 R_2	W_3 E_3 R_1	W_1 E_1 R_1	W_1 E_1 R_2	W_2 E_1 R_1	W_3 E_3 R_1	W_2 E_3 R_3	M_3 E_3 R_1	W_2 E_1 R_1	W_1 E_1 R_1	W_2 E_1 R_1	W_1 E_3 R_3	W_3 1 R_1
Columbium 1950–2900	W_1 E_1 R_2	W_3 E_3 R_1	W_1 E_1 R_1	M_3 E_2 R_1	W_2 E_1 R_1	W_1 E_1 R_1	W_2 E_2 R_3	2	W_2 E_1 R_1		W_1 E_2 R_2	W_1 E_3 R_2	W_3 1 R_1
Platinum 1773–4300							W_1 E_3 R_3					W_1 E_3 R_3	
Iron 1535–3000	W_1 E_3 R_3	W_2 E_3 R_3	W_1 E_1 R_1	M_3 E_2 R_1	W_3 1 R_1	W_2 E_1 R_1			W_1 W_1 R_3		W_1 E_3 R_2		W_1 E_1 R_1
Nickel 1452–2900	W_1 E_1 R_2	W_1 E_3 R_1	W_1 E_1 R_1	W_1 E_3 R_3	W_1 E_3 R_1	W_3 E_3 R_1			W_1 E_2 R_3		W_1 E_3 R_2		W_1 E_1 R_1
Chromel 1350	W_1 E_3 R_3	W_1 E_1 R_1	W_1 E_1 R_1	M_3 E_3 R_1	W_1 E_1 R_1	W_1 E_1 R_1			W_1 E_1 R_3		W_1 E_3 R_2		W_1 E_1 R_1
Silver 960–1950	W_1 E_3 R_3	W_2 E_3 R_3	W_1 E_1 R_1		W_2 E_3 R_3	W_3 E_2 R_1							W_1 E_3 R_3

Filament Material	Magnesium 651–1110	Manganese 1260–1900	Nickel 1452–2900	Platinum 1773–4300	Selenium 200–688	Silver 960–1950	Strontium 752–1150	Tellurium 452–1390	Thallium 303–1650	Thorium 1845–3000	Tin 231–2270	Titanium 1800–3000	Vanadium 1715–3000	Zinc 419–907
Tungsten 3370–5900	M_3 E_1 R_1	W_1 E_1 R_1	W_1 3 R_3	W_1 4 R_2	W_3 1 R_1	W_2 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_2 E_1 R_1	W_1 E_2 R_1	W_3 E_3 R_1	W_1 E_1 R_3	W_1 E_1 R_2	W_1 E_1 R_1
Tantalum 2850–4100	M_3 E_1 R_1	W_1 E_1 R_1	W_1 E_3 R_3	W_1 E_3 R_3	W_3 1 R_1	W_1 E_1 R_1	5 E_1 R_1	W_1 E_1 R_1	W_2 E_1 R_1	M_3 E_3 R_1	W_2 E_1 R_1	W_1 E_1 R_1	W_1 E_3 R_3	W_1 E_1 R_1
Molybdenum 2620–3700	M_3 E_1 R_1	W_1 E_1 R_1	W_1 E_3 R_3	W_1 E_3 R_3	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_3 1 R_1	M_3 E_1 R_1	W_2 E_1 R_1	W_1 E_2 R_3	W_1 E_1 R_1	W_1 E_1 R_1
Columbium 1950–2900	M_3 E_1 R_1	W_1 E_1 R_1	W_1 E_3 R_3	W_1 E_3 R_3	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1		W_3 1 R_1	W_1 E_2 R_1	W_1 E_2 R_1	W_1 E_1 R_1
Platinum 1773–4300			W_1 E_3 R_3											
Iron 1535–3000	M_3 E_1 R_1	M_3 E_2 B			W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1		W_2 E_1 R_1			W_1 E_3 R_3
Nickel 1452–2900	M_3 E_1 R_1	W_1 E_3 B			W_2 E_1 R_1	W_1 E_1 R_1	5 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1		W_3 E_3 R_1			W_1 E_3 R_3
Chromel 1350	M_3 E_1 R_1	W_1 E_2 B			W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_1 E_1 R_1	W_3 1 R_1		W_1 E_1 R_1			W_1 E_3 R_3
Silver 960–1950					W_1 E_1 R_2		M_3 E_3 R_1	W_1 E_3 R_3	W_1 E_3 R_3		W_3 1 R_3			W_1 E_3 R_2

Notes: Numbers given with each material are melting and boiling points respectively.

EXPLANATIONS:

- W_1 Wets filament well
- W_2 Forces of wetting not large—droplets may fall
- W_3 Metal will not wet filament
- M_3 Not melted
- E_1 Evaporates readily
- E_2 Evaporates slowly
- E_3 No evaporation
- R_1 No reaction with filament
- R_2 Slow reaction—little effect on evaporation
- R_3 Filament burned out by reaction
- B Filament burned out from excess temperature required to melt metal
- 1 No wetting, but globule supported by surface tension
- 2 Fine wire wrapped on filament should work
- 3 Iron forms low melting point alloys—tungsten wrapped tightly about iron core should yield differential evaporation of iron from tungsten-iron alloy.
- 4 Platinum evaporates slowly due to low vapor pressure
- 5 Refractory shell was formed

Table 2—*PREFERRED FILAMENT MATERIALS*

(Listed in order of merit)

Metal to be Evaporated	Filament
Aluminum	Tungsten, tantalum, molybdenum, columbium
Antimony	Chromel, tantalum, tungsten
Barium	Tungsten, tantalum, moly, columbium
Beryllium	Tantalum, tungsten, moly
Bismuth	Chromel, tantalum, tungsten
Cadmium	Chromel, columbium, tantalum
Cobalt	Columbium
Copper	Columbium, moly, tantalum
Germanium	Tantalum, moly
Gold	Tungsten, moly
Iron	Tungsten
Lead	Iron, nickel, chromel
Magnesium	Tungsten, tantalum, moly, columbium
Manganese	Tungsten, tantalum, moly, columbium
Nickel	Tungsten
Platinum	Tungsten
Selenium	Chromel, iron, moly
Silver	Tantalum, moly, columbium, iron
Strontium	Tungsten, tantalum, moly, columbium
Tellurium	Tungsten, tantalum, moly, columbium
Thallium	Nickel, iron, columbium, tantalum, moly
Thorium	Moly
Tin	Chromel
Titanium	Tungsten, tantalum
Vanadium	Tungsten, moly
Zinc	Tungsten, tantalum, moly, columbium

is excellent for boats. Tantalum is much less subject to embrittlement in vacuum than either of the others; thus, tantalum heaters last much longer.

Many people report a great deal of trouble with tantalum due to its gettering properties; it picks up contamination and then gives it off at the worst time.

Many metals, such as chromium, which are not readily evaporable, may be evaporated easily if they are first electroplated onto the filament. Boats require a great deal higher current flow in the filament, 50–100 amperes; unless the current supply is large, it is well to make the boats as thin and as narrow as possible.

XII. Lens Coating

Anti-reflection coatings on lenses consist of a thin layer of suitable transparent material; magnesium fluoride is almost universally used because, although it is not the best material, optically, it provides the most durable coating. The coating must be ¼ wavelength thick, and should have a refractive index equal to the square root of the index of the glass; this would theoretically require a different coating material for each kind of glass and a different thickness for each wavelength of light; it is obvious that in a practical case the coating is a compromise with the theoretical requirements. Coatings are usually made ¼ wavelength thick for light near the middle of the visible spectrum—about 5300 angstroms, in the green; this furnishes the greatest reduction in white light reflectivity.

Anti-reflection coatings work because of interference of light; the light reflected from the lower boundary of the coating interferes destructively with that reflected from the upper boundary—the thickness requirement of the film controls the phase relationship, and the index requirement controls the amplitude relationship; when the amplitude of the two light beams are equal and their phase difference 180°, the destructive interference is complete, and the reflectivity is zero. Further discussions of the theory of coatings is available in the literature.

Magnesium fluoride is a white crystalline solid; for coatings, it must be especially prepared in a form of high purity; commercial grades are not satisfactory for optical work. It is generally prepared in granular form, which is more satisfactory than powder, because of spattering. It is evaporated from a porcelain crucible, a tungsten filament wound in a flat spiral being set a millimeter or two above the surface of the fluoride. It may also be evaporated from molybdenum boats, from built-up crucibles, or even from a cake embedded in a tightly-wound helical coil.

The proper thickness of coating is determined by watching the reflected image of a suitable light (a fluorescent tube is best) in one of the surfaces which is being coated. There will, of course, be two reflections from a lens, one from each surface; be sure you are watching the right one. As the thickness of the coating builds up, it reaches the ¼-wavelength optimum for blue light first, blue light being of the shortest wavelength. In this condition, the blue reflection is reduced most, and the reflected image is deficient in blue light, appearing of a straw color. The straw fades away and is replaced by violet; this is the correct appearance of an anti-reflection coating for highest white-light efficiency. If the coating is allowed to build up, it will become blue and then green. A green reflection indicates a coating which is ½ wavelength thick for green light, the reflectivity now being a *maximum* for this wavelength, and equal to the reflectivity of uncoated glass. When magnesium fluoride is used as a protective coating for mirrors, a ½ wavelength coating should be laid down. When coating an aluminized mirror with a transparent material, the thickness is measured on a clear glass sample mounted at the same distance from the source as the mirror.

For a durable coating, it is necessary to heat the lenses to at least 300° F; in general, the hotter the lenses, the harder the coating. Hardness is usually tested by rubbing the coated surface with a soft pencil eraser. Standard specification for a hard coating is that it be not scratched or sleeked by 40 strokes

with a *clean* pencil eraser. Unfortunately, the most durable coatings are usually of less optical efficiency; the index of refraction of these baked coatings seems to be somewhat higher than those laid down cold. It is therefore sometimes desirable to use a soft coating, laid down on a cold lens, in such locations in an instrument that they will not be subjected to damage. A coating for the outside surface of an objective, however, should be of the highest durability.

For a good coating, the pressure should be at least as low as 10^{-4} mm; lower is better. Metal evaporation can be successfully carried out at higher pressures but, in general, the lower the pressure, the better are the results.

XIII. Interference Filters

If a coating consisting of alternating layers of high- and low-index materials is built up on a glass surface, an interference filter is produced. These filters may, by the proper selection of materials, thicknesses, and number of layers, be given almost any light-selective properties desired; they may be made to reflect yellow light and transmit blue; to transmit (or reflect) a narrow region anywhere in the spectrum, and so on. Since they operate on the principle of interference, they are essentially non-absorbent. The interference theory is quite complicated, mathematically, and much has been written about it in the literature, where will also be found much material respecting particular types of filters and their composition.

Cryolite or magnesium fluoride is the customary low-index material for these filters; titanium dioxide and zinc sulfide are commonly used for high-index layers.

XIV. Other Dielectric Films

Multiple layer coatings on mirrors have been used by Turner to increase the reflectivity of aluminum to as high as 98 percent. On low-index crown glass, where a magnesium fluoride film is not very effective in reducing reflections, due to the small difference of index between coating and glass, multiple layer coatings have been proposed which are more efficient; the simplest is to lay down a layer of relatively high index, followed by a low-index film.

Quartz is evaporated with difficulty because of its high boiling point, but evaporated silicon monoxide oxidizes to quartz upon exposure to air and, when properly applied, supplies a hard protective film for mirrors, plastics, etc. This method was developed by German scientists and is presented in the Whipple report (Office of Technical Services, Dept. of Commerce, Washington, D. C. Report PB 4158).

XV. Cleaning of Optics

For any coating operations, the items to be coated must be thoroughly cleaned. If coating is to be done on cemented lenses and heat is to be used, the lenses must be de-cemented prior to coating and then recemented. The cemented surfaces are not coated.

Soap and water is probably the best method for cleaning optics. The modern detergents, such as Dreft, Orvus, Tide, Vel, etc., are more effective for this work than ordinary soap, as they leave no film behind. The washing should be followed by a thorough scrubbing with a non-abrasive cleanser, precipitated chalk being the customary material. This is sold under such trade names as Wet-Me-Wet, etc.

After cleaning, the items must be dried, and this is the most difficult part. Such items as degreasers and centrifuges are sometimes resorted to, but wiping with clean white laundered cloth is usually quite satisfactory. The final wiping should be done with a lintless cloth, such as Celanese.

Any of the various cleaning solvents, such as alcohol, acetone, benzene, and others may, of course, be used, especially if there is grease to be removed.

XVI. Vacuum Leaks

The search for small leaks in the vacuum system is one of the more discouraging aspects of high vacuum work. The customary method with a small installation is to go over the equipment with an acetone spray, watching the gages carefully. When a leak is sprayed with acetone, the volatility of the solvent will cause the pressure to rise rapidly, and the gage will respond quickly. When the pressure is sufficiently low that the ionization gage may be used, the search for leaks by this method is greatly aided, since the gage deflection will be much greater than will be the case if the leak is so large as to preclude attaining a pressure of a micron or less.

The search for leaks is made much easier if vacuum valves are provided, as pointed out elsewhere in this chapter since this makes possible the isolation of various sections of the system for separate testing.

For large industrial systems, mass-spectrometer leak detectors have been developed and are very effective. The instrument detects the presence of a specific gas, such as helium, which is permitted to enter through the leak by spraying the outside of the system with the gas. These instruments can detect extremely tiny leaks. They are, however, very expensive, and not likely to be used by the individual with one small bell-jar.

XVII. Sputtering

This coating technic was in common use for many decades before thermal evaporation was developed. It is carried on at relatively high pressure (several millimeters), and often in an atmosphere of inert gas, such as helium or argon. A cathode of the coating material is the source, and either the item to be coated is made the anode (if a conductor) or an anode is mounted behind it. A high voltage is impressed between cathode and anode, and the consequent electrical discharge creates high-velocity particles in the residual gases, which in turn bombard the cathode and liberate particles which are drawn to

the anode and deposited. The phenomenon is relatively complex and the results depend greatly on the voltage, the pressure, the nature of the residual gas and other factors.

To do sputtering with a system containing high-speed pumps means the maintenance of a carefully controlled leak. The process is very slow, but this slowness has a certain advantage in that it permits precise control. Sputtered films differ somewhat in structure from evaporated films. Not all materials can be sputtered with equal effectiveness; the voltage and pressure requirements vary with the material of the cathode.

Bibliography

A brief list of selected technical articles (volume and page) and books.

Vacuum practice, general principles:

Woodrow, *Phys. Rev.* 4, 491 (1914).

Dushman, *Gen. Elec. Rev.* 23, 493 (1920); 23, 605 (1920); 23, 672 (1920); 23, 731 (1920); 23, 847 (1920); 24, 58 (1921); 24, 244 (1921); 24, 436 (1921); 24, 669 (1921); 24, 810 (1921); 24, 890 (1921); *Jrl. Frank. Inst.* 211, 689 (1931).

Hickman, *Jrl. Frank. Inst.* 213, 119 (1932).

Bailey, *Chem. and Met. Eng.* 41, 358 (Jul. 1934).

Morse, *Electronics* 12, 33 (1939).

Kurie, *Rev. Sci. Inst.* 19, 485 (1948).

*Strong, "Procedures in Experimental Physics," Prentice-Hall, Inc., New York, 1945.

Dushman, "Scientific Foundations of Vacuum Techniques," John Wiley & Sons, New York, 1949.

*War Dept. Tech. Manual TM9–1501, "Operation and Maintenance of Optical Coating Equipment."

*Navy Dept., Bureau of Ordnance Pub. OP1512, "Optics Filming."

Vacuum technics and miscellaneous apparatus:

Andrews, *Amer. Chem. Soc. Jrl.* 53, 1674 (1931)	Getters
Hull, *Jrl. Appl. Phys.* 5, 384 (1934)	Glass-metal seals
DuMond, *Rev. Sci. Inst.* 6, 285 (1935)	Bellows
Taylor, *Rev. Sci. Inst.* 6, 243 (1935)	Oxygen supply
Garner, *Rev. Sci. Inst.* 8, 329 (1937)	Seals
Loeb, *Jrl. Appl. Phys.* 8, 495 (1937)	Glow Discharge
Rose, *Rev. Sci. Inst.* 8, 130 (1937)	Vacuum aids
Rubens, *Phys. Rev.* 54, 348 (1938)	Vacuum joints
Stahl, *Jrl. Appl. Phys.* 20, 8 (1939)	Thermal joints
Morse, *Rev. Sci. Inst.* 11, 277 (1940)	Baffles
Hull, *Jrl. Appl. Phys.* 12, 698 (1941)	Glass-metal seals

* Required reading.

MOORE, *Jrl. Sci. Inst.* 21, 124 (1944); 21, 162 (1944)	Vacuum connections
LAURITSEN, *Rev. Sci. Inst.* 19, 919 (1948)	Vacuum fittings
MONK, *Jrl. Appl. Phys.* 19, 485 (1948)	Weighing in vacuum

Vacuum Pumps:

LANGMUIR, *Jrl. Frank. Inst.* 182, 719 (1916)	Vacuum pump
BYCK, *Phys. Rev.* 39, 553 (1932)	Diffusion pump
HICKMAN, *Jrl. Frank. Inst.* 221, 215 (1936); 221, 383 (1936)	Pump oils
HO, *Jrl. Appl. Phys.* 2, 386 (1932)	Diffusion pumps
COPLEY, *Rev. Sci. Inst.* 6, 361 (1935)	Pump nozzles
EDWARDS, *Phys. Rev.* 47, 259 (1935)	Diffusion pump
HENDERSON, *Rev. Sci. Inst.* 6, 66 (1935)	Oil pump
ZABEL, *Rev. Sci. Inst.* 6, 54 (1935)	Oil pump
HICKMAN, *Jrl. Appl. Phys.* 11, 303 (1940)	Diffusion pumps
BROWN, *Rev. Sci. Inst.* 16, 316 (1945)	Silicone oils
WITTY, *Jrl. Sci. Inst.* 22, 201 (1945)	Vacuum pumps
ALEXANDER, *Jrl. Sci. Inst. Phys. Ind.* 25, 313 (1948)	Glycerol pump
BLEARS, *Rev. Sci. Inst.* 19, 847 (1948)	Pump speeds

Vacuum Gages:

MCLEOD, *Phil. Mag.* 47, 110 (1874)	McLeod gage
HALE, *Electrochem. Soc. Trans.* 20, 243 (1911)	Pirani gage
WOODROW, *Phys. Rev.* 4, 491 (1914)	General
DUSHMAN, *Phys. Rev.* 5, 212 (1915)	Molecular gage
DEVRIES, *Jrl. Op. Soc. Amer.* 18, 333 (1929)	Pirani gage
CUYDENDALL, *Rev. Sci. Inst.* 6, 371 (1935)	Pirani gage
HOAG, *Rev. Sci. Inst.* 7, 497 (1936)	Ionization gage
DUNLAP, *Rev. Sci. Inst.* 8, 37 (1937)	Thermocouple gage
BOWIE, *Rev. Sci. Inst.* 11, 266 (1940)	Ion gage circuit
RAINWATER, *Rev. Sci. Inst.* 13, 118 (1942)	Ionization gage
TURNER, *Phys. Rev.* 66, 37 (1944)	Knudsen gage
DUSHMAN, *Phys. Rev.* 68, 278 (1945)	Ionization gage
FLOSDORF, *Chem. and Met. Eng.* 52, 68 (Nov. 1945)	McLeod gages
DAYTON, *Vide* 2, 349 (1947) (Fr.)	Gage calibration

Evaporated Mirrors:

STRONG, *Phys. Rev.* 37, 228 (1931)	Evaporation
WILLIAMS, *Phys. Rev.* 41, 255 (1932)	Chromium on glass
SPENCER-JONES, *Nature* 134, 622 (1934)	Aluminum mirrors
STRONG, *Astro. Jrl.* 83, 401 (1936)	Evaporation
AUWARTER, *Jrl. Appl. Phys.* 10, 705 (1939)	Rhodium mirrors
WILLIAMS, *Astro. Jrl.* 77, 316 (1939); *Pop. Astronomy* 57, 1 (1939)	Evaporation; 82-inch mirror
KROLL, *Electrochem. Soc. Trans.* 87, 55 (1945)	Evaporation

Filaments for Evaporation:

COUNTRYMEN, *Jrl. Appl. Phys.* 8, 432 (1937)	Wetting filaments
*CALDWELL, *Jrl. Appl. Phys.* 12, 779 (1941)	See table in text
*OLSEN, *Jrl. Appl. Phys.* 16, 425 (1945)	Filaments and crucibles

Historical References on Anti-Reflection Coatings:

TAYLOR, "Adjustment and Testing of Telescope Objectives;" T. Cooke & Sons, York, England 1896	Discovery of effect
WOOD, "Physical Optics" (1913) 3d Ed. pp. 190 *et seq.* Macmillan Co., New York (1934)	Basic theory
KOLLMORGEN, *Trans. Ill. Eng. Soc.* 11, 220 (1916)	Chemical attempts
WRIGHT, "Ord. Dept. Doc. 2037," p. 76 (1921)	Experiments
BLODGETT, *Jrl. Op. Soc. Amer.* 24, 313 (1934); *Phys. Rev.* 51, 963 (1937)	Oil films; Stearate films

Anti-Reflection Lens Coatings:

*STRONG, *Phys. Rev.* 59, 209 (1936); *Jrl. Op. Soc. Amer.* 26, 73 (1936)	First announcement
*BLODGETT, *Phys. Rev.* 55, 391 (1939)	Basic theory
CARTWRIGHT, *Phys. Rev.* 55, 595 (1939)	
BLODGETT, *Phys. Rev.* 57, 921 (1940)	
CARTWRIGHT, *Jrl. Op. Soc. Amer.* 30, 110 (1940); *Phys. Rev.* 57, 358 (1940); 57, 1060 (1940)	Performance
FRENCH, *Nature* 146, 687 (1940)	Cryolite films
VASICEK, *Phys. Rev.* 46, 925 (1940)	Thickness measurement
MORSE, *Jrl. Op. Soc. Amer.* 31, 756 (1941)	Performance
TYLER, *Jrl. Op. Soc. Amer.* 32, 211 (1942)	Performance
TOWNSLEY, *Rev. Sci. Inst.* 16, 143 (1945)	Testing durability
TAIMER, *Jrl. Op. Soc. Amer.* 36, 701 (1946)	German coatings
DELL, *Proc. Phys. Soc.* 62, 81 (1949)	Cryolite films

Chemical Lens Coatings:

JONES and HOMER, *Jrl. Op. Soc. Amer.* 31, 34 (1941)	
NICOLL and WILLIAMS, *Jrl. Op. Soc. Amer.* 33, 434 (1943)	

Multiple-Layer Coatings:

CARTWRIGHT, *Phys. Rev.* 55, 1128 (1939)	
TROUTMAN, *Jrl. Op. Soc. Amer.* 32, 631 (1942)	
VON ARDENNE, *Zeits. Angew. Phot.* 4, 15 (1942) (Ger.)	
*MOONEY, *Jrl. Op. Soc. Amer.* 35, 574 (1945)	Theory
KING, *Jrl. Op. Soc. Amer.* 36, 513 (1946)	Two-layer
CABALLERO, *Jrl. Op. Soc. Amer.* 37, 176 (1947)	Theory

* Required reading.

LOCKHARDT, *Jrl. Op. Soc. Amer.* 37, 689 (1947)	Three-layer
VASICEK, *Jrl. Op. Soc. Amer.* 37, 623 (1947)	
WEINSTEIN, *Jrl. Op. Soc. Amer.* 37, 576 (1947)	Measurements
MUCHMORE, *Jrl. Op. Soc. Amer.* 38, 20 (1948)	Theory
Interference Filters:	
*BANNING, *Jrl. Op. Soc. Amer.* 37, 792 (1947)	
*HADLEY, *Jrl. Op. Soc. Amer.* 37, 451 (1947)	
Structure of Evaporated Films, etc.:	
OLIVER, *Phys. Rev.* 61, 313 (1942)	Structure
BOETTCHER, "Off. Tech. Serv. Dept. Commerce, Rep. PB36469"	Conductivity
WEALE, *Proc. Phys. Soc.* 62, 135 (1949)	Resistivity
Non-metallic films:	
*PFUND, *Jrl. Op. Soc. Amer.* 24, 99 (1934)	ZnS films
SMETHHURST, *Jrl. Sci. Inst.* 22, 52 (1945); 22, 130 (1945)	PbS mirrors
*BANNING, *Jrl. Op. Soc. Amer.* 37, 688 (1947)	TiO mirrors
Sputtering:	
PATTERSON, *Phil. Mag.* 4, 652 (1902)	
FRUTH, *Jrl. Appl. Phys.* 2, 280 (1932)	
BARNES, *Jrl. Frank. Inst.* 219, 100 (1935)	
TOWNES, *Phys. Rev.* 65, 319 (1944)	
Miscellaneous:	
WATSON, *Can. Jrl. Res.* 8, 412 (1933)	Leak finding
WEBSTER, *Rev. Sci. Inst.* 5, 42 (1934)	Leak finding
*STRONG, *Rev. Sci. Inst.* 6, 97 (1935)	Cleaning surfaces
*GAVIOLA, *Jrl. Op. Soc. Amer.* 26, 153 (1936)	Parabolizing by evaporation
STRONG, *Phys. Rev.* 49, 291 (1936)	Aluminum gratings
OSTERBERG, *Jrl. Op. Soc. Amer.* 32, 631 (1942)	Metal and non-metal
TROUTMAN, *Jrl. Op. Soc. Amer.* 32, 631 (1942)	Metal and non-metal
*SCOTT, *Jrl. Op. Soc. Amer.* 36, 711 (1946)	SiO on mirrors
WHIPPLE, "Off. Tech. Serv., Dept. Commerce, Rep. PB4158"	SiO on mirrors
TURNER, *Jrl. Op. Soc. Amer.* 36, 811 (1946)	Increasing reflect
BILLINGS, *Jrl. Op. Soc. Amer.* 37, 123 (1947)	Bolometers
BANNING, *Jrl. Op. Soc. Amer.* 37, 686 (1947)	Neutral filters
*SCHULZ, *Jrl. Op. Soc. Amer.* 37, 509 (1947)	Aspheric surfaces
COMER, *Anal. Chem.* 21, 418 (1949)	Silica evaporation
———, *Military Eng. Mag.* Jan.–Feb. 1949, p. 43	Beam splitters

[EDITOR'S NOTE: Those who lack access to libraries at which the periodical literature cited by the author is on file may purchase photostats of articles

* Required reading.

from the Library of Congress, Washington, D. C. or the New York Public Library. Give full reference and ask for estimate. In 1953 the charge was above 25 cents per pair of facing pages. The addresses of the publishers of the periodicals themselves are as follows:

Analytic Chemistry, American Chemical Society, Easton, Pa.
Astrophysical Journal, 5750 Ellis Ave., Chicago, Ill.
Chemical and Metallurgical Engineering, 330 W. 42 St., New York, N. Y.
Electronics, 330 W. 42 St., New York, N. Y.
General Electric Review, Schenectady, N. Y.
Journal of the American Chemical Society, Back Issue Dept., 1155 16 St., Washington 6, D. C.
Journal of Applied Physics, 57 E. 55 St., New York 22, N. Y.
Journal of the Franklin Institute, Franklin Institute, Philadelphia, Pa.
Journal of the Optical Society of America, 57 E. 55 St., New York 22, N. Y.
Journal of Scientific Instruments, The Institute of Physics, 47 Belgrave Square, London, S.W. 1, England.
Nature, Macmillan and Co. Ltd., St. Martin's Street, London W.C. 2, England.
Philosophical Magazine, Care Messrs. Taylor and Francis, Ltd., Red Lion Court, Fleet Street, London, England.
Physical Review, 57 E. 55 St., New York 22, N. Y.
Popular Astronomy, Northfield, Minn.
Proceedings of the Physical Society, 1 Lowther Gardens, Prince Consort Road, London S.W. 7, England.
Review of Scientific Instruments, 57 E. 55 St., New York 22, N. Y.
Transactions of the Illuminating Engineering Society, 32 and Elm Streets, Baltimore, Md.]

SUGGESTED SOURCES OF SUPPLY

Equipment:

A complete line of vacuum equipment and supplies is carried by:
Optical Film Engineering Co., 2737 No. 6th St., Phila. 33, Pa.
Distillation Products, Inc., Ridge Road, Rochester, N. Y.
National Research Corp., 100 Brookline Avenue, Boston, Mass.

This includes complete units, bell jars, mechanical and diffusion pumps, gages, pump oils, special electrodes, bell jar gaskets, valves, vacuum grease, etc.

Mechanical pumps:

Kinney Manufacturing Co., 3565 Washington St., Boston, Mass.
Central Scientific Co., 1700 Irving Park Blvd., Chicago, Ill.
W. M. Welch Co., 1515 Sedgwick St., Chicago, Ill.
F. J. Stokes Machine Co., 5900 Tabor Rd., Philadelphia 20, Pa.

Vacuum Valves:

Kinney Manufacturing Co., 3565 Washington St., Boston, Mass.

Gages:

Ionization gages: Optical Film Eng. Co.
Distillation Products, Inc.
National Research Corp.

Pirani gages: Distillation Products, Inc.

Thermocouple gages: National Research Corp.
Continental Elec. Co., 188 W. Randolph St. Chicago, Ill.

McLeod gages: Central Scientific Co., 1700 Irving Park Blvd., Chicago, Ill.
Eimer & Amend, 635 Greenwich St., New York, N. Y.
Electronic Products Co., Los Angeles, Calif.
General Electric Co., Schenectady, N. Y.
General Physical Lab., 509 Fifth Ave., New York, N. Y.

Knudsen gages: Distillation Products, Inc.

Phillips gage: North American Phillips Co., 100 E. 42nd Street, N. Y.
Distillation Products, Inc., Radio Corp. of America, 30 Rockefeller Plaza, New York, New York

Miller gage: Miller Labs., Latham, New York.

Electrical Equipment:

General Radio Co., 30 State St., Cambridge, Mass. (Variacs, meters)
Weston Electric Instrument Co., Freylinghausen Ave., Newark, N. J. (meters, photocells)

Materials and Supplies:

Central Scientific Co., 1700 Irving Park Blvd., Chicago, Ill. (chemicals, vacuum grease, lab. supplies)
Eimer and Amend, 633 Greenwich St., New York, N. Y. (chemicals, lab. supplies)
American Cystoscope Makers, 129 E. 78th St., New York, N. Y. (fluoride)
General Electric Supply Corp., (your local branch) (Glyptal)
Union Carbide and Chemical Co., 30 E. 42nd St., N. Y., N. Y. (fluoride)
Kearfott Engineering Co., 117 Liberty St., New York, N. Y. (Hermeflex vacuum seal)
Universal Shellac and Supply Co., 540 Irving Ave., Bklyn., N. Y. (fluoride)
Sauereisen Cements Co., Pittsburgh 15, Pa. (Insulute insulating cement)
Molybdenum Corp. of America, 500 5th Ave., New York, N. Y. (tungsten, molybdenum)
Fansteel Metallurgical Corp., North Chicago, Ill. (tantalum, columbium)
J. T. Baker Chemical Co., 100 E. 42nd St., New York, N. Y. (chemicals and metals)
Hoskins Mfg. Co., Grand Central Terminal, New York, N. Y. (Chromel)
Dow Corning Corp., Midland, Mich. (Silicone oils)
Handy and Harman, Inc., 82 Fulton St., New York, N. Y. (rare metals)
Miller Rubber Products Co., 29 Warren St., New York, N. Y. (Neoprene)
Cerro de Pasco Copper Corp., 40 Wall St., New York 5, N. Y. ("Cerroseal 35," a glass-to-metal or glass-to-glass sealing material)

Small Pinholes

By C. R. Burch, F.R.S.
Warren Research Fellow, H. H. Wills Physics Laboratory
Bristol University, Bristol, England

What size star ought we to use for the knife-edge test? Contradictory opinions have been published. Ellison (ATM, p. 84) "has known grotesque errors result from using too fine a hole." The user who did this "saw a series of diffraction bands inside the margin of his mirror, and took them for a turned down edge." G. W. Ritchey, on the other hand, writes (quoted from ATM, p. 294): "When the knife-edge test is used with an extremely small pinhole between $1/250$ and $1/500$ of an inch in diameter, illuminated by acetylene, or what is much better, oxy-acetylene or electric arc light, minute zonal irregularities are strongly and brilliantly shown, which are entirely invisible with large pinhole or insufficient illumination." What in fact determines the delicacy of the knife-edge test?

If light traveled in straight lines, a given zone would show quite black on a fully bright mirror (or conversely) if its tilt with respect to true figure was just enough to divert the rays reaching it from every part of the pinhole, so that they fell completely clear of the image of the pinhole formed by the rest of the mirror. The delicacy of the test would then be inversely proportional to the diameter of the pinhole (provided enough light could be got through the pinhole). If on the other hand we ask, not that a given zone should show fully bright, but merely that it should show *appreciably* bright on a fully black mirror, the delicacy of the test will be limited only by the intrinsic brilliance of the source feeding the pinhole. On the "ray" theory of light, then, we should make the source as bright as possible, and the pinhole only just large enough to let through a reasonable amount of light.

But, as we hope to test correct to a small fraction of a wavelength, we must take into account the wave properties of light. We can then argue that since the mirror cannot produce a "point" image of a "point" pinhole, but produces an "Airy disk" of finite width, we shall not gain much in delicacy by reducing the diameter of the pinhole below that of the Airy disk produced by the mirror —which depends on the focal ratio at which the mirror receives the light from the pinhole.

Thus, for testing a spherical mirror of diameter D, radius of curvature $R = 2F$, we should use a pinhole of the order of smallness of $0.01F/D$ mm diameter. So, for example, a spherical mirror of $D = 6$ inches, $R = 8$ feet, should be tested with a pinhole not bigger than 0.008 mm = 0.00032 inch diameter—a hole 6 times smaller than the smallest hole advised even by Ritchey.

This raises immediately the question of whether one will see a series of diffraction rings round the edge of the mirror—for if such rings are seen, much of the advantage of the small pinhole would presumably be lost. You cannot do good optics by guessing what things would look like if they were not surrounded by diffraction rings.

When I first used the knife-edge test, I used a hole 0.013 mm diameter, and saw about 6 diffraction rings inside the edge of the mirror (no knife-edge being present). It was difficult to know what to do about these rings, and in desperation I decided to work out theoretically how they should behave. My result was that they should be invisible, because their spacing on the retina should only just equal the resolving power of the eyelens, and the retina would then be incapable of resolving them. I looked at the mirror again, and was able to count 6 distinct rings. I then remembered that Lord Rayleigh had made a similar calculation many years ago. On referring to it, I found that he also concluded (in effect) that no rings should be visible. I looked at the mirror for the third time, and could not see any diffraction rings. . . !

It was all very mysterious: I could understand the mirror showing its contempt for my theoretical treatment, but it must have known that Lord Rayleigh made the same calculation before. A year later, I found the explanation: a visitor, looking at the mirror, complained of diffraction rings, which I could not see, and it occurred to me to look at it through his spectacles, which he had taken off. I then saw the rings, and when he wore his spectacles he saw no rings.

Theory predicts that, if you focus your eye not on the mirror but in front of it or behind it, you will see diffraction rings around its edge. (The extreme example of this is the series of rings seen in the extra-focal image of the star, which is after all, also the extra-focal image of the mirror!)

The reason why anyone with normal sight tends to focus his eye anywhere but on the surface of the mirror is simply that, if for a brief moment he malfocuses the mirror, he sees diffraction rings, and his eye automatically tries a further change of focus in the direction that enabled it to see something—the rings—which it had not seen before. Therefore the proper advice to give to such an one, who complains of diffraction rings, may be cast in the epigrammatic (if exasperating) form, "If you don't look at them, you won't see them!" If he still sees them, there is nothing for it but the right spectacles, and—in the last resort—a friendly oculist to paralyze the focusing muscles of his eye with the appropriate "dope," so that he cannot unconsciously vary his focus. But it is worth while, before adopting so drastic a measure, first simply to use the test for some hours. Refraining from malfocusing one's eye is like riding a bicycle—most of us have to learn it by practice but, when learnt, it is quite automatic.

There remains the question of how to get enough light through a hole as small as 0.008 mm diameter. It is necessary to use a source of very high intrinsic brilliance, such as a gas-filled lamp, or a Pointolite, or an arc, and since these sources are too small to provide the required solid angle of light even when placed as close to the hole as is practicable, it is necessary to use a condensing lens, to form an image of the source on the hole. One need not, however, correct the aberrations of the condensing lens completely, or even at all. These aberrations will cause the image of the *hole* which the lens forms on the source to be larger than it would otherwise be, but provided this image is not larger than the source, the aberrations will not reduce the light issuing from the hole, nor will they falsify the test by appearing on the mirror. I use a 12-volt, 16-watt gas-filled lamp, the filament of which is coiled in a very close helix, and a simple biconvex lens of 1-inch focal length to image it (with unit magnification) via a prism on to the pinhole. To adjust this star, one puts one's eye very close to the pinhole, and moves the lamp (the base of which is fixed on three "leveling" screws) until the blurred patch of light seen through the pinhole is as wide and as bright as possible. The resulting cone of light is wide enough for testing a system imaging at $f/8$: if a wider cone is needed, either the lens must be corrected, or a wider source must be used. As the lateral aberrations of a lens are proportional to its focal length (for given aperture), the focal length of the lens should be as short as the size of the lamp-bulb permits.

One can sometimes find natural holes of the order of 0.01 mm diameter in "tinfoil": the following account of the technic of *making* even smaller holes is quoted from the *Monthly Notices* of the R.A.S., March 1936 (p. 452).

"The principal difficulty I found in making pinholes .0025 mm diameter, by piercing tinfoil with a needle, lay in making the needle really sharp. But Dr. J. M. Dodds, of the Metropolitan-Vickers Co., solved this difficulty by the following honing technic. The needle, mounted on a rod, is first honed on a fine stone until the diameter of its 'point' does not exceed 0.01 mm. This is not difficult, provided one inspects the point frequently during honing with a microscope. The final honing is done on glass. Lay the needle on a glass plate, and press heavily with one finger behind its point. Lift the rod in which it is mounted slightly so that the needle is bent through several degrees. Then, still pressing with the finger, simultaneously twist and withdraw the slightly lifted rod, so drawing out the needle under the pressing finger. This process is repeated until on inspection under 500 diameters magnification the needle looks quite 'sharp'—that is, its 'point' is of the order of 0.001 mm diameter or even less. Fifteen minutes honing on glass usually suffices.

"The 'tinfoil' in which cigarettes are wrapped forms an excellent material for the pinhole. The foil is tacked (at its edges only) to a glass plate; the needle point is then placed very gently on it, and the needle rotated without pressure through at least one revolution and then lifted off. Some practice is necessary to avoid dragging the point sidewise in lifting it off. If the needle is not rotated the hole will not be reasonably circular. The needle requires rehoning after a few piercings. Not every pierce is successful, but one can in this way make reasonably circular pinholes 0.002 mm diameter, and occasionally even smaller."

There are two main points of difference in the behavior of the knife-edge test when it is carried out not with a large pinhole, but with a pinhole—an "artificial star" as some term it—smaller than the resolving power of the mirror (say, 0.001 f/D mm dia. for a sphere tested at its center: 0.0005 f/D mm for a paraboloid tested at its focus, with a flat).

First, the test becomes noticeably more delicate, especially for slow errors of curvature—simple spherical aberration, and more particularly coma and astigmatism. For example, one obtains appreciable "paraboloid" shadows on a 12 inch paraboloid of $f/18$. The test becomes more sensitive without diaphrams than when diaphrams are used, but zonal focal measurements taken without diaphrams can give hopelessly wrong results—as was predicted by Lord Rayleigh, many years ago. A simple (though admittedly loose) way of explaining this is to say that when the knife-edge is not at focus, its shadow is preceded by diffraction fringes (not to be confused with eye-malfocus diffraction rings seen in the absence of the knife-edge). Thus a large error, on one part of the mirror, by putting the knife-edge out of focus for that part, can produce diffraction fringes on an error-free part of the surface. Accordingly, the only part of the error which one can be certain of interpreting correctly is the *largest* error present. This diffraction fringe difficulty automatically decreases as the errors are reduced and vanishes when the mirror is error-free. The mirror then shadows symmetrically as the knife-edge is advanced, but not uniformly, the center darkening before the edges. If the test were interpreted on a "ray" basis one would then say that, since the edges shadow last, one edge must be turned up, and the other turned down—in fact, that the mirror is comatic. One can, however, check whether coma is really present, for if it is, on bringing in the knife-edge in the opposite direction, the edges will shadow before the center.

The second point is that the delicacy of the test—expressed in wave lengths—becomes independent of the focal ratio of the mirror, provided that the test is made null-fashion, without diaphrams. When diaphrams must be used—as in testing a wide aperture paraboloid at its center of curvature—the limit of observational accuracy always corresponds to an uncertainty of the tilt of each zone amounting to a given fraction of a wavelength at the edge of the zone. It is extremely difficult to reduce this error to one hundredth of a wavelength per zone. Now, the effect of such an error is cumulative: if one zone is measured wrongly by $\lambda/100$ the resulting height calculated for the 10th zone from it, will be in error by $\lambda/10$—a by no means negligible amount. That is why it is preferable to test wide aperture paraboloids, for which many zones would be necessary, at the focus, with the aid of a flat.

Diffraction effects can complicate the "paraboloidal shadows" seen at the center of curvature so much that even at the modest aperture of $f/8$ there may sometimes be difficulty in locating irregular error from the "general run" of the shadows. It may then be preferable to gain ease of interpretation at the expense of sensitivity by increasing the diameter of the pinhole "till it is as big as a porthole" and obvious diffraction troubles disappear. We have to fall back on "ray" theory to determine a reasonable size for the "porthole." On this basis, if we wish to see the "paraboloidal shadows" ranging in contrast from fully black to fully bright, we should make the "porthole" diameter equal to that of the geometrical circle of least confusion produced by the mirror. That is, for a paraboloid of diameter D, focal length f, we should use a "porthole" of diameter $D/64(D/f)^2$. So, for example, a 12-inch paraboloid of $f/8$ would require a "porthole" 0.003 inch in diameter.

But to detect a given error we should then have to look for differences

of contrast considerably smaller than those with which the same error would show in a spherical mirror tested at its center with a really small star: this is especially the case with the three errors of longest period: coma; astigmatism; and "error" of absolute focal position.

[EDITOR'S NOTE: The preceding chapter was in ATMA from 1937 to 1944, then was separated from it, and is now made available in ATM3.]

The Theory and Application of the Concave Diffraction Grating *

By C. Fred Clarke

The purpose of this paper is to explain the construction and operation of a small grating spectrograph. In order to accomplish this it will be necessary: (1) to review briefly the theory of the grating, (2) to give the mechanical details of the necessary construction of the spectrograph, (3) to consider in detail the difficulties and limitations arising in the adjustment and operation of the apparatus, and (4) to compare its resolving power with the equipment available in this laboratory.

To meet the above objectives it was necessary to provide a mounting for the grating which would: (1) be flexible, (2) provide easy adjustment from one setting to another, and (3) give accurate resetting to any desired region of the spectrum.

Theoretical Considerations: An optical grating consists of a piece of glass or speculum metal which has been ruled with from 3000 to 30,000 lines to the inch. The glass allows the light to pass between each ruled line but the ruled line is practically opaque. The speculum metal acts as a mirror, each groove acting as a small reflector. The ruling of these gratings is a delicate, expensive, and slow task. There has been developed, by T. Thorp, R. J. Wallace, and others, a method of reproducing these gratings by making a collodion or pyroxylin cast of the original, and mounting this cast on some suitable foundation.[1] Rowland discovered that if a grating were ruled on a concave mirror the grating would produce sharp images, itself, without any lens system being necessary.

The concave grating used in this problem is a Wallace replica of a grating ruled on Michelson's engine at the University of Chicago. The cast is mounted on a silvered glass mirror, which in turn is mounted on a block of plaster of Paris. This grating has 25,110 lines to the inch, and a focal length of 106.0 cm. The lines are 3 cm long and the ruling extends for 5 cm.

From the elementary theory of the diffraction grating the relation between the angle of the incident ray θ_1, the angle of the diffracted ray θ_2, and the wavelength λ, for any plane grating, is given by the equation[2]

$$n\lambda = a(\sin\theta_1 + \sin\theta_2) \qquad (1)$$

where n is the spectral order observed and a is the grating spacing; *viz.*, the distance from a point in one ruled line to a corresponding point in the adjacent line or, simply, the reciprocal of the number of lines per unit length of

* A portion of an unpublished masters thesis from the Department of Physics, Michigan State College, 1935. I wish to express my appreciation to Dr. C. D. Hause who suggested this problem and who has guided throughout; to Prof. C. W. Chapman for his cooperation in furnishing the necessary equipment; to George L. Chapman for his guidance in the mechanical construction, and to the physics staff for many helpful suggestions and encouragements.

[1] Charles F. Meyer, "The Diffraction of Light, X-rays, and Material Particles," p. 130, p. 182.

[2] Meyer, p. 116.

grating. This elementary theory is applicable to any plane transmission or reflection grating. If this equation is applied to each element of a concave reflection grating an expression should be found which would determine the focal relation.

In the development of this focal relation for the concave grating, the grating space a is considered constant along the arc. In practice a grating is ruled with the spacing constant along the chord. However, since the aperture of a grating is small, the spacing along the arc or chord will not differ appreciably.

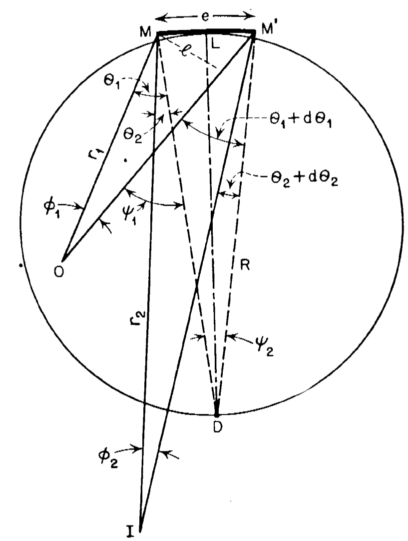


Figure 1

Drawings by J. F. Odenbach after the author

(It can be shown that this constant spacing along the chord instead of along the arc is essential in the perfection of the image.)[3]

In Figure 1 let O be the source and its image I formed by the grating MM'. With DL, the radius of curvature of the grating as a diameter, draw a circle tangent to the grating at its center. Consider the two rays from O, and OM', incident on the grating. Let e represent the small element of the grating between M and M'. The angles θ_1 and $\theta_1 + d\theta_1$, and θ_2 and $\theta_2 + d\theta_2$ are the angles of incidence and diffraction since any line from D is normal to the grating surface. In order to form a diffracted image in a given order of a particular wavelength it is necessary that $n\lambda$ remain constant over the surface of the grating. This condition may be expressed by differentiating the grating

[3] Meyer, p. 430.

equation with respect to θ and setting this equal to zero. The correct focal relation will then be that which satisfies this equation.

$$d(n\lambda) = d[a(\sin\theta_1 + \sin\theta_2)]$$

Since a is a constant for any particular grating this equation reduces to

$$\cos\theta_1 d\theta_1 + \cos\theta_2 d\theta_2 = 0 \qquad (2)$$

In order to have an image, θ_1 and θ_2 must compensate for each other to satisfy equation (2).

Letting R represent the radius of curvature of the grating, r_1 the distance OM, and r_2 the distance IM in Figure 1, by geometry

$$\phi_1 + \theta_1 = \psi_1 = \psi_2 + \theta_1 + d\theta_1$$

or

$$d\theta_1 = \phi_1 - \psi_2 = \frac{l}{r_1} - \frac{e}{R}$$

by using radian measure to represent the angles ϕ_1 and ψ_2.

$l = e \cos\theta_1$ since for small arcs the arc may be substituted for its chord or the chord for the arc (the error introduced being small) and the element of the grating surface is small. Therefore

$$d\theta_1 = \frac{e\cos\theta_1}{r_1} - \frac{e}{R}$$

and similarly $d\theta_2$ may be written

$$d\theta_2 = \frac{e\cos\theta_2}{r_2} - \frac{e}{R} \qquad (3)$$

Substituting these values in equation (2) gives

$$\cos\theta_1\left\{\frac{e\cos\theta_1}{r_1} - \frac{e}{R}\right\} + \cos\theta_2\left\{\frac{e\cos\theta_2}{r_2} - \frac{e}{R}\right\} = 0 \qquad (4)$$

If $r_1 = R\cos\theta_1$, and $r_2 = R\cos\theta_2$, equation (4) is satisfied. This condition exists when O and I both lie on the circle having DL as a diameter. Other conditions may satisfy this equation but this one is of particular significance. This circle is commonly called the Rowland circle and is understood to be the circle tangent to the center of the grating using the radius of curvature as its diameter.

In general practice a narrow slit is used as the source O. It follows from equation (4) that if the slit is placed anywhere on the Rowland circle, its image will be in focus on this circle also, and for any given θ_1, its position will depend upon n and λ of equation (1).

Figure 2 is a sketch of the Eagle mounting.[4] Light enters the slit S and is reflected to the grating G where it is diffracted to the plate P. Here the

[4] *Astrophysical Journal*, Vol. 31, p. 120 (1910).

various wavelengths are separated over the plate. Optically the slit S is just above or below the center of the plate P. Since it is necessary that the grating and plate remain on the Rowland circle as they are rotated, the corresponding change in the chord is made, as illustrated in Figure 3. The center of the Rowland circle moves along the normal to the line PG as the machine is adjusted to the various spectral orders. From Figure 2 it is evident that the

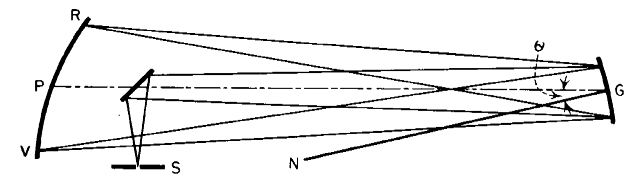


FIGURE 2

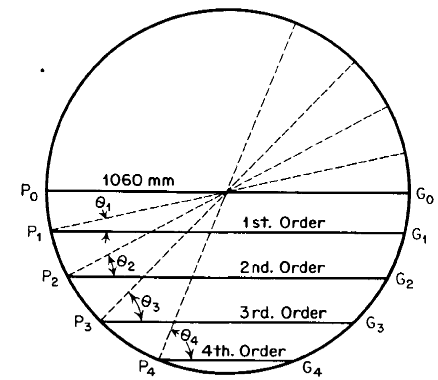


FIGURE 3

angle of incidence θ_1 and the angle of diffraction θ_2 are identical. Therefore equation (1) reduces to

$$n\lambda = 2a\sin\theta \qquad (5)$$

for the Eagle type of mounting. It is also evident from equation (4) that if all points on the plate P are to be in focus at the same setting it must have the curvature of the Rowland circle.

Definitely to illustrate these positions, take the iron line $\lambda = 4859.757$A and calculate the required positions with equation (5). This particular grating has 25,110 lines per inch, or 9885.8 lines per cm. Therefore $a = 10115.4$A. $R = 106.0$ cm. From equation (5) is obtained

$$\theta = \arcsin \frac{n\lambda}{2a} \qquad (6)$$

TABLE 1

N	Θ	PG	R	D
1	13 34′	103.04	7.5	2.3
2	28 43′	92.96	15.9	6.2
3	46 06.5′	73.49	25.6	14.3
4	73 55′	29.36	41.2	30.9

Figure 3 gives graphically the relative positions of the camera and grating for the orders as shown in Table 1. As the length of the chord is changed, the grating and the plateholder must rotate equal amounts in opposite directions in order to remain tangent to the Rowland circle.

It is clear from equation (6) that in the same position in which the first order diffracted image of $\lambda = 4859.75$A is obtained, will occur the second order of $\lambda = 2429.87$A and the third order $\lambda = 1619.75$A; neglecting, of course, the probability of absorption of these shorter wavelengths.

CONSTRUCTION

There are four main parts to a grating spectrograph: (1) the grating support, (2) the camera or plateholder, (3) the slit and mounting, (4) the general support for these three arranged in a manner which will provide the necessary adjustment.

In the Eagle mounting[5] it is necessary to have the slit and center of the plate optically coincident. This is impossible mechanically. However, a very close approximation to this ideal may be had by lifting the plate just above the plane of the Rowland circle which includes the optical axis of the grating, and then placing the slit just below this circle, both coincident with a line through the circle perpendicular to the plane of the circle.

Actually this last may be accomplished in two ways. The slit may be mounted directly beneath the plateholder (the disadvantage being that only one exposure may be obtained on any given plate, as there is no opportunity to move the plate into successive positions without covering up the slit with the plateholder). Or the slit may be mounted perpendicular to this optical path and just below the plane of the Rowland circle with a 45° totally reflecting prism at the foot of the perpendicular, and the optical path adjusted until it is the same length as in the previous condition. This is similar to the mounting used in the Littrow type of prism spectrographs.

The distance between the grating and the plateholder must be capable of a wide range of lateral adjustment and must be capable of reset positions quickly

[5] E. C. Baly, "Spectroscopy," Vol. 1, pp. 205–212.

and easily. The maximum length must be the focal length of the grating, in this instance 106 cm. The minimum length will depend on the spectral order possible with the grating at hand. This one was constructed with a range of 42 to 16 inches from grating to plate. This adjustment is the length of the chord of the Rowland circle.

As the chord is changed in the Rowland circle the grating must remain tangent to the circle and the curve of the plateholder must always coincide with this circle. Therefore, rotational motion must be given to the change from one part of the spectrum to another and from one order to another.

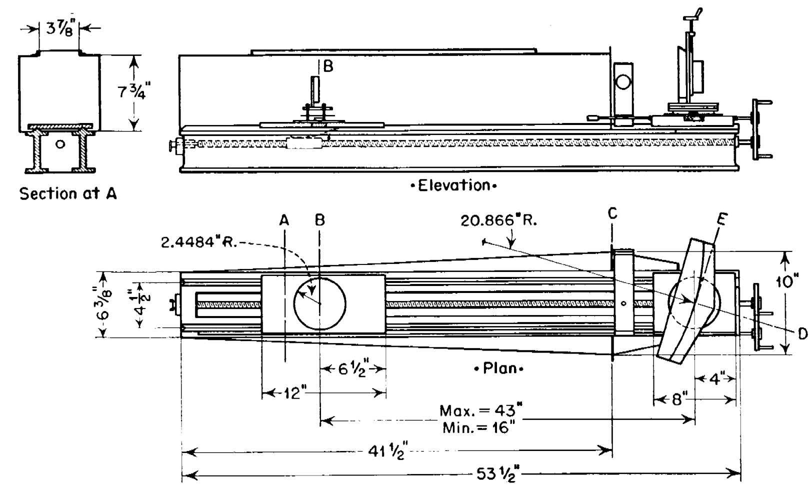


FIGURE 4

This will amount to a right hand motion of one and a corresponding left hand motion of the other, of equal amounts.

The simplest support seemed to be a lathe bed, although a U-beam or even a flat plate could be machined as a track for the lateral movement of the grating carriage. This one is a wood-turning lathe bed 53³⁄₁₆ inches long by 6⁵⁄₁₆ inches wide. The camera, slit, and grating are mounted on carriages machined to the ways of the lathe bed. The camera carriage is mounted permanently on one end of the bed since it receives the greatest mechanical stresses during operation. The slit carriage clamps to the bed and may be changed at will by loosening two clamping screws. This carriage also supports the totally reflecting prism. The grating carriage is free to move laterally on the ways and is controlled by a screw the length of the bed with a pitch of 0.1 inch. The plan, elevation and a section are shown in Figure 4.

The grating carriage, the details of which are shown in Figure 5, is of ⅜-

inch rolled brass stock 5½ by 12 inches. The V-ways are cut lengthwise. In the upper side a circular recess is turned 4.8968 inches in diameter in which the worm gear rests. The center of this is cut and threaded for a ¾-inch mounting stud. A recess is cut on one side for the worm. Cone bearings on either end of this worm hold it in position against the worm gear. A square shaft through the worm allows the longitudinal motion of the carriage. This worm and gear have a pitch of $1/13$ R.H.

The diameter of the circular plate, 4.89 inches, is such that 200 threads are cut in its periphery. Thus one complete revolution of the worm moves the worm gear $\pi/100$ radians, which is one division on the calibrated dial mounted just above the plate. The worm gear was cut with a standard 13 thread tap by constructing a jig to fit into the tool post of the lathe to carry

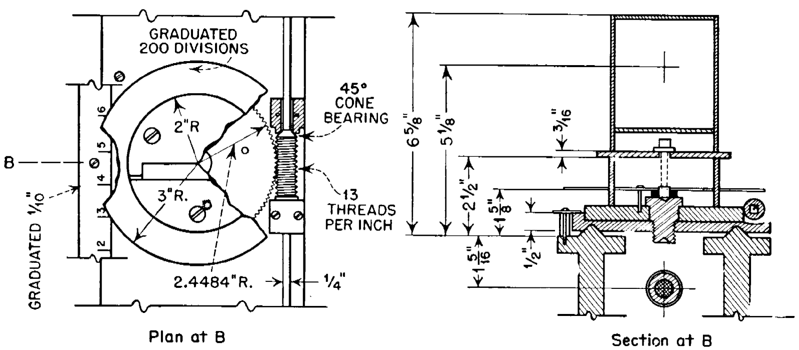


FIGURE 5

the gear level with the centers annd allow free rotation of the gear. The tap in the lathe will automatically feed the circular plate as it cuts the gear.

Just above this worm gear and supported by it is the circular scale 6 inches in diameter. Above this is the grating mounting, supported by three leveling screws and held in place by a coil spring. The grating is capable of being tilted either forward and backward or to either side and its height is also controlled by these leveling screws. It may be given a slight rotational motion by two screws at the top of the mounting.

The carriage is connected to the screw by a 4-inch cast babbit nut linked with a flat spring. This suffices for the reset purposes required of this apparatus; but, if direct measurements are necessary, a direct mounting should be used such as is used on comparator screws. Then, by dividing the dial in 100 parts, the movement could be read directly to 0.001 inch.

The details of the camera and its carriage are shown in Figures 6 and 7. The carriage is made of a rolled iron plate ¾-inch thick, 6 by 8 inches. A circular recess is also turned in this plate of the same diameter as that in

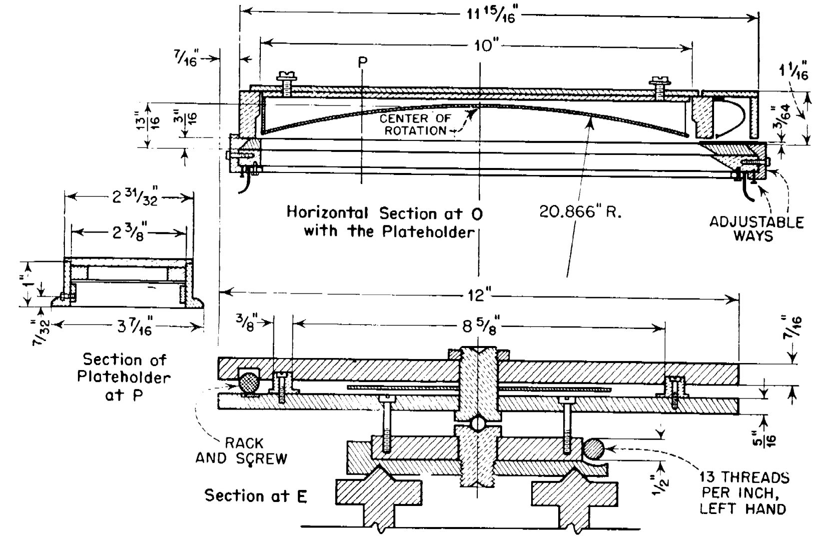


FIGURE 6

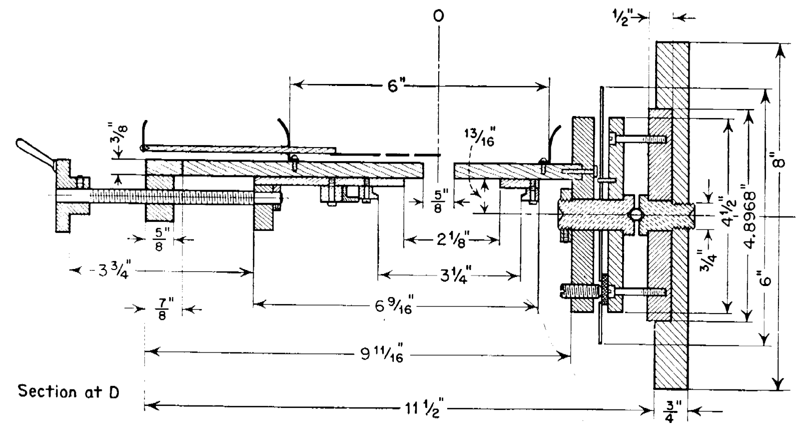


FIGURE 7

the grating carriage, 4.89 inches. V-ways are cut lengthwise of this plate. Both are cut deeper to compensate for its added thickness. The circular plate is cut to a worm gear the same as for the grating except that a left-hand tap is used. This worm gear is held in place by a ¾-inch studscrew into the iron plate. A steel ball in the center of this stud carries a brass bolt which supports the camera mounting plates. The lower plate is clamped to the worm gear by four studs, giving opportunity to level in either direction. The upper plate is fastened to the lower plate by means of the brass bolt supporting the camera and two circular ways bolted near either end of the lower plate with corresponding ways in the upper plate. This allows rotation

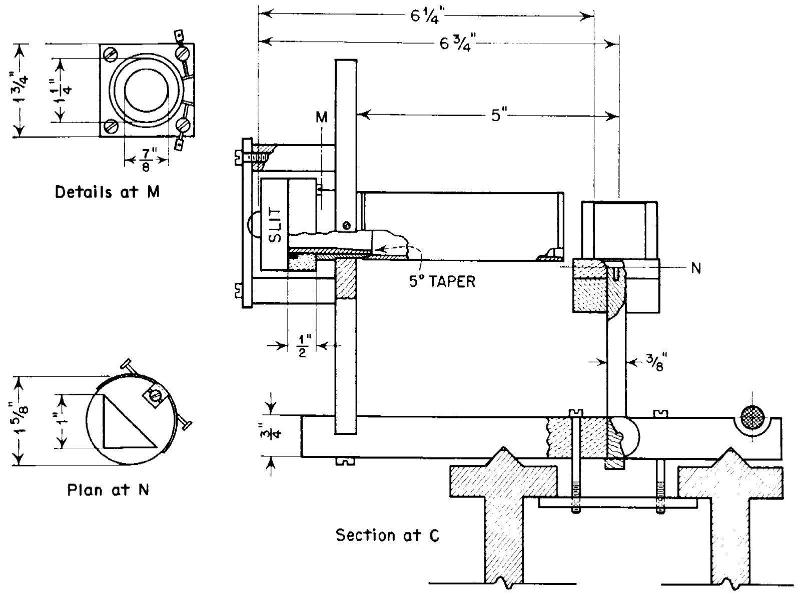


FIGURE 8

of one plate with respect to the other, which gives opportunity to correct for errors in the worm gears. Between these plates and fastened to the lower one is a 6-inch calibrated and verniered dial identical with the one used in the grating mounting. The upper plate is rotated over the lower one by means of a worm meshing in a rack near one end of these plates. The amount of rotation is read from the circular scale.

On the upper plate is mortised a ⅜-inch brass plate 12 inches wide and 9¹¹⁄₁₆ inches high. This is so placed that the emulsion of the photographic plate in the plateholder is directly above the center of the two supporting bolts. This places the center of the photographic plate coincident with the center of rotation of the camera. Hence any rotation of the camera alone should in nowise alter the focus of the center of the plate.

On this vertical plate in vertical ways (see section *O*, Figure 6) is a carriage which supports the plateholder. This carriage is free to move through a vertical distance of 6 cm and is controlled by a screw at the top. These ways are also high enough so that they give covering to the ends of the plateholder and with the upper and lower clamps furnish a complete light seal between the plateholder and its carriage.

The back of this carriage, except a small distance on each side which is left as a bearing surface, is machined down about 0.008 inch to permit these surfaces to be painted a dull black which furnishes a very usable light seal. On the back of the camera a Z-bar was formed into a square box 11½ by 6 inches, over which the light-tight cloth hood is fastened. This frame also contains a ways whereby a mask can be lowered. This mask is suitably cut with horizontal slots of varying width which allow different widths to be exposed on the plate.

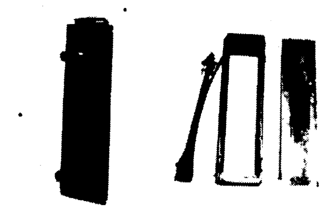


FIGURE 9

The slit mounting, details of which are shown in Figure 8, consists of an iron bar ¾ by 2 by 8 inches in which ways are milled so that it will fit rigidly on the lathe bed. One end extends 5½ inches from the center of the bed. It is held in place by a clamping plate directly beneath the ways of the bed, and secured by means of two clamping screws. Five inches from the center of the ways a mortice is cut so that a brass bar ⅜ inch thick will set vertically on this carriage. This bar carries the slit and its mounting and shield. The mounting is made by taking a heavy 1-inch brass tube and fitting a brass collar to a press fit and then sweating the two together leaving ½ inch of the tube extending on one end to fit in the square block which backs up the slit. This block fits over this tube against the collar and is held in place by a ring nut countersunk flush with the square block. The block is held to the slit by means of four studs, two of which have holes drilled and tapped at right angles in their heads to carry adjusting screws. These adjusting screws face each other and engage pins set in the collar, thus controlling the rotation of the slit in its mount. This collar is turned to fit the hole in the vertical brass bar and to carry on its other end a ¾-inch brass tube which acts as a shield to the pencil of rays from the slit to the prism.

At the center of the ways on the slit mounting carriage is a $\frac{5}{16}$-inch hole with a permanent key mounted in one side of the hole and a setscrew with knurled nut on the opposite side. A brass shaft with a keyway fits in this hole and carries at its upper extremity a double brass plate. The lower plate is fixed rigidly to the vertical support, the upper one is left free to turn as two screws arranged opposite in a slot in the upper disk engage a pin in the lower disk which extends into the slot of the upper disk. This upper disk carries the totally reflecting quartz prism. Thus we have two adjustments on this prism; one a rotational movement in the horizontal plane and the other a movement of translation along the axis of rotation.

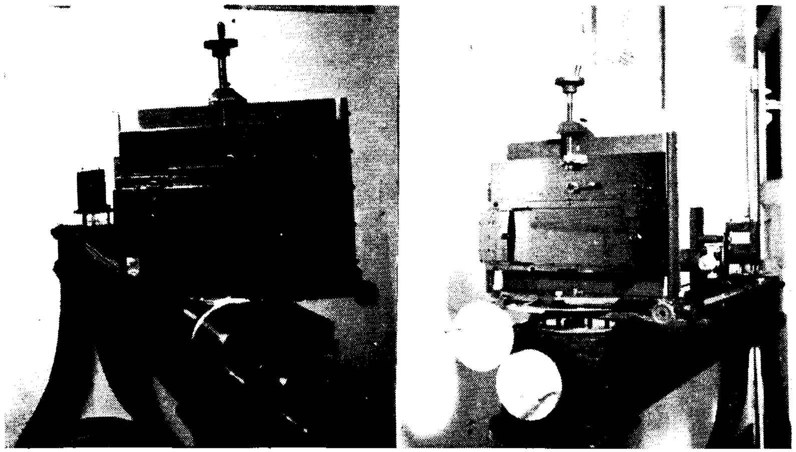


FIGURE 10

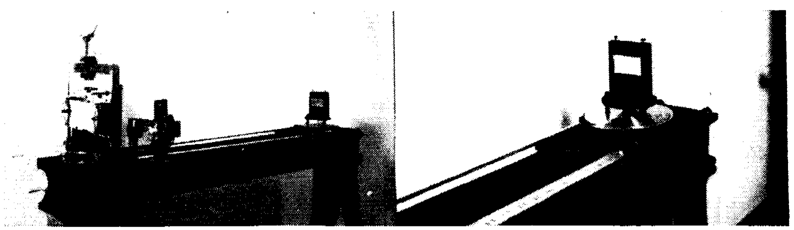


FIGURE 11

A hood covers the lower end of the slit. This hood has a hand door in the top for convenience and is connected to the camera by means of a light-tight cloth hood. The bottom of the lathe bed is covered with a piece of sheet iron. This allows the apparatus to be operated in a light room, thus adding greatly to its adaptability and efficiency.

Figures 9, 10, 11, 12 show parts of the equipment and the finished spectrograph.

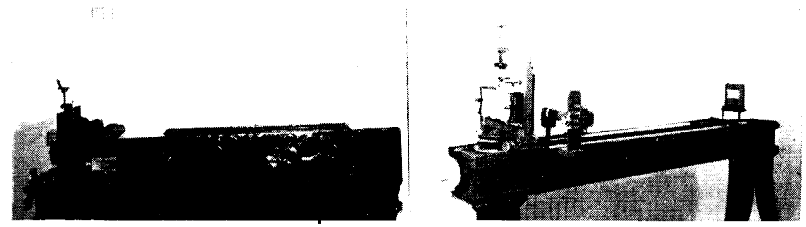


FIGURE 12

ADJUSTMENT AND OPERATION

To arrange the spectrograph to photograph any particular spectral region two major and one minor adjustments are necessary. The major adjustments consist of a lateral movement of grating with respect to plate and a rotational adjustment of grating and plate. The minor adjustment consists of a small additional rotation of the plate.

In this discussion the rotational motion R controlled by the left hand dial will be considered the independent variable and the other adjustments will be considered in respect to it. The rotational dial controls both the camera and the grating, giving to one a left hand and to the other a right hand motion simultaneously. This is accomplished by a left hand screw on the camera and a right hand screw on the grating. Each revolution of the screw imparts a rotation of $\pi/100$ radians, which is equivalent to one division of the graduated dial. There is approximately one fourth turn of backlash in this train. Any difference in backlash between the two gears is eliminated by setting as the dial reading increases. The bearings on the screws are cones and can be adjusted if necessary.

The lateral adjustment is obtained by the control dial. There is about one sixth turn of backlash in this adjustment but all settings are taken as the scale readings increase. Any lateral play in the screw may be eliminated by tightening the centering pin at the rear of the instrument.

A small knob at the right of the camera rotates the plateholder independently and can be used to apply the necessary correction to keep the plate on the Rowland circle. This correction is also read on the graduated dial.

When setting up the instrument the slit is set to give vertical lines on the plate. Then the grating is rotated by means of screws at the top of its mounting until the ends of the lines seem to be symmetrical. If the rulings of the grating and the slit are not optically parallel the lines will have a rhomb shape caused by the successive images not exactly coinciding. The spectrum is brought into the slot in the camera by means of the three leveling screws on the grating carriage.

The mask may be set to give different widths of spectra across the plate.

The prism should be set so that the entering beam of light is normal to the longitudinal axis of the instrument. When the slit is opened and no condensing lens is used the pencil rays form an outline of the slit which should center on the grating.

The curvature of the plateholder must be relatively high in order that the

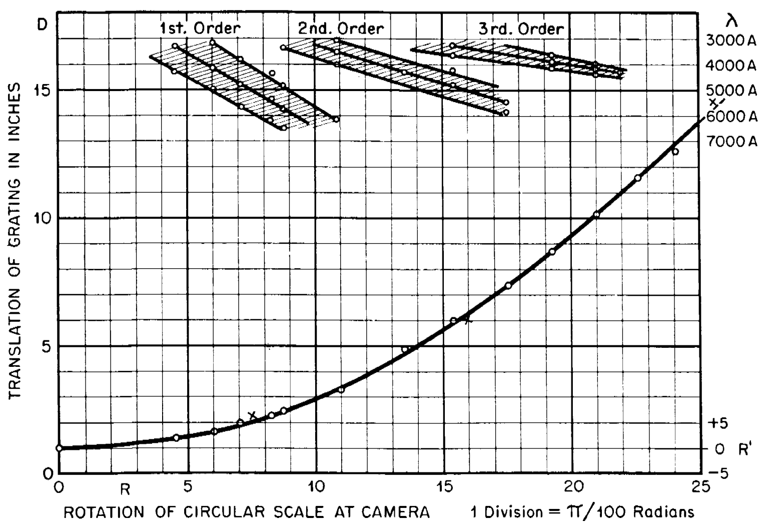


FIGURE 13

emulsion will coincide with the Rowland circle. Extra-thin glass plates have been tried with poor success. The necessary curvature breaks them. Films were used for the exposures for this paper.

Trial exposures have been taken of different spectral regions and the results correlated in Figure 13 from which dial settings for any particular range may be obtained. At the top of the figure three shaded areas give the part of the spectrum covered by the plate at any setting of R. The center line of each shaded part gives the approximate wavelength in angstrom units at the center of the plate. The main curve gives the corresponding lateral setting for each rotational setting. A very interesting correlation should be pointed out. The circles, from which the curve is plotted, are from experimental results while the X's are the theoretically computed results from Table 1.

Reset trials using this curve as a standard have given very favorable evidence of its reliability.

Limitations of Grating: This instrument has very definite limitations, and some very definite advantages. The collodion of which the grating is made gives a sharp limit in the ultraviolet at about 3100A. It appears that below this limit a rapidly increasing amount of absorption takes places. The upper limit, as far as observable, is dependent only on the photographic emulsion available. However, suitable filters must be used to eliminate the overlapping higher order as illustrated by the overlapping of the shaded areas in Figure 13, and explained earlier in this paper.

The rotation of the plate is limited to about $25\pi/100$ radians or 45° by the reflecting prism and its mounting. From Table 1 it is seen that the green line of iron $\lambda = 4859.757$A in the third order will be near the center of the plate at this limit. Further rotational adjustment is of no advantage with this instrument, however, as the imperfections of the grating are such as to give poor definition in the third order and, therefore, no advantage over lower orders. The reflecting prism and mounting could easily be moved if any advantage were to accrue.

Aberrations: Several aberrations will be mentioned. The central image appears as a sharp image of the slit with considerable diffused light on each side and with several false images symmetrically arranged. In Figure 13 a picture of this central image is shown. As a narrow mask was moved over the grating the intensity of these false images varied continuously. The most probable explanation seems to be that small parts of this grating are acting independently as well as collectively to form various images. This may be due to uneven shrinkage of various parts of the collodion transfer. The diffused light, no doubt, comes from the dust on the surface of the collodion.

These false images carry over into the spectra and appear as light lines on one side of the parent line giving to the spectrogram the appearance of being out of focus.

Ghosts: In the ruling of a grating any periodic error in the ruling engine produces in the spectra from that grating false images of a line which are called ghosts. These by their nature are symmetrical with the parent line. They have been studied by Rowland, Anderson, Quincke, Pierce, and others and many of their causes have been analyzed.[6]

Figure 14, at B, gives a picture of the ghosts present near the mercury line 5460A. In order to photograph these the plate was exposed about *15* minutes under conditions such that an exposure of *one* minute produced an over-exposed line. The plate shows that the ratio of intensity of parent line to ghost is high; so high, in fact, that only when dealing with faint lines near a very intense line is there any danger of mistaking them.

The only ghosts found are those which are commonly known as Rowland ghosts. They are caused by a periodic error in the screw of the ruling engine. They are symmetrical about the parent line and relatively close to it. Their

[6] Meyer. p. 173.

relative intensity increases in the higher orders. However, this 5460A line showed no ghosts in the second order after an exposure of 80 minutes and only slight ghosts after an exposure of eight hours.

Astigmatism: The images formed by a grating are, in general, astigmatic.[7] That is, a concave grating produces a line image of a point source. Since a slit source is a succession of point sources the spectral lines will be a composite of superimposed lines. These lines when combined will form a line which decreases in intensity toward its ends.

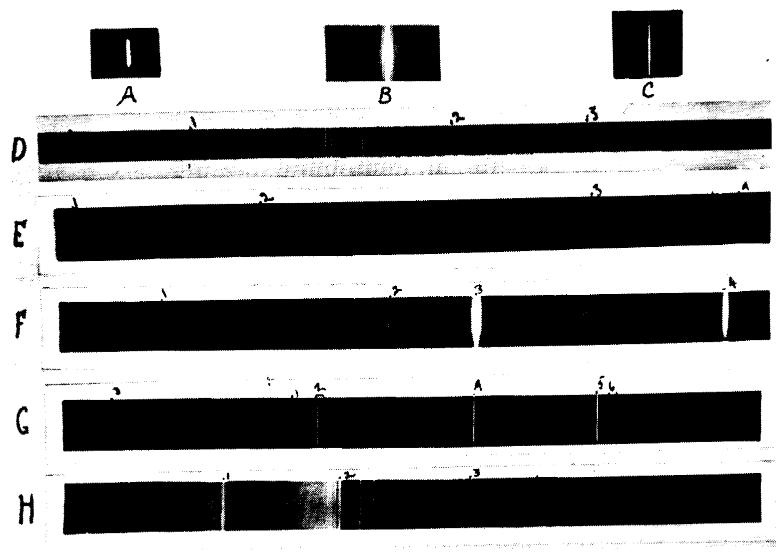


FIGURE 14

This astigmatism has two serious disadvantages: (1) it decreases the intensity of any given line, thus requiring longer exposures, (2) it prohibits the use of a mask in front of the slit to facilitate comparison spectra. The characteristics of the Eagle mounting are such that this astigmatism is considerably less than in the common mountings. It is about one half, in the first order, of that produced by the Rowland mounting. This mounting is sufficiently stigmatic that a wedge may be used in front of the slit (see Figure 13) from the ultraviolet through the green of the first order. For above the red of the first order and for other orders a mask, which may be adjusted easily without disturbing the camera, has been placed in front of the camera carriage. This facilitates the use of the instrument in comparison spectra work.

[7] Meyer, p. 158.

Resolving Power: The resolving power of the optical instrument is its ability to separate the images of two objects which are close together. In spectroscopy the resolving power is determined by the ability of a spectrograph to separate wavelengths that are nearly the same. It may be defined by the ratio $\lambda/\Delta\lambda$, where λ is the wavelength of either of a pair of lines which can just be resolved and $\Delta\lambda$ is the difference of their wavelengths.

By means of Figure 15 the relation of the resolving power to the constants of a plane grating may be developed. This result may then be applied to any grating. If AB is the grating surface having m lines, and if n is the order of the spectra, then BF must be equal to $mn\lambda$. This wave front will give rise to the diffraction pattern p, and the first minimum of the diffraction pattern will be given by the wavefront AE when $EF = \lambda$. Therefore, $BE = (mn\lambda + \lambda)$. A wavelength $\lambda' = \lambda + \Delta\lambda$ will give rise to a diffraction pattern p'. The wavefront necessary to produce this pattern will be AE, and

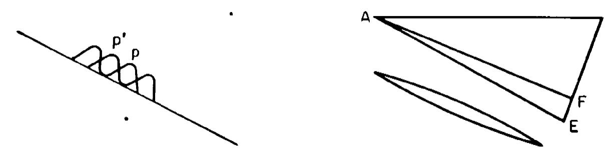


FIGURE 15

the increment FE will be equal to $mn\Delta\lambda$. Therefore, BE will be equal to $(mn\lambda + mn\Delta\lambda)$. By equating these two values of BE it develops that,[8] which

$$mn\lambda + \lambda = mn\lambda + mn\Delta\lambda \quad \text{or} \quad \lambda/\Delta\lambda = mn \qquad (7)$$

gives the theoretical resolving power of a grating spectrograph as dependent only on the trial total number of lines of the grating and the order. For a prism instrument the resolving power is given by the formula[9] where t is the

$$\frac{\lambda}{\Delta\lambda} = -t\frac{\Delta\mu}{\Delta\lambda} \qquad (8)$$

thickness of the prism at its base, and μ is the index of refraction of the material of the prism for the particular region of λ. $\Delta\mu/\Delta\lambda$, which is the dispersive power of the prism, varies for different wavelengths and various substances.

By equation (7) the theoretical resolving power of this grating is $50000n$, or approximately 50000 in the first order. From experimental results the two iron lines at $\lambda = 4934$A are well defined at about $1/10$ mm separation on the plate. The resolving power is then $4934/.675 = 7320$ which is about $1/6$ of the theoretical. At $\lambda = 3402$A two lines are well defined giving a resolving power

[8] Meyer, p. 198.
[9] Meyer, p. 204.

of $3402/.639 = 5330$. In the second order the iron lines at $\lambda = 4957$ are barely resolved which is equal to a resolving power of $4957/.301 = 16400$. In comparison with these results the Littrow, L-253, in this laboratory, gives the following resolving powers in the same regions. The Littrow barely resolves the two lines at $\lambda = 4919$A and has a resolving power in this region of $4919/1.51 = 3260$, while at $\lambda = 3402$A it easily resolves .320A which is a resolving power of $3402/.320 = 10{,}600$ approximately. These two lines give, in brief, the comparison of the resolving power of the two instruments. Below 4200A the Littrow has a greater resolving power than the grating in the first order. At 3700A the dispersion of the Littrow and the grating in the first order are almost identical. Above 4200A the dispersion of the quartz train rapidly decreases while that of the grating remains almost constant. The dispersion of this instrument in the visible region in the first order is such that this region covers more than a 10-inch photographic plate. Therefore, for wavelengths in the visible and above, this grating has a definite superiority when compared with the Littrow. In the second order this resolution is approximately doubled.

Illustrative Spectra: Figure 14 is composed of photographic prints of various plates and illustrates some of the possibilities and limitations of the apparatus. Though the detail of the original is lost in a print much can be shown in this way.

A is a picture of the central image. The extraneous lines are very definite on the plate although they blend in the print.

B is the green line of Hg $\lambda = 5460$A with its ghosts in the first order.

C is the same line in the second order.

D is a photograph of the iron arc from 3200A to 4900A in the first order. 1 corresponds to $\lambda = 3399$A, 2 to $\lambda = 4045$A, and 3 to $\lambda = 4283$A.

E is a photograph of the iron arc from 4800A to 7100A in the first order. As an illustration of the close proximity to linear dispersion even in this region the separation of the lines $\lambda = 4859$A (1) and 5328A (2) is 51 mm, giving 9.18A/mm, and the separation of the lines $\lambda = 5328$ and 6137A (3) is 89 mm, which gives 9.09A/mm and the separation of the lines $\lambda = 6137$ and $\lambda = 6494$A (4) is 40 mm, which gives 8.95A/mm.

In *F*, lithium and potassium chlorides were used in the carbon arc and an iron comparison was placed by means of the mask. 1 is the iron line $\lambda = 5328$A. 2 is the sodium D lines, $\lambda = 5890$A and 5896A. 3 is the lithium line $\lambda = 6103$A. 4 is the lithium line $\lambda = 6708$A, a doublet, which is resolved by this spectrograph.

In *G* the mercury arc was used and its spectra is shown in the region $\lambda = 3100$A to $\lambda = 4300$A. The comparison is iron placed by means of the wedge in front of the list. The dispersion is almost linear for from the triplet lines $\lambda = 3650$A, 3655A and 3663A to the pair $\lambda = 3131$A and $\lambda = 3125$A the distance is 57 mm, which gives a dispersion of 8.9A/mm (see *E*). 1 is $\lambda = 3581$A, 4 is $\lambda = 4046$A, 5 is $\lambda = 4350$A, 6 is $\lambda = 4383$A.

H is a photograph of the cyanogen bands in the region $\lambda = 3300$A to $\lambda = 4800$A. This was obtained by photographing a naked carbon arc. 1, 2, and 3 are band heads at $\lambda = 3590$A, $\lambda = 3883$A, and $\lambda = 4216$A respectively. The comparison is iron.

Conclusion: This instrument proves novel in several ways. The direct mechanical link between the grating and camera rotation has proved successful and is of great convenience in rapid resetting to previous values. The dispersion and resolving power in the visible and infrared is definitely much better than can be found in any glass or quartz instrument of an equal cost. It is easily portable. It can be used in a light room the same as a prism spectrograph. It is sufficiently stigmatic that weak sources may be used with good success. The ghosts are extremely weak compared to any parent line and should never offer any serious problem. The spectra in the first order is very near to a normal spectra, that is, the dispersion along the plate is almost a linear dispersion.

The diffused light from the grating is a problem and if an original could be obtained much better results would be expected. The threads of the worms and worm wheels would be better if made after the Acme type instead of the 45° type. The grating mounting could be improved by a provision for a rotational motion about the normal to the center of the grating.

Bibliography

Charles F. Meyer, "The Diffraction of Light, X-rays, and Material Particles." [Out of print.—*Ed.*]

E. C. Baly, "Spectroscopy," Vol. I. [Out of print.]

Kayser, "Handbuch der Spectroscopie, "Vol. I.

John Browning, "Spectroscope."

Schuster and Nicholson, "The Theory of Optics," pp. 111–130.

Preston, "The Theory of Light," pp. 261–278.

Handbuch der Physik, Band XVIII, pp. 340–345; Band XIX, p. 821; Band XX, pp. 57–65, 298–305.

H. T. Smyth, "Some Stigmatic Grating Mountings." *Journal of the Optical Society of America*, Vol. 25, No. 9, p. 312.

G. W. Moffitt, "Autocollimating Spectrograph," *Journal of the Optical Society of America*, Vol. 25, No. 5, p. 142.

D. L. MacAdam, "Focus of a Concave Grating Spectrograph." *Journal of the Optical Society of America*, Vol. 23, No. 5, p. 178.

[Editor's Note: It proved to be impossible to recover the original drawings and photographic negatives for this chapter, these having been lost after the author removed to South Africa (Helderberg College, Somerset West, Cape Province). The drawings from the original thesis were redrawn by Joseph F. Odenbach, reproduction draftsman, and the author was able after much searching to find some small photographic negatives which are here reproduced.]

The Design and Construction of a Five-Foot Wadsworth Type Grating Spectrograph

By Strathmore R. B. Cooke and Robert A. Wilson [1]

The purpose of this chapter is to describe in detail the design and construction of a grating spectrograph constructed in the Mineral Dressing Laboratories of the Montana School of Mines. The instrument was designed to fulfill a need in the laboratory for a quick and easy method of identifying the metallic elements dealt with in mineral dressing and other metallurgical problems.

Using ordinary methods, spectrographic analysis is suitable for the identification of about 70 of the 92 elements. By employing specialized technics most of the remaining elements may be detected. An analysis can be carried out in a few minutes, producing results for immediate study. This assists the investigator to control subsequent experimentation without waiting for chemical analysis. As a supplement to chemical analysis the spectrograph is invaluable since the presence or absence of metallic elements can be quickly and positively determined.

By using carefully controlled conditions and proper auxiliary equipment quantitative spectrographic analysis may be made. The best accuracy so far obtained has been between 3 and 5 percent of the amount of the element present. Compared with chemical results the accuracy is low when used with high element percentages. For amounts below 5 percent the absolute accuracy of spectrographic methods is extremely high.

In the fall of 1939 the senior author considered building a grating spectrograph and he subsequently worked out the basic optical design for the instrument. The mechanical design was worked out by both authors, and most of the machine work was done by the junior author in the school shops. The instrument was completed in the summer of 1940. Since that time it has been in constant use and has proved almost indispensable.

The assistance of Dr. G. L. Shue of the Physics Department, and the availability of tools from that department, is also deeply appreciated. Dr. Shue offered various invaluable suggestions including the method by which the focal curve of the camera was cut.

General History: Spectroscopy had its origin in the middle of the 17th Century but was not developed to a usable stage until a relatively recent date. In 1666 Sir Isaac Newton observed that on passing a ray of sunlight through a glass prism a regular series of colored images appeared. He concluded from this experiment that rays of different color were refracted differently. Unfortunately, Newton used a round hole to produce the beam of light and thus just missed the real significance of his discovery. It was not

[1] This chapter is a condensation of a thesis submitted to the Montana School of Mines by the junior author, in partial fulfillment for the degree of Master of Science in Mineral Dressing.

until 1802 that Wollaston discovered that by using a narrow slit for orienting a beam of sunlight a spectrum was produced that was crossed by numerous dark lines parallel to the slit.

In 1814 Fraunhofer, an optician in Munich, made a study of these lines and the methods of producing them. By placing a convex lens between the slit and the prism he obtained a better spectrum and eventually used a telescope for the observation of this spectrum. This instrument was the first prism type of spectroscope.

The spectrum lines, known as Fraunhofer lines, were discovered in great numbers in the solar spectrum and the discoverer, in his observations, recognized that the position of the lines was constant. He mapped the position of 576 lines. Fraunhofer then turned his attention to the actual measurement of the wavelength of light. It had been suggested in 1801 by Thomas Young that the wave theory of light accounted for observed interference phenomena and Fraunhofer, utilizing this conception, succeeded in developing the theory and in constructing a grating. Using this grating he measured the wavelength of the sodium *D* lines with a considerable degree of accuracy.

The diffraction grating had been invented in 1785 by an astronomer, David Rittenhouse. Because he did not follow up his work it remained for Fraunhofer to discover the real significance and possibilities of the diffraction grating. Fraunhofer's first gratings were made by winding fine wire over a frame consisting of two fine screws. The threads of the screws served to space the wires equally. He was able to make gratings with as many as 340 lines per inch. In order to increase the number of lines he finally turned to the use of a dividing machine of which no description has survived. Fraunhofer first ruled through gold foil placed on glass, and later on a glass plate covered with a thin film of grease. He was able to produce gratings with 1800 lines per inch. Finally, by using a diamond point, he succeeded in ruling directly on the glass surface. Using this method he produced a grating having 8000 lines per inch.

Although Fraunhofer used most of his gratings for transmission he also discovered that reflection gratings could be made and that the grating law held for both types.

The gratings ruled by Fraunhofer and by F. A. Nobert, a Prussian instrument maker, remained the best available until 1870, when L. M. Rutherfurd, a lawyer, became interested in the problem. After several years of experimenting he succeeded in making the first gratings ruled on speculum metal, an intermetallic compound containing 32 percent tin and 63 percent copper. This compound is very hard and possesses, when polished, a very high reflectivity without much tendency to tarnish. Most of Rutherfurd's gratings had about 17,300 lines per inch, ruled on an area of 1 to 2 inches square. They were the first gratings giving better spectra than could be produced by the most powerful prisms then in use.

Most of the gratings in use today are concave, and this type was invented by Henry A. Rowland of the Johns Hopkins University. Rowland built a vastly improved ruling mechanism capable of ruling gratings up to 30,000 lines per inch. He also developed the theory and practice of ruling on a spherical surface.

The Diffraction Grating: The simple theory of the transmission diffraction grating can be illustrated as in Figure 1, left. Light enters through the slit and is rendered parallel by placing the slit at the focus of a collimating lens L_1. This parallel light then travels through the grating and is refocused by lens L_2 at M_0. From Huygens' principle, the grating rulings may be considered as secondary or new sources of spherical wave fronts. If monochromatic light is used the problem is simplified. Suppose some of the light is diffracted at an angle to the original direction. From the geometry of Figure 1, right, it can be seen that if the distance BC is equal to one wave-

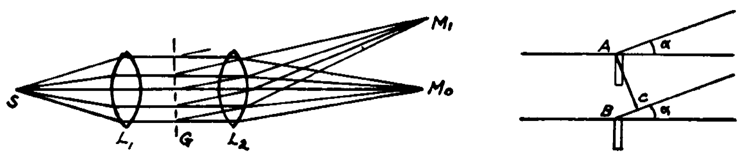


FIGURE 1

length then all rays of light diffracted at angle α will be in phase with each other and reinforcement will occur.

From the figure,

$$\frac{BC}{AB} = \sin\alpha \qquad BC = AB\sin\alpha$$

Calling the grating space b instead of AB the reinforced sit image at M_1 is

$$b\sin\alpha = \lambda \qquad (1)$$

The grating space is assumed to be constant across the grating so that all rulings contribute to the image M_1. The same principle is true if the distance BC is any whole number of wavelengths such as 2, 3. The general equation then becomes,[2]

$$b\sin\alpha = n\lambda \qquad (2)$$

when n is a whole number. If polychromatic light is used in place of monochromatic light a spectrum will result since sin α varies with λ. A little consideration will show that spectra will be formed on either side of the undeviated central beam. The equation indicates that the shortest wavelengths in the spectra will be nearest the undeviated beam or nearest to M_0. The first order spectrum is produced when the phase difference n is 1 and the second order is produced when n is 2. The spectra of different orders overlap.

To obtain sharply focused spectra by the use of a plane grating two lenses

[2] A. C. Hardy and F. H. Perrin, "The Principles of Optics," p. 286 (1932).

are required, one to collimate the light and the other to image the resulting spectra. Rowland discovered that by ruling a grating on a concave spherical surface the grating itself would produce a perfectly focused spectrum. Lenses with their inherent aberrations and ultraviolet absorption could then be eliminated.

The Rowland Mounting: The mounting devised by Rowland (Figure 2) consisted of a concave grating mounted on the reference circle with the camera directly opposite to it and on the grating normal. The slit was fixed and, in moving from one spectral region to another, the reference circle also moved. This was accomplished by moving the grating toward the slit and by moving the camera away from the slit at right angles to the grating motion.

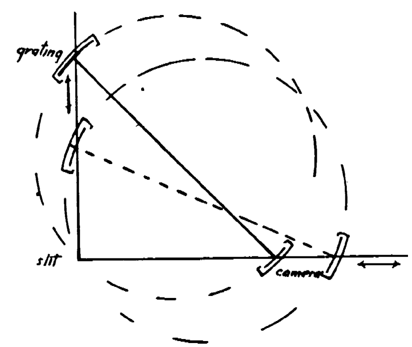


FIGURE 2

The grating and photographic plate were mounted on a beam and separated by the diameter of the reference circle. The angle between the grating center, the slit, and the camera center must always be 90°.

The Abney Mounting: The Abney Mounting (Figure 3, left) is a variant of the Rowland mounting and depends on the Rowland reference circle as its principle of operation. The photographic plate is curved to conform to the reference circle and is mounted on the grating normal. The slit is mounted so that it may be moved along the reference circle to give any desired spectrum region at the camera. The slit mounting usually consists of a beam pivoted at the center of the Rowland circle with the slit mounted on the circumference.

The Paschen Mounting: In the Paschen Mounting (Figure 3, right) there are no movable parts. The grating and slit are firmly mounted on piers in their proper places on the Rowland circle. The plateholder is also fixed and usually constructed so that its range extends along practically the entire Rowland circle.

The amount of astigmatism present varies with the angle the incoming rays form with the grating normal.

The main disadvantage of a Paschen mounting is its space requirement. Proper temperature control becomes difficult as the space occupied increases.

The Eagle Mounting: This mounting (Figure 4) is based on the Rowland reference circle but is so constructed that the space occupied is small in comparison with other types. The image of the slit is reflected by a right angle prism to the grating, which focuses the spectrum on the photographic plate situated behind the prism and slightly below it. Different regions are reached by moving the grating toward the prism and by rotating both prism and plate so that both conform to the reference circle.

The Eagle mounting is an excellent design as it has less than half the

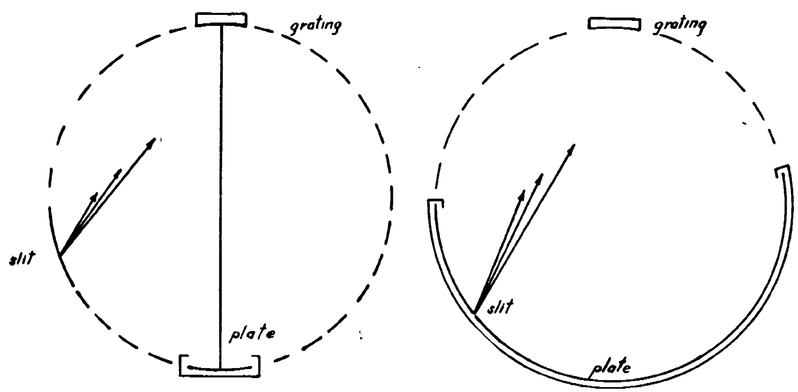


FIGURE 3
Left: Abney mounting. Right: Paschen mounting.

astigmatism of either the Rowland or Abney types. It possesses the disadvantage of requiring simultaneous translation and rotation of the grating and a rotation of the camera.

The Wadsworth Mounting: The Wadsworth mounting is the only grating mounting in common use that does not depend on the Rowland reference circle as its principle of operation. This mounting, because the spectra produced are free from astigmatism at the grating normal, is also known as the stigmatic mounting. A schematic drawing, Figure 5, shows the various parts. Light from the excitation source, usually an arc, is brought to focus on the slit. After passing through the slit, the light falls on a paraboloidal mirror and is reflected as a parallel beam directed to the grating. For the reflected beam to be parallel it is necessary that the slit and the reflecting mirror be separated by the focal length of the mirror. The light then falls on the grating, by which it is resolved into its component wavelengths. Because the grating is concave each separate wavelength is brought to focus as an image

of the slit in the focal curve. The slit and the grating may be so close together that mirror aberration is very small and the resulting image is without appreciable astigmatism. The camera or film holder is mounted at right angles to the grating normal. The grating is pivoted about a vertical axis through its optical center. The camera and grating are mounted on the same

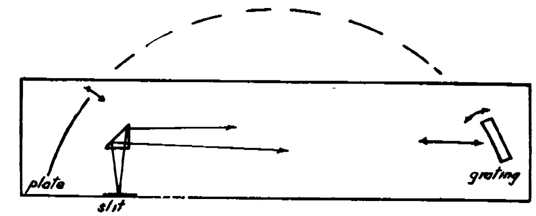


FIGURE 4
Eagle mounting

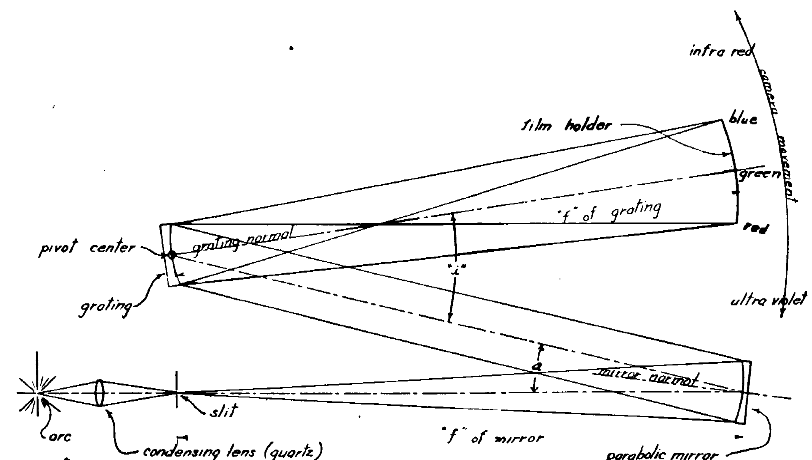


FIGURE 5
Wadsworth mounting

swing arm so that in changing from one desired spectral region to another the entire structure is rotated through an arc about the pivot center. For every change of the position of the arm the angle of incidence i, changes and hence the wavelength brought to focus on the grating normal will change. To maintain focus with each change of position of the arm the distance of the grating to the camera must be altered. When the instrument is to be used in different wavelength regions, movement of the camera along the arm is necessary to focus.

The distance from the grating to the camera along the grating normal may be calculated for any given grating by the use of the equation

$$D = \frac{R}{\cos i + 1} \qquad (3)$$

D is the distance from the grating to the camera along the normal, R is the radius of curvature of the grating, and i is the angle between the incident beam and the grating normal. In comparison with other mountings it may be seen that as the angle i increases from zero the distance D increases from $R/2$ to slightly more than $R/2$. Mountings based on the Rowland circle require that the distance D equal R, and thus a Wadsworth mounting needs only about half as much space as the Rowland type for a given grating. The linear dispersion of the instrument varies with the distance D, and so the Wadsworth mounting has about half the dispersion of other mountings at no sacrifice in the optical resolving power.

Actually the astigmatism equals zero at the grating normal but for all practical purposes it is equal to zero over the entire length of the photographic plate provided the plate is not made too long. This lack of astigmatism results in a decided increase in the image intensity. In this mounting there is an additional gain because the grating is mounted at about half the distance from the camera compared with other mountings. This increases the aperture ratio about four times. The intensity gain from this type of mounting has been estimated by Meggers and Burns [3] to be between five and ten times over that of other mountings.

The wavelength brought to focus at the center of the camera may be determined by the equation

$$\lambda = \frac{e \sin i}{n} \qquad (4)$$

λ is the wavelength brought to focus at the center of the plate, e is the grating space, i is the angle between the incident and the diffracted beams, and n the order of the spectrum. In the instrument being described the grating is so ruled that practically all the light energy is in the first order spectrum, leaving only a few percent to be distributed among the other orders and the undeviated beam. Actually the amount of light in the other orders is so small that they do not interfere even on long exposures.

The advantages of this type of concave grating mounting can be summarized as follows: (1) The mounting is free from astigmatism. (2) The instrument need be only half as large as other types for equivalent resolving power. This reduces vibration and temperature change effects. (3) The spectrum intensity is from five to ten times as great as with other mountings.

[3] W. F. Meggers and K. Burns, Scientific Papers, Bureau of Standards, No. 441 (1922).

(4) The resolving power of such a mounting is the equal of that of any other mounting with any given grating, but the linear dispersion is approximately halved.

The disadvantages may be summarized as follows: (1) The parabolic mirror used must be of high optical quality, ⅛ wavelength. (2) The various parts of the instrument must be carefully made so that wavelength settings and focus are accurately reproducible. (3) Some authors claim that this mounting is more likely to be thrown out of adjustment than others. The instrument built in this laboratory showed no need of readjustment after nine months of operation.

Properties of a Stigmatic Grating Mounting: The properties of gratings have been considered very completely in texts on physical optics.[3, 4] The fundamental formulas derived by Baly [5] can be applied to any grating mounting.

Let S equal the distance from the slit to the grating, R the radius of curvature of the grating, D the distance from the grating along its normal to the primary astigmatic focus, i the angle of incidence, and θ the angle of diffraction. Then the distance from the grating to the focus is given by equation 5.

$$D = \frac{SR \cos^2\theta}{S(\cos i + \cos\theta) - R\cos^2 i} \qquad (5)$$

Since the distance D is made infinite by collimating the incident beam of light the quantity S ($\cos i + \cos\theta$) becomes infinitely large compared to ($R \cos^2 i$). This later quantity may then be neglected and the equation rewritten,

$$D = \frac{R\cos^2\theta}{\cos i + \cos\theta} \qquad (6)$$

If the distance from the grating to the focus, at the grating normal, is required, then θ equals zero and $\cos\theta$ equals unity. The equation then becomes

$$D = \frac{R}{\cos i + 1} \qquad (7)$$

A given wavelength refracted from the grating will form constructive interference in the first order when

$$\lambda = b(\sin i \pm \sin\theta) \qquad (8)$$

Sin θ becomes negative when the incident beam and the diffracted beam are on opposite sides of the grating normal. At the grating normal θ equals zero, therefore, $\sin\theta$ equals zero and the equation becomes

$$\lambda = b \sin i \qquad (9)$$

[3] C. F. Meyer, "The Diffraction of Light, X-rays, and Material Particles," (1934).
[4] Wood, "Physical Optics."
[5] E. C. C. Baly, "Spectroscopy," Vol. 1 (1929).

From equation (9) the wavelength focused at the center of the photographic plate depends on b, the grating space and on i the angle of incidence of the collimated beam. For a given grating the wavelength varies directly as the sine of the angle of incidence. This means that, for a grating ruled with 15,000 lines per inch, irrespective of the radius of curvature, the wavelength at the grating normal will be determined by i, the angle of incidence.

The shape of the focal curve may be determined from equation (6). In this equation the distance D applies not only along the grating normal but also along the entire focal curve. To determine the focal curve for any given value of i, both R and $\cos i$ become constants and D may then be determined for various values of θ, the angle of diffraction from the grating normal.

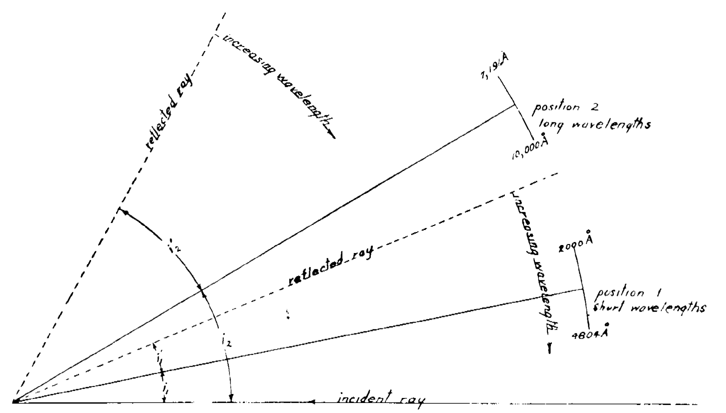


FIGURE 6

For every different value of i there is a different focal curve. The shape of the curve is determined by the values of θ; its position in space is determined by the values of $R/\cos i$.

From the fundamental grating equation (8) it is evident that a spectrum is produced on both sides of the grating normal and the direction of increasing wavelengths is to each side of the reflected or undeviated beam of light. In this equation n is the order of the spectrum, λ is the wavelength and b the grating spacing. In Figure 6 the angle i' denotes the angular measurement from the grating normal to the reflected beam or ray.

When the film holder is in position 1 and 2, the angle of incidence i_1 equals i_2, which is the corresponding angle between the normal and the undeviated unreflected beam. The wavelength increases on each side from this reflected beam. In position 1, the camera is near the undeviated reflected beam and therefore records a short wavelength region. In position 2, the camera is at a greater angular distance from this undeviated beam and records a longer wavelength region. If it were possible to have the incident ray on the grating normal then the angle of incidence would become zero, and from equation (9)

$$n\lambda = b \sin i \qquad (9)$$

the wavelength recorded at the center of the plate would equal zero. Then the wavelengths would increase symmetrically on each side of the plate.

Design Calculations: The most important part of a grating spectrograph is the grating and hence it is natural that the design of the entire instrument should center about the grating constants. When the construction of this instrument was started a grating was not available but the grating constants were obtained from the Physical Laboratory of the University of Chicago, the manufacturers of the grating used. The constants were specified within the tolerances shown. This permitted construction of the spectrograph before receipt of the grating. Only minor adjustments were necessary when the grating was installed.

Grating Specifications

Number of lines per inch	15,000
Ruled area	1½ by 2½ inches
Diameter	3 1/16 inches
Thickness	9/16 inch
Focal length	5 feet ± 1/32 inch
Radius of curvature	10 feet

With these constants known the various design calculations were made. The required wavelength range for the instrument was from 2,000 angstrom units (A) to 10,000 angstrom units. The calculations were based on the assumption that the grating had 15,000 lines per inch. The number of grating lines could depart slightly from this value but sufficient latitude in design was allowed to compensate for all reasonable differences so that the desired spectral regions could be reached.

To reduce astigmatism at the ends of the photographic plate it was decided that the plate length should not exceed 10 inches, that is, 5 inches on each side of the normal. When the film holder was designed it was found desirable to reduce the film length to 9 3/16 inches. However, the design was based on a 10-inch plate.

Table 1 was computed using equations (3) and (5). These gave the wavelength at the center of the plate and the distance between the center of the grating and the center of the plate for the different values of the angle of incidence i.

$$D = \frac{R}{\cos i + 1} \qquad D = \frac{10 \times 12 \times 2.54}{\cos i + 1} \qquad (7)$$

$$n\lambda = b \sin i \qquad (9)$$

$$\lambda = \frac{1693 \times 10^{-7} \sin i}{1 \times 10^{-8}} \qquad \frac{1693 \sin i}{10^{-8}}$$

TABLE 1

i	$\cos i$	$\sin i$	d (cm)	A
5°	.99619	.08716	152.68	1476
10°	.98481	.17365	153.56	2940
15°	.96593	.25882	155.04	4382
20°	.93960	.34202	157.14	5790
25°	.90631	.42262	159.89	7155
30°	.86603	.50000	163.34	8465

b = grating space in centimeters

$= 1693 \times 10^{-7}$

angstroms = cm $\times 10^{-8}$

This calculation shows that for the angles given the distance from the grating to the plate varies from 153 to 163 cm. It also shows that the smallest angle of incidence i will probably be somewhere between 5° and 10°. The actual determination of this angle was the next calculation. The distance from the grating to the plate was taken as 153 cm, a compromise focal length. The plate extended 5 inches, or 12.7 cm, on each side of the normal. With this information the angle of diffraction θ was calculated, as shown in Figure 7.

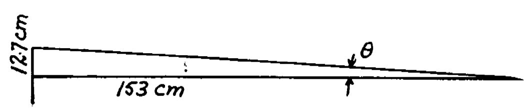


FIGURE 7

$$\frac{12.7}{153} = \tan\theta \qquad \theta = 4°45'$$

The angle of diffraction θ is 4°45′. It was necessary next to determine the minimum angle of incidence, i, when the end of the plate recording the short wavelengths just reaches 2,000 angstroms. The basic grating formula was used

$$n\lambda = b(\sin i \pm \sin\theta) \qquad (8)$$

Since the calculations were based on the first order spectrum, n becomes unity. When the angle θ is on the opposite side of the grating normal from the angle i, the sign becomes negative and when θ and i are on the same side of the normal, the sign is positive. This indicates that the shorter wavelengths are on the opposite side of the normal from the incident ray as has been previously pointed out.

$$1 \times 2000 \times 10^{8} = 1673 \times 10^{7} (\sin i - \sin 44°45')$$

$$\sin i = .20094$$

$$i = 11°35'$$

This is the minimum value required to reach 2000 angstroms and, although not exact, as average values were taken, it is sufficiently accurate for design purposes.

With the information obtained from these calculations the wavelengths recorded at the center and the long wavelength end of the plate were determined (Figure 8). The results are:

$$\lambda = b \sin i \qquad (9)$$

$$\lambda = 1693 \times 10^{-7} \times \sin 11°35'$$

$$\lambda = 3402 \text{ angstroms (at the center of the plate)}$$

$$\lambda = b(\sin i - \sin\theta) \qquad (8)$$

$$1693 \times 10^{-7} (\sin 11°35' - \sin 4°45')$$

4804 angstroms

$$D = \frac{R}{\cos i + 1} = 154.23 \text{ cm (focal distance)} \qquad (7)$$

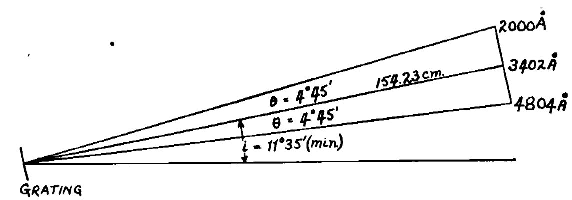


FIGURE 8

The calculations for the maximum value of i were carried out in the same manner. When the long wavelength end of the plate just reached 10,000 angstroms

$$n\lambda = b(\sin i + \sin\theta) \qquad (8)$$

$$1 \times 10{,}000 \times 10^{-8}\ 1693 \times 10^{-7} (\sin i + \sin 4°45')$$

$$\sin i = .50786$$

$$i = 30°31'$$

This is approximately the maximum for the angle i. In this position the wavelength recorded at the center of the plate is given by

$$\lambda = b \sin i \qquad (9)$$

$$\lambda = 1693 \times 10^{-7} \sin 30°31'$$

$$\lambda = 8598 \text{ angstrom units}$$

The wavelength recorded at the other end of the plate is given by

$$\lambda = b(\sin i - \sin \theta) \qquad (8)$$

$$\lambda = 1693 \times 10^{-7} (\sin 30°31' - \sin 4°45')$$

$$\lambda = 7196 \text{ angstrom units (Figure 9).}$$

The accurate focal distance is then

$$D = \frac{R}{\cos i + 1} = \frac{304.8}{1.86148} = 163.74 \text{ cm.}$$

The calculations up to this point show that the minimum angle of i should be slightly less than 11°35′. It may be approximated to 10° for latitude in design. Also the maximum value of i should be slightly over 30°31′; say 32°. The

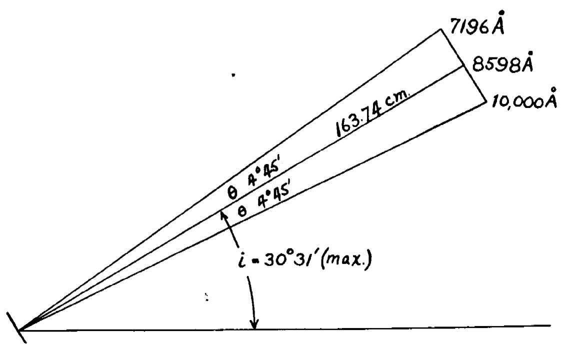


FIGURE 9

focal distances should be adjustable from slightly less than 154.23 cm to slightly more than 163.74 cm respectively.

The focal curve next required determination. There is a different focal curve for every single i but the actual difference between the individual focal curves is very slight, as the calculations show, so the focal curve was constructed for a mean value of i. Since most metallurgical spectrographic work is performed in the blue and ultraviolet region it was decided to make the first film holder with a focal curve to fit this region. The value of i finally decided on was 13°30′, and the focal curve made to correspond to this value. It was found that this film holder was perfectly satisfactory for all other spectral regions on this instrument.

From equation (6)

$$R = 10 \text{ feet} = 304.8 \text{ cm},$$

$$i = 13°30',$$

$$\cos i = 0.23345$$

The distance D (Figure 10) to the point of focus was calculated for various values of θ and the results are presented in Table 2.

TABLE 2

θ	$\cos\theta$	r	D	z	y	$\tan\theta$	x
0°00′	1.00000	154.535	154.535	0.000	0.000	0.000	0.000
0°30′	.99996	154.541	154.526	0.015	0.015	.00873	1.349
1°	.99985	154.558	154.501	0.057	.057	.01746	2.698
1°30′	.99966	154.588	154.457	0.131	.131	.02619	4.047
2°	.99939	154.629	154.394	0.235	.235	.03492	5.396
2°30′	.99905	154.682	154.316	0.366	.366	.04366	6.747
3°	.99863	154.747	154.219	0.528	.527	.05241	8.099
3°30′	.99813	154.825	154.103	0.722	.721	.06116	9.451
4°	.99756	154.913	153.968	0.945	.943	.06993	10.807
4°30′	.99692	155.012	153.824	1.188	1.184	.07870	12.162
5°	.99619	155.126	153.655	1.471	1.465	.08749	13.52

$i = 13°30'$

The distance D (Figure 10) represents the distance in centimeters from the grating center to the point of focus: z equals the difference between r and D. These quantities are used to determine y and x, Table 2, and Figure 10. With

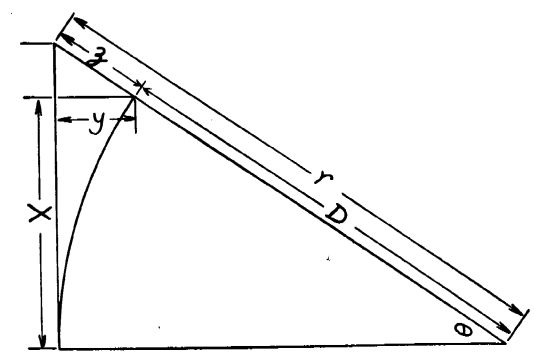


FIGURE 10

the values of y for various values of x it was possible to plot the focal curve for a given value of i (13°30′).

The focal curve is very nearly a parabola and since only a small portion near the normal is used practically no error is introduced by considering it as being parabolic.

The general equation of a parabola is

$$y = Kx^2$$

and the value of K was determined from the information already calculated. Transposition of (10) gives $K = y/x^2$
Using the values of x and y for $\theta = 5°$ the equation becomes

$$K = \frac{1.465}{(13.520)^2}$$

$$K = .00815$$

Then

$$y = .00815\,x^2$$

when dimensions are in centimeters. This permitted the values of y to be determined for any desired value of x.

In making the focal curve an approximate curve was first laid on two strips of 3/16-inch brass each 10 inches long. A hacksaw was then used to cut a rough curve as close to the scribed curve as possible and a file was used to smooth it. This permitted the curve to be machined in a shaper in one traverse, taking light cuts and thus not straining the brass. (With care, the curve could be finished by file alone, for the small aperture of the spectrograph—about $f/20$—gives considerable depth of field. However, to use the full resolving power of the instrument the job should be done on a shaper or some similar machining device.)

The crossfeed screw gave x values and the vertical head screw gave the y values. Starting from the center of the brass, each half of the focal curve was cut by setting the vertical feed at zero and advancing this feed to the proper setting for each corresponding crossfeed setting. The shaper used had a vertical screw with 8 threads per inch, or .125 inch per revolution. The horizontal drive was through a 30-tooth ratchet, so that with every stroke of the ram the crossfeed screw was advanced 1/30 of .250 inch, or .0083 inch, when the feed was set to pawl one notch at a time. Each inch of crossfeed represents 120 strokes of the ram. One half of the curve was calculated from the center out, as follows: from Table 2 we find that x is 13.52 cm for $\theta = 5°$. Converting to equivalent strokes of the ram, we obtain: $13.52/2.54 \times 30 \times 4 = 638.740$ strokes. The vertical component of this setting (y in Table 2) is 1.465 cm. Converting to thousandths of an inch, we have:

$$\frac{1.465}{2.54} \times 1000 = 576.771 \text{ (thousandths)}$$

The value of K was then calculated in terms of strokes on the crossfeed and thousandths on the vertical feed.

$$y = Kx^2 \qquad (10)$$

$$K = \frac{y}{x^2} = \frac{576.771}{(638.740)^2}$$

$$K = .00141369$$

The equation then becomes

$$y = .00141369\,N^2$$

Using this equation, the setting on the vertical head feed was calculated for each stroke of the ram, starting from the center. The calculations for one half of the curve were tabulated as in Table 3.

N = number of strokes from center.

y = setting of the vertical screw in *thousandths of an inch.*

Construction of the Main Frame: The frame of the spectrograph consists of a bed of steel Ts as shown in Figure 11. The members are marked A, B,

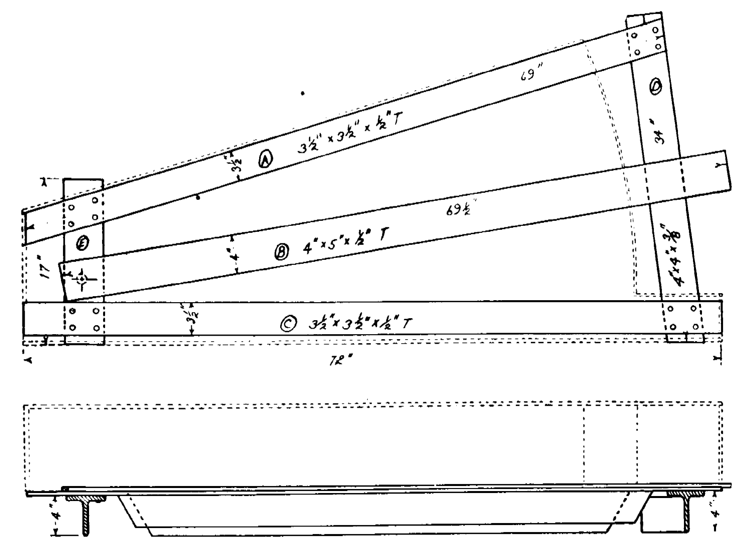


FIGURE 11

C, D, and E, and will be referred to by these letters in this description. All the Ts are of hot-rolled steel so that there is a minimum of strains present in the fabricated structure. To avoid introducing new strains the webs were cut with a hacksaw rather than with a torch. Since it was desirable to have the frame accurate and rigid the tops of members A, B, C, D, and E were machined true and smooth. The undersides of the ends of members A, B, and C were machined because they overlap and rest on the tops of members D and E. The two short Ts D and E are $4\frac{1}{2}$ by 4 by 3/8 inches and of the lengths shown. The side beams A and C are $3\frac{1}{2}$ by $3\frac{1}{2}$ by ½ by 69 inches and 72 inches respec-

TABLE 3

N	y (thousandths of an inch)
0	0.000
1	.001
2	.005
3	.013
4	.023
5	.035
6	.051
	....
100	14.137
	....
200	56.548
	....
638.74	576.770 = 1.465 cm.

tively and the center swinging beam is 4 by 5 by ½ by 69 inches long. The end member D is set at an angle, as shown in the drawing, so that the swinging beam B can travel from side to side with a minimum of longitudinal overlap change on beam D. The position of D depends on the position of the pivot center on which B swings. The ends of D should be almost equidistant from this pivot center so that the roller truck carrying the swinging end of B will be able to travel the full arc without allowing the rollers to get off the beam D.

The corners of the frame are fastened together by ½-inch SAE bolts. The frame was laid out on a bench and clamped in position during the drilling and reaming of the corner holes. Lock washers were used and the bolts were drawn up tightly. This type of construction provides a very strong, rigid, and accurate frame.

The pivot center of beam E is placed as close as possible to beam C. The grating is centered over the pivot and it is desirable to keep the angle between the light from the slit and the reflected collimated light from the mirror at minimum. This angle is indicated as angle a, Figure 5.

Since the center of curvature of the grating is placed directly over the pivot center, the dimensions of the grating cell should be kept at a minimum, as a large holder would tend to swing into and restrict the light from the slit.

The mounting of the center beam B is very important since it carries the grating on the pivot end and the camera on the swinging end. The pivot end of B is carried on a ½-inch steel ball held between two cupped steel bearings. The steel cups were made as shown in Figure 12. The pivot cups are fastened to B and E by four 6–32 flat-head machine screws. A ½-inch hole is provided to hold the dowel end of the bearing cups.

The camera end of the beam B is mounted on a traveling carriage of the design shown in Figure 13. This carriage consists of a ⅝-inch steel plate

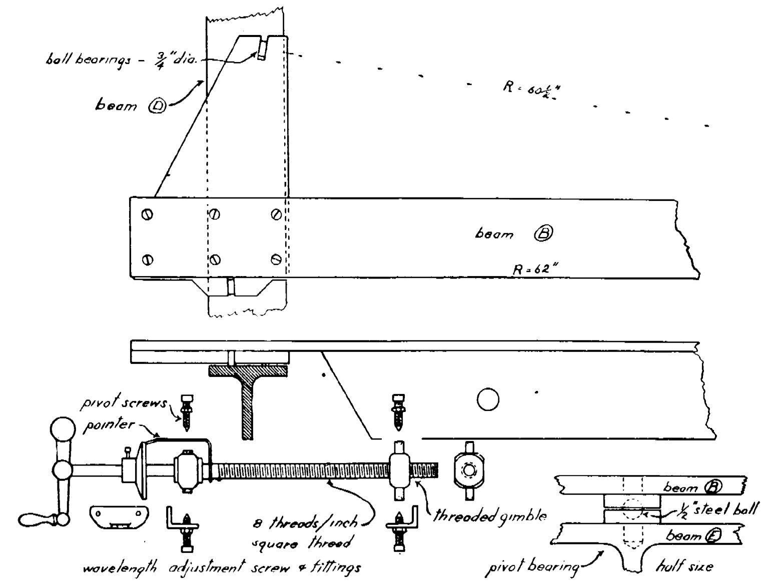


FIGURE 12

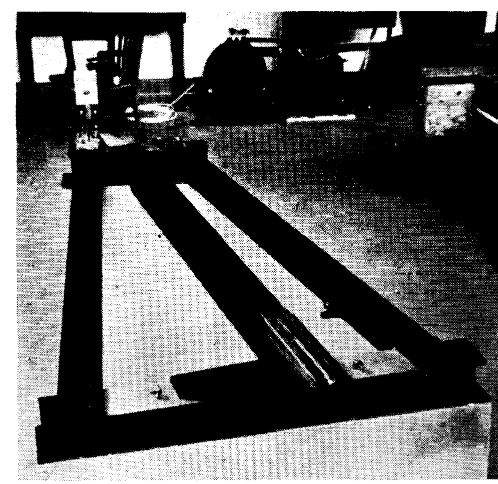


FIGURE 13

bolted to the underside of B and carried on ball bearings 11/16 inch in diameter. The bearings are mounted on ¼-inch tool steel axles that lie in ¼-inch milled slots in the underside of the ⅝-inch steel plate. The axles must be mounted slots in the underside of the ⅝-inch steel plate. The axles must be mounted on radii from the pivot center so that the rollers will follow their proper arcs without longitudinal sliding. The two rollers were mounted on different radii in order that they might travel as near to the center of beam D as possible.

The carriage plate was machined in a milling machine. The radii on which the axles were to be mounted were scribed on the underside of the ⅝-inch plate while it was bolted in place to the beam B. Then the plate was removed and set up in the milling machine so that the cutter was in alinement with the scribed radius. When properly alined the cutter machined a ¼-inch slot 15/32 inch deep and about 1½ inch long. By milling the axle slots 15/32 inch deep,

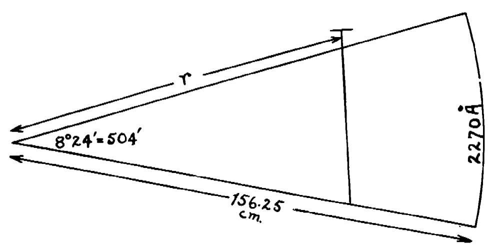


FIGURE 14

the ball-bearing rollers project 1/16 inch below the bottom of the plate and are level with the top. The slots for the rollers were machined the width of the bearings and accurately at right angles to the axle slots. These slots are cut clear through the ⅝ inch plate.

The beam B then is mounted on a three-point support, a steel ball and two rollers. Since the rollers travel along a machined surface, and the ball pivot is accurate, the mounting is stable and any given setting can be reproduced without optical tests.

The control of the position of the swinging beam is very important as its position determines the spectrum region covered by the camera. This control is obtained by a steel screw mounted in a pivoted bronze bearing and is pivoted on the side beam A and the nut is pivoted on the swinging beam B. This screw and its mountings are shown in Figure 12.

The pivot centers for the screw are situated equidistant from the pivot on which B swings and the distance from the ball pivot to the screw pivots is 123.25 cm. This dimension was calculated to give a change of about 40 angstroms at the camera per revolution of the screw. Since the focal length is slightly different between any two settings of beam B, and since the screw represents a chord of the arc, this calculation is only approximately correct. The calculations were made using the average focal length. (Figure 14).

Focal length on the long setting	157.95 cm.
Focal length on the short setting	154.54 cm.
	2)312.49
average	156.245 cm.

For small values arc = chord = $r\theta = \dfrac{r \times 504 \times \pi}{180 \times 60}$

Chord for 1 revolution of the screw $= \dfrac{2.54}{8} = \dfrac{r\,\mu'\,\pi}{180 \times 60}$

Angstroms per minute of arc $= \dfrac{2270\mu'}{504}$

Angstroms per revolution of the screw $= \dfrac{2270}{504} = \dfrac{2270 \times 180 \times 60 \times 2.54}{504 \times \pi \times r \times 8}$

Angstroms per revolution $\dfrac{4930}{r}$

Angstroms per revolution 40, then $r = 123.25$ cm.

The Slit Mounting: The slit through which the light emitted from the arc enters the spectrograph is a very important part of the instrument and must be very accurately made. The types available vary slightly in détail but almost all of them have accurately ground hard steel jaws of which at least one can be moved to vary the width of the spectrum line produced. With the time and tools available it was deemed advisable to purchase a slit rather than to make it. The one obtained for the spectrograph was a Gaertner slit costing about $85 in 1941.

The slit is mounted as shown in Figure 15. The slit is attached to a brass plate ⅜ by 9 by 3 inches. This plate is mounted on the base by two cast-iron angles which were machined to an accurate right angle in the shaper. The angles are secured to the base by four ¼–20 N.C. machine cap screws tapped into the frame. The holes through which these screws pass are slotted so that an adjustment can be made in the position of the slit by sliding it along the frame. This adjustment is necessary since the slit is mounted at the focal length of the spherical mirror and the final adjustments made when the instrument is assembled. These slots are about ½ inch long, giving ¼ inch adjustment with the ¼-inch screws.

The slit plate is secured to the angles by four ¼–20 N.C. bolts. The bolts are tapped into the brass and the nuts are used as lock nuts.

The center of the slit is 6 inches above the top of the frame beam C, so as to coincide with the optical center of the other parts. A brass sleeve was turned and fitted into the upright brass plate and secured with a lock screw as shown in the drawing. This sleeve was used because the thickness of the upright plate (⅜ inch) was inadequate properly to support the protruding tube on the slit case. The hole in the upright brass plate was bored by mounting the plate on the lathe face plate and machining to a firm push fit for the adapting sleeve.

As the slit must be in exact parallelism with the grating rulings, some provision must be made to rotate it into position. This adjustment was made out of $\frac{3}{16}$-inch brass strips $1\frac{1}{16}$ inch wide bent to form a small right angle, as shown in Figure 15. A $\frac{1}{2}$-inch brass rod was turned and threaded with $\frac{1}{4}$–20 N.C. threads for the adjustment screws. These two screws are tapped into the brass angles and provided with lock nuts. The heads of the adjusting screws and the lock nuts are drilled with $\frac{1}{8}$-inch hole to take an adjusting key.

The two adjustments are mounted above and below the slit case to one

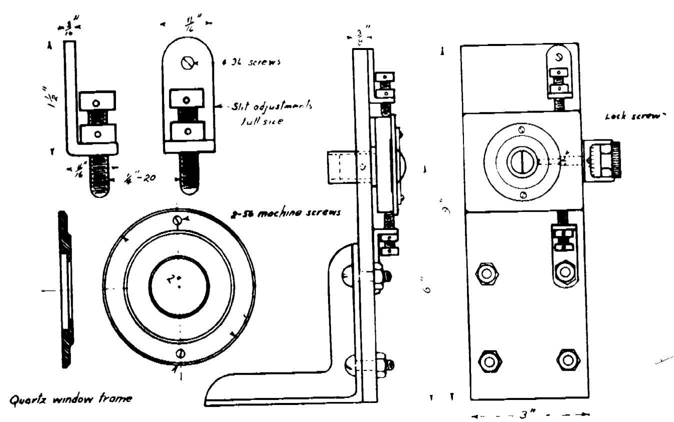


FIGURE 15

side of center, as shown. The brass angles are fastened to the upright plate by three 6–32 flat-head machine screws tapped into the plate. In the lower adjustment one of the $\frac{1}{4}$–20 bolts takes the place of a 6–32 screw.

The slit is provided with a thin quartz window to protect it from dust. This window is not provided by the slit manufacturer and the frame had to be made up as shown in Figure 15. The frame was turned down from 2 inch brass rod. In order to have both sides machined smooth, the piece was turned to size on the rod and then cut off. A piece of aluminum was then chucked in the lathe and recessed to fit the frame, which was then cemented into the recess with celluloid dissolved in acetone and finish turned on the back. The window frame is fastened to the slit case by two 2–56 machine screws tapped into the slit case in such a way that they do not interfere with the operation of the jaws. The quartz window was purchased from the Bausch & Lomb Optical Company at a cost of about one dollar.

The Mirror and Mounting: The spherical (long-focus paraboloidal) mirror

was made from a disk of glass 3 inches in diameter and $\frac{1}{2}$ inch thick to a focal length of 178.9 cm, and then was aluminized, aluminum being superior to silver because of its higher reflectivity in the ultraviolet.

The mirror is held in the mounting cell by three small brass strips attached to the edge of the cell by three small round-head screws. The brass strips extend out onto the mirror edge and touch it only very lightly.

The light entering the spectrographic slit is directed to the mirror which in turn reflects the light to the grating. In order that the collimated light may

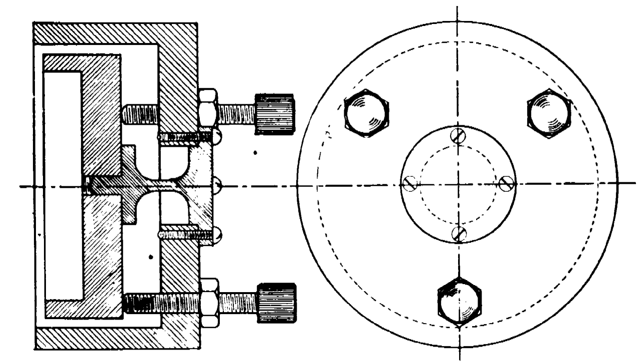


FIGURE 16

be properly directed to the grating, the mirror must be mounted in a cell that will fill the following requirements:

1. The mirror must be held free from strain.
2. The holder must have all degrees of freedom of adjustment.
3. The holder must be easily adjusted and locked.
4. The holder must be very rigid and strong to prevent loss of adjustment.
5. The holder must be reasonably easy to construct and mount. These requirements are identical with those of the grating mounting with the exception of the additional adjustment which will be discussed in the description of the grating mounting.

The design of mounting selected as the most nearly fulfilling the requirements is shown in Figure 16. The main casting is made of aluminum billets, as aluminum is easily melted and machined. Some scrap aluminum was melted down in an iron crucible but the first attempts at casting were not successful. After some experimental work, a little copper and tin was added and proved a decided help in producing smooth castings. The molten metal was poured into a short section of 6-inch pipe to a depth of about 3 inches. The pipe served as a mold and the aluminum was easily removed when it had cooled sufficiently. Due to the shrinkage of the top of the casting, the bottom was used as the back, allowing the porous portion to be removed in machining.

The inner cell in which the mirror is mounted is made of steel, as is the suspension support. Steel was selected as the best material for this part since the coefficient of expansion is low.

Since the amount of adjustment available is limited in this type of mounting, the entire holder must be placed accurately on the frame and be within one degree of arc of proper alinement. This accuracy is easily obtained and presented no great difficulty.

The mirror holder was mounted on the beam of the frame *C*, Figure 11. To bring the optical center of the mirror to 6 inches above the frame, which corresponds to the center of the slit, a hardwood mounting block was made out of a piece of well-seasoned oak. The block was squared up to size in the shaper and then drilled so that a ½-inch bolt could be used to mount it on the lathe face plate. After bolting it to the lathe face plate, the two corners nearest the center were set at the radius of the cell from the lathe center. Then the bolt was drawn up tightly to prevent further movement and the block bored to the proper diameter. Since the block represents only a section of the periphery of the cylinder to which it is bored it is difficult to measure the diameter directly. This difficulty was eliminated by using the aluminum cell which was to rest on the block as a test cylinder. When the block fitted properly on the cell the piece was finished.

Construction of the Grating Holder: The grating holder was constructed in much the same manner as the mirror holder except that one additional motion was necessary to aline the rulings with the slit. Apart from this the grating has all degrees of freedom, controlled by the three screws in the outer cell. As with the mirror holder, the cell containing the grating is mounted on a flexible steel suspension and is controlled by the three screws on the outer cell. Another cell within this intermediate cell holds the grating. These two inner cells were machined accurately so that a good bearing surface existed between them. Steel was used for the center suspension and the two inner cells, while aluminum was cast in a 6-inch pipe for the outer cell. The adjusting screws were turned from ½-inch brass rod and threaded with ½–20 U.S.S. thread.

The dimensions of the inner cell were determined by the size of the grating. The grating is held in this cell by three small brass clips screwed to the edge of the cell and extending out ⅛ inch on the grating face. When installing the grating great care should be exercised to prevent damage, and in setting or adjusting the grating nothing should be allowed to touch the surfaces of the ruled area. It is necessary for the grating to be held in place securely but without pressure. To this end the grating rests on a paper pad.

The mounting (Figures 17, 18) of the completed grating holder on the spectrograph frame was effected in the same manner as with the mirror holder. A block of well seasoned hardwood was machined square in the shaper and turned on the lathe face plate to fit the contour of the holder. The finished mounting was reduced to 6 inches between the grating normal and the top of the outer frame members so that all parts were on the same optical level. In centering the holder over the ball pivot it was found that best results were obtained by mounting the holder and marking the position of the base on the swinging

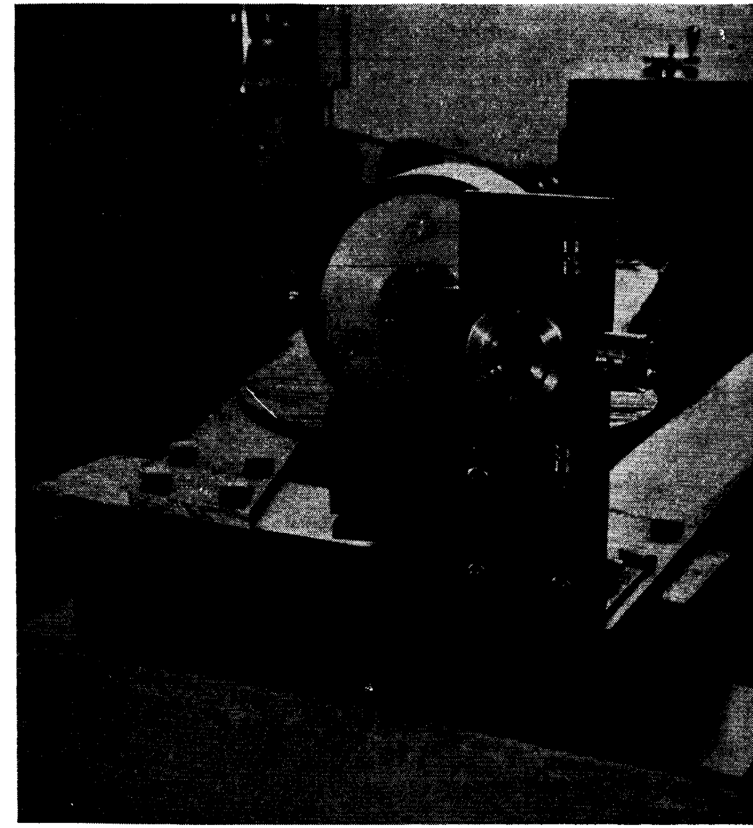


FIGURE 17

frame member. The holes for the ½-inch rod were then drilled and the holder remounted in its proper position. The ¼-inch rods were threaded on both ends, the top end being screwed into the outer cell and the bottom secured by two nuts under the top web of the steel T. In order to provide a small amount of adjustment for the mount the holes in the swinging beam were drilled slightly oversize. This allowed accurate centering of the grating when the instrument was finally adjusted.

Construction of the Camera: This part (Figure 19) of the spectrograph was constructed of rolled sheet brass. The base of the camera (Figure 20) is a brass plate ¼ by 10 by 3 inches. An opening 9$\frac{3}{16}$ by 1$\frac{11}{16}$ inches was cut by laying out the pattern and drilling numerous small holes along the lines to be cut. After drilling, the small sections of brass between the holes were cut with a jeweler's saw. The rough edges of the rectangular hole were then carefully filed smooth and to exact size.

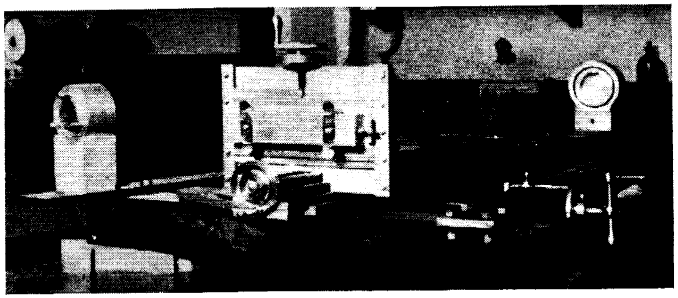


FIGURE 18

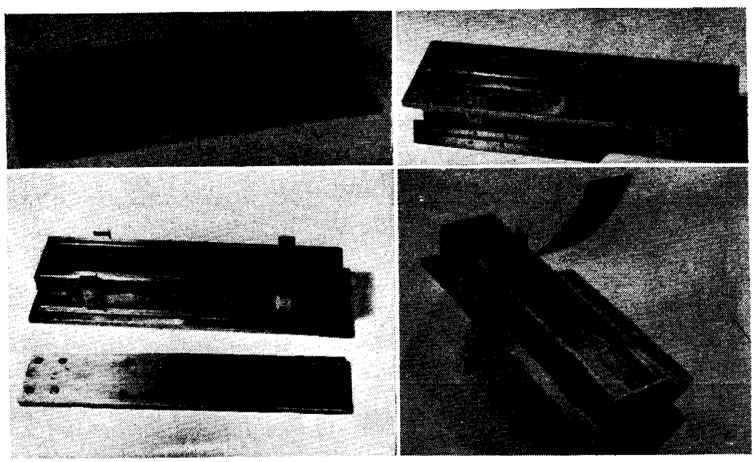


FIGURE 19

The body of the camera is made of ⅛-inch brass plate cut to the sizes shown and assembled with 2–56 steel screws. All parts of the camera were carefully machined on the shaper to exact fit.

The pieces marked *f* are two brass plates ¾ by $\frac{3}{16}$ by 9$\frac{3}{16}$. These two plates are very important as they support the edges of the film and hold the

film to the exact focal curve. In the design calculations the focal curve is a parabola. This curve was cut in the brass plates by first carefully laying out the calculated curve on the brass and then shaping it roughly with hacksaw and file. The two pieces screwed together were then set up in the shaper and machined in the manner already mentioned in "Design Calculations." When the machining was completed the curved surface was smoothed up with light filing and polishing paper.

The photographic film is held to this curve by a spring brass strip fastened to one end of the camera and controlled by a small cam at the other end. This provides pressure against the focal curve and tension along the spring. This

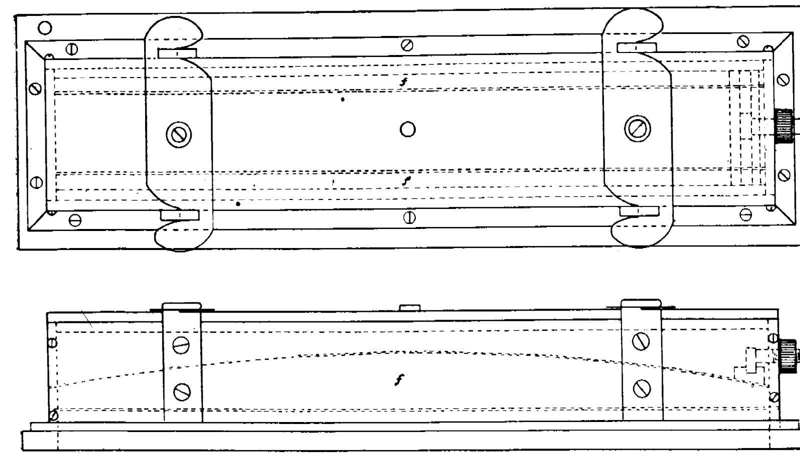


FIGURE 20

cam can be turned to release the brass strip and allow the film to be loaded and unloaded at will. The camera is provided with a dark slide made of this spring steel running in grooves along the camera sides. The dark slide provides a means for loading the camera in the darkroom and bringing it to the spectrograph without danger of fogging the film.

As has been indicated in the design calculations, it was necessary to provide for a camera movement of about 10 cm along the swinging beam of the frame. This was accomplished by using a cross compound slide from an old lathe. This part included the gib ways, tool post block and the feed screw. The block was machined square with the slide and the entire camera mount attached to it (Figure 21) shows the assembly in elevation.

The entire camera assembly was mounted on an aluminum plate ⅜ by 12 by 8 inches. This plate (Figure 22) was machined smooth on the face next the camera to provide a suitable bearing for the vertical movement of the camera slide. It was fastened by one 1/4–20 machine screw tapped into the tool post block. By using only one screw it provided a slight movement of the camera around a horizontal axis so that both sides of the film holder could be brought to the same level. This movement is controlled by the vertical adjustment screws. These screws are fastened to a rectangular steel bar 12 inches long

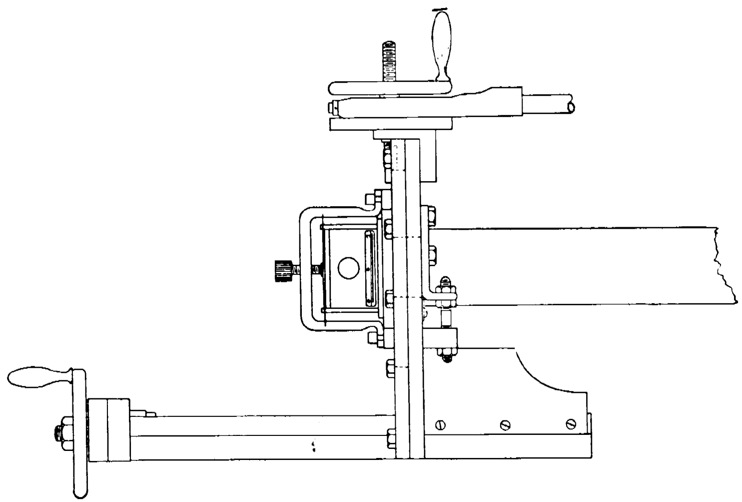


FIGURE 21

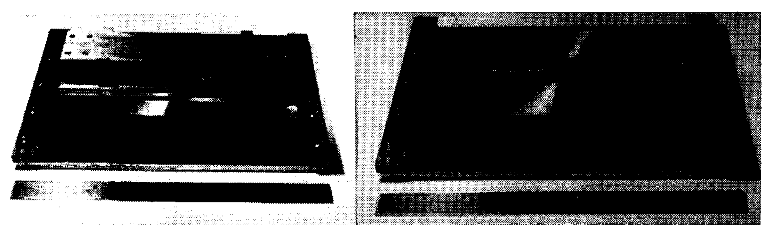


FIGURE 22

that extends along the back of the aluminum plate. This bar is securely screwed to the tool post block.

The camera was provided with a vertical movement by a gibway running vertically on the aluminum base plate. The edges of the brass plate to which the camera is attached were machined perfectly parallel to a 45° bevel in the shaper. Two brass rectangles 3/8 by 1 by 8 inches were also machined with 45°

angles and fastened to the aluminum plate by five 1/4–20 cap screws. The holes in one of these gibs were slightly elongated to allow adjustment of the ways.

The camera is held between two brass strips 1/2 by 1/4 by 10 1/4 inches. The strips are screwed to the vertical slide with 2–56 flat-head machine screws. A small brass dowel pin extending from the vertical side plate prevents the camera from moving horizontally between the brass strips.

The vertical movement of the camera slide is controlled by a screw having 24 threads per inch. The screw is threaded into a hand wheel which in turn rests in a bearing attached to the top of the aluminum base plate. The hand wheel was fitted with a 4-to-1-ratio worm and gear so that, with a long shaft

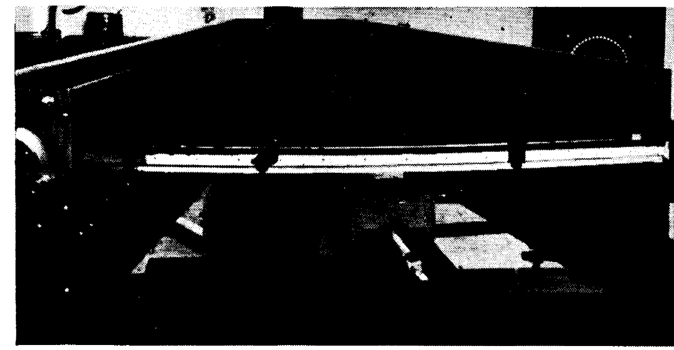


FIGURE 23

extending to the slit end of the instrument, the camera could be controlled from the operator's position.

The camera is held to the vertical slide by a yoke that slips over the camera and hooks under the heads of the two steel screws in the two brass strips that support the camera.

Construction of the Light-tight Cover: After all other elements of the spectrograph had been completed the light-tight cover (Figure 23) was built. The first patterns were cut from cardboard and an almost complete mock-up finished before the final cover was made out of plywood. Three-ply fir board 3/8-inch thick was used. The actual design had to be fitted into the other parts of the instrument and was therefore worked out piece by piece rather than by a previous design.

The cover consists of a bottom deck, sides and a top, together with baffles and sliding tape. The bottom deck is supported by the sides and is mounted 3 inches above the top of the swinging beam. The edges are supported on 1 by 1-inch strips of wood screwed to the deck and sides. All corners and joints in the cover were reinforced by 1 by 1-inch strips. These strips also served as additional light baffles and made extremely close fitting of the joints unnecessary.

A hole was cut to admit the grating holder. A baffle was fastened to the base of the grating holder to prevent the passage of light into the instrument. The sides were screwed to the frame with 6–32 screws tapped into the edge of the T-section.

The plateholder mounting was difficult to render light-tight, but after several designs had been discarded the problem was solved by fitting a thin and very flexible steel tape to a piece of ¼-inch plywood through which passed the sheet iron extension from the plateholder mounting. The ¼-inch plywood was fitted between wooden guides cut to the arc described by the swinging beam.

FIGURE 24

The tape bends sharply and slides along both sides when the plateholder is removed. To facilitate the installation of the top when the tape was in place a hole was cut in the top which allowed the tape to be reached from the inside. The outside of the sheet iron extension from the plate mounting was covered with black velvet and the entire inside of the plywood cover painted with a dull finish blackboard paint. Besides this, various baffles were installed to prevent stray light from reaching the photographic film.

When the light-tight cover was completed a small plywood door was fitted to the grating holder and provided with a flexible shaft and control knob which is operated from outside the spectrograph. This cover keeps dust and stray chemical fumes from the grating when it is not in use.

The entire cover, when finally assembled, became a single unit and may be

removed in one piece when necessary. After a complete sanding the plywood was stained with dark oak oil stain and given three coats of good varnish.

Excitation System: The excitation system of the spectrograph consists of an arc stand (Figure 24) and a motor-generator set with controls. Usually 220 volts d—c is most desirable for the arc, but as no d—c generator of that voltage was available an old four pole generator delivering 125 volts was used. The motor was borrowed from the Anaconda Copper Mining Company and is a 10 hp unit operating on three-phase 220 volts a—c. The generator was set up on its old slide base and belted to the motor. The generator turns at 1800 rpm. The generator was provided with its original field and line resistance to control the d—c voltage and prevent overloading (Figure 25) when the arc was struck.

By adjusting the field resistance the voltage was stepped up to 150 volts. This has proved adequate for most spectrographic analysis. The line resistance is adjusted so that the current does not exceed 10 amperes in ordinary use.

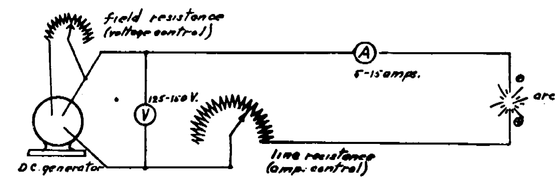


FIGURE 25

The motor was provided with a three-phase line switch and a magnetic starting box. The entire control system was mounted on a 1-inch plywood panel which was supported on angle irons fastened to the floor and wall of the laboratory. Electrical conduit was used to bring the direct current to the arc stand.

The Arc Stand: The arc stand was purchased from the Bausch & Lomb Optical Company and is their standard model straight-line stand. The electrodes are held between metallic clamps which can be moved vertically or horizontally by insulated adjustments. A quartz lens is mounted between the arc and the slit to keep the arc image focused on the slit.

Just in front of the slit is mounted a motor-driven sector disk with adjustable opening. The variable opening sector provides for the reduction of the amount of light entering the instrument. This allows samples to be burned for a longer time without danger of overexposing the film.

The entire arc stand is mounted on a heavy bench built for the purpose and securely fastened to the floor.

In operation it is desirable to have the electrodes, especially the lower electrode which is usually positive, easily removable. For this reason a graphite holder was turned out and placed in the lower electrode clamp. When the graphite electrodes are used the ¼ by ¾-inch graphite rod containing the sample is set in the graphite holder. In using the iron arc, the upper electrode is replaced with an iron rod and a small piece of iron, 1/4 by 3/4 inches, is slipped into the graphite holder.

The Ventilation System: The arc must be properly ventilated to remove noxious fumes. The nitrous oxides and other elements and compounds released by arcing are more or less poisonous and to safeguard the operator a sheet iron hood was built and installed over the arc. The hood is 12 inches square, 12 inches high and connects to a 3-inch sheet metal tube that rises to the laboratory ceiling and thence to the wall where it discharges through a hole cut to the outside. At the discharge end a small suction fan of the Sirocco type having a capacity of 90 cubic feet per minute provides ample draft to prevent

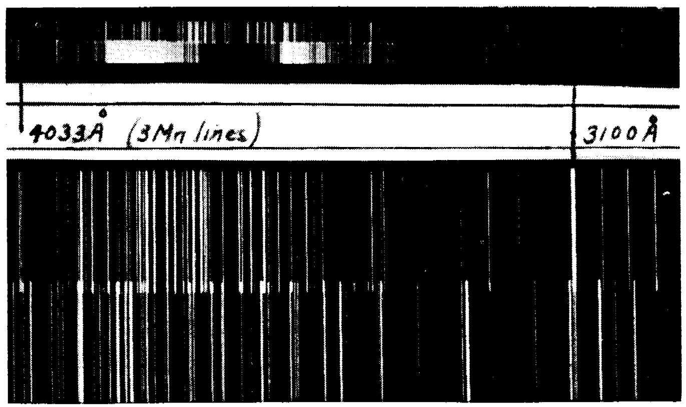


FIGURE 26

Spectrogram in the ultraviolet region. Upper spectrum: iron arc. Lower: A raie ultime powder.

fumes from the arc circulating into the laboratory. Many spectrographic laboratories use a hood that is completely covered in but in this installation the small open hood placed about 12 inches above the arc provides ample discharge. To help steady the uprising current around the arc and to shield the operator from the arc a rectangular shield, open on one side, is fitted to the bench. This shield can be moved away from the arc when necessary.

Final Adjustment of the Spectograph: The adjustment of this type of spectrograph is not difficult. Excellent results (Figure 26) were obtained after a few simple optical and photographic tests.

After the instrument was set up and the mirror and grating installed the slit and mirror were separated by the focal distance of the mirror. This distance was checked by a direct measurement rather than by optical test, as the accuracy needed at this point is not extremely great.

The mirror was the next part to be alined. By turning the three screws

that provide motion for the mirror the reflecting surface was collimated so that by looking through the hole in which the slit is mounted a reflection of the grating surface could be seen. Final adjustment of the mirror was effected with the slit in place and closed to the point where the grating image could just be seen. The slit wedge was then installed and closed to the last notch, leaving only a short portion of the center of the slit through which the mirror could be viewed. By then adjusting the three screws in the mirror cell the reflecting surface was brought into final alinement and locked in place with the lock nuts.

Next, the grating was adjusted so that the grating normal was made to pass directly through the center of the camera. The grating had been set previously directly over the pivot center. The pivot setting is not critical and was done mechanically. A small piece of brass 35 mm wide was cut and drilled on the horizontal center line with two holes about 1 inch apart. A small light bulb was fitted behind one of the holes and covered with a small brass tube to prevent light from going in any direction except through the hole. This testing device was then placed in the film holder so that midway between the two holes corresponded to the center of the camera and the point through which the grating normal should pass. By adjusting the three screws on the back of the grating holder the grating was brought into such a position that the reflection of the point of light could be seen through the other hole. Due to the rulings on the grating surface it was necessary to use the unruled portions around the edges when viewing the reflected ray.

With these tests completed the instrument had the collimated light from the slit fully illuminating the grating and the alinement between the grating and the camera was correct.

It was necessary next to determine whether or not the entire optical path was in the same plane. This instrument did not need any such adjustment but the adjustment, if needed, could have been made by raising or lowering either the slit or the mirror until the slit image coincided with the film center.

The only remaining test was for focus. This was done in the visible region by placing a ground glass on the focal curve. With light coming from the arc through a wide slit the camera was roughly focused. The position of the dividing head on the focusing screw was noted and then turned back several divisions. With a photographic film in the camera, several spectra were recorded using a shortened slit and moving the camera vertically between exposures. The focusing screw was advanced one division for each new spectrum recorded. The position of the best focus was recorded and marked, so that it could be easily reproduced without retesting. The focus depends on the region in which the swinging beam is set and it was therefore necessary to provide markings on the wavelength range control screw so that the range could be reproduced accurately and the camera brought up to the predetermined focus. The instrument was provided with three sets of markings, that is, three focus positions for the three main wavelength settings, ultraviolet, visible, and infrared. Focal settings for ultraviolet and infrared must be made photographically.

After the instrument was completely adjusted and checked it was found that all settings could be accurately reproduced and after ten months of operation it showed no need of adjustment.

Bibliography

HARDY, A. C. and F. H. PERRIN, "The Principles of Optics," p. 286 (1932).
MEGGERS, W. F. and K. BURNS, Scientific Papers Bureau of Standards, No. 441 (1922).
MEYER, C. F., "The Diffraction of Light, X-rays, and Material Particles," University of Chicago Press (1934).
WOOD, R. W., "Physical Optics."
BALY, E. C. C., "Spectroscopy, Textbooks of Physical Chemistry," Vol. 1 (1929).
"Amateur Telescope Making," Scientific American, Inc.
STRONG, "Procedures in Experimental Physics," Prentice-Hall, Inc., New York.
PORITZKY, A., "A Stigmatic Grating Spectroscope." Proceedings of the Fifth Summer Conference on Spectroscopy and Its Applications, 1938.
DIEKE, G. H. "Characteristics of the Eagle Mounting of the Concave Grating," Sixth Summer Conference on Spectroscopy and Its Applications (1939).
HARRISON, GEORGE R. "The Testing and Use of Concave Diffraction Gratings," Proceedings of the Seventh Summer Conference on Spectroscopy and Its Applications (1940).

[EDITOR'S NOTE: The books by Meyer and by Baly are out of print, as are the proceedings of the several summer conferences cited above. They may be consulted in some of the larger libraries.]

[EDITOR'S NOTE: A typescript copy of the preceding thesis was submitted to the senior author for general checkup and the occasion was seized for scribbling informal questions at various places in the margins and inviting informally scribbled replies. This underhanded editorial trick brought out, as it always does, useful data for the builder.

On the Wadsworth type of mounting: "I readjusted it about once a year, as the instrument showed slight signs of creep in the un-normalized steel T-beams. But then, we also had jaw crushers and mill machinery in the next room and a freight railway a few hundred feet away."

On the slit: "I made the one in ATMA, page 503, some years ago and it works very well on the instrument described. For slit see also Martin, L. C., 'Optical Measuring Instruments,' page 126, Figure 75, *b*." (Out of print.)

On the generator: "I believe it was an old Edison. At times I used 20 amps and the old lady groaned. The belt slap from our set-up made us punch-drunk after several hours' operation. A rectifier system would be OK and quiet."

General costs: Central Scientific Co., Chicago. Bench $17; arc stand, $25; sector about $17 (This can be cut out of metal sheet, and an old sewing machine motor would bring the cost down to $5); quartz lens, $17. Bench, arc stand, quartz lens, no sector, for use with small Littrow spectrograph, $102.

Bench, arc stand (110-v), quartz lens, sector disk and motor, for large Littrow spectrograph, $506. These current prices merely give a general idea."

On the value: "Including motor-generator (or power supply) it would cost perhaps $4000 or $5000 for an instrument of equivalent performance. Omitting labor, the actual cost, including grating, slit, arc-bench, supplies, was about $500."

On the grating: "Replicas are less expensive. One 1¾ by 2½ inches said to cost about $60 today, would be fine. But the $10 variety are not good enough for this job, though a very serviceable *small* spectrograph can be made from one. Grade A replicas (Wallace or Wood) are good for many purposes; in fact, Wood's grating replicas are famous in astronomical use. But many replica gratings are too small in aperture to be of much use in a large instrument. I'll take a 1 by 1-inch replica and get spectrograms from it but I will not be proud of the instrument. A lot of our work was in the analysis of ores and minerals where *high* resolution was needed for trace quantities of elements, something that cannot be done with a low-dispersion instrument."

On some typical work done with this instrument: "See Sloss, L. L., and Cooke, S. R. B., 'Spectrochemical Sample Logging of Limestones,' *Bulletin of the American Association of Petroleum Geologists* 30,1888 (1946) or Perry, E. S., and Cooke, S. R. B., 'Spectrographic Prospecting for Beryllium in Pegmatites of Western Montana,' *American Mineralogist* 31,499 (1946)."

On the mirror: "The mirror should be an off-axis affair but the tilt is so small that I could never detect the induced astigmatism."]

Craft

A Composite Chapter of Spectroscopic Sidelights

[Editor's Note: Extremely little about ordinary everyday adjusting technics and common procedures in handling spectrographs will be found in treatises on spectroscopy. Most of this lore is transmitted orally from instructor to student in the laboratory and never gets into print. In Forsyte, W. E., "Measurement of Radiant Energy," McGraw-Hill Book Co., New York, there are about 4 pages on the adjustment of spectrometers (prism type), also 3 pages on the adjustment of the Wadsworth type of grating spectrograph. There is practical advice on calibration (and much else on spectrographic analysis) in Cutting, Theodore A., "Manual of Spectroscopy," Chemical Pub. Co., New York, N. Y. This book impressed one disappointed spectroscopist as "naive," thus unconsciously recommending it to the tyro.

The collection of reprinted articles that follows contains all the definite instructions for spectrograph building, other than the preceding chapters, that could be gleaned in 25 years' watch on the literature of optics. While there are numerous descriptions of spectrographs in the periodical literature, such descriptions are not slanted toward the constructor. Commenting on this, Roger Hayward writes, "Did you ever try to make anything from a textbook diagram? I tried it when in high school. My textbook said nothing about the correct width for a slit. Guessing, I made mine ⅛-inch wide and of course it didn't work, nor did my 60-cent ornamental prism and reading glass suffice. Not until a quarter century later did I see the *D* lines through a spectrograph that I built. Baly's 'Spectroscopy,' now out of print, was helpful, as would be the 'Practical Spectroscopy' of Harrison, Lord and Loofbourow today. But even these don't instruct in building." Asked how he gained his constructional data Hayward replied, "I knew a spectroscopist, had a theoretical physicist tutor me in atom structure, and I also knew an experimental physicist. Thus I gradually acquired a general idea about the peculiarities of spectrographs. Only then did I design one for an instrument manufacturer." Hayward's physicist friends lived close at hand. Few amateurs are that lucky (or, on the other hand, plan to design spectrographs professionally). Yet, the situation being as described, the amateur is fortunate in having available the two preceding chapters—college theses—since they are almost uniquely definite about spectrograph construction. (College rules require that theses be bound and deposited permanently in the institution's library, hence it is probable that others equally useful in building optical instruments are gathering dust on forgotten shelves.)

No claim is made that the preceding chapters, plus the collection of data that follows, will make plain sailing of spectroscopy, even for the case-hardened, flea-bitten advanced amateur optical worker who studies textbook optics in addition. There will still be broad gaps between these stepping stones, and the literature of spectroscopy is more hole than matter. (The average amateur

likes it that way, since it leaves him partly on his own resources.) The answer is not so encouraging to others than optical workers, who sometimes inquire for the detailed plans of a spectrograph with instructions for building and using it. A typical example is a manufacturing jeweler who wishes to test his alloys and his gems but is too busy or insufficiently interested to study up the surrounding lore. Such persons could build and use a spectrograph, as an owner can drive a car with even less knowledge of car mechanics and principles. When the car is out of order there are plenty of local trouble shooters with judgment based on training, but where is there a spectrograph trouble-shooting garage? Unless he will go to the added labor of doing considerable reading to fill in background and acquire judgment in spectroscopy he may find himself out on the end of a limb.]

The Spectroscope in Astronomy

By Dr. Paul W. Merrill *

Very nearly all our information concerning astronomical bodies comes to us in the light we receive from them. This light is not a single homogeneous thing, but a most complex bundle of different colors (or vibrations) which in an ordinary observation are tumbled together in a heterogeneous heap called the image. Here the details are so hidden and confused that most of the important messages they carry are illegible. It is in spectroscopic observations only that the individual component vibrations are interpretable, for here they are laid side by side in a neat row called the spectrum, where each may be seen by itself. The intensification or weakening of any vibration in the octave or more which can be observed thus becomes obvious. The number of vibrations that can be individually recognized depends upon the power of the spectroscopic apparatus, or, more precisely, upon the "purity" of the spectrum it forms, but in actual practice the number runs into thousands.

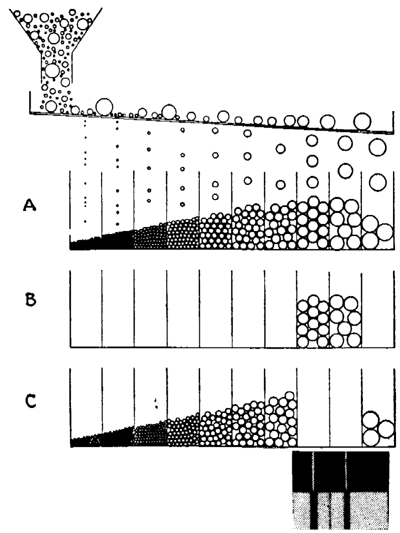
Thus a "direct" observation, for example, viewing a star in a telescope or its image upon a photographic plate, is like looking at a city from such a distance that it appears but a small blur on the landscape, while a spectroscopic observation corresponds to walking along the streets and examining the buildings one by one. Or, again, a direct observation is studying a book from the outside, trying to guess its contents by its size, weight, and general appearance; while a spectroscopic observation is opening the book and reading it through line by line.

It is from a detailed study of the individual vibrations or narrow portions of the spectrum (usually called spectral lines), that we get our greatest insight into the constitution of the stars. With an ease and certainty that seems almost magical, we recognize in stellar atmospheres atoms precisely similar to those known on earth. We can tell whether they are approaching or receding.

* The Mt. Wilson Observatory, in "Leaflet 42," Astronomical Society of the Pacific, by permission.

We can even ascertain what certain constituents of the atoms, the electrons, are doing; whether they remain regularly in place forming complete atoms, or whether some of them habitually stay away from home, leaving the parent atoms electrically upset over their absence.

It is, therefore, essential to understand clearly what a spectral "line" really is. In most spectroscopes the light is admitted through a narrow slit; the prisms and lenses are so arranged that the light is spread into a rainbow-



Mechanical analogue to illustrate the analysis of light by a spectroscope. A: *Continuous spectrum.* B: *Bright lines (sodium flame).* C: *Dark lines (sodium lines) in the solar spectrum. Spectra underneath: the upper one shows bright lines of sodium and the lower one the solar spectrum with dark* (D_2 *and* D_1) *lines of sodium.*

colored ribbon formed by numerous adjacent images of the slit. If the light consists of a complete sequence of colors without abrupt change in brightness, no lines are visible and the spectrum is said to be "continuous." This kind of light comes from incandescent *solid* bodies like the filament of an electric lamp. In the wide open spaces of a tenuous *gas,* however, an atom may be undisturbed long enough (one hundred-millionth of a second is sufficient) to express its own individuality; it then emits a series of discrete wavelengths or colors which appear in the spectrum as narrow bright "lines" at right angles to the length of the spectrum, arranged in a pattern characteristic of the particular chemical atom. Or if the gas lies between a source of continuous light and the spectroscope, it may subtract or "absorb" its characteristic wavelengths; the

same pattern of narrow lines will then appear dark on a bright background, like the Fraunhofer lines in the solar spectrum. The chemical origin of the light can thus be ascertained from the pattern of bright or dark lines, just as the city from which a letter was dispatched is revealed to the recipient by the postmark—if he can decipher it.

An analogy may possibly assist those to whom light waves seem so intangible that the fundamental significance of spectral lines is not readily grasped. Imagine a shot-sorting machine which automatically distributes shot according to size into a row of narrow bins. (See illustration.) Just as a spectroscope analyzes a ray of light into its constituent colors, so the machine will "analyze" a batch of shot of many different sizes, sending each into its special bin. Each bin will then correspond to one size of shot only, just as one position in the spectrum (spectral line) corresponds to one definite wavelength. A cross-section of the bins will form a shot spectrum: if all sizes of shot are present with a smooth progression of the numbers entering successive bins, the correspondence is to a continuous spectrum (*A* in illustration); but if certain definite sizes only are represented, all but a few lines will remain empty, and we have the analogy of a bright-line spectrum *B*. The condition *C* corresponding to the dark-line spectrum will be obvious to the reader. The details of the analogy are as follows:

Shot grader = Spectroscope.
Shot = Light.
Diameter of shot = Wavelength or color of light.
Small shot = Violet light.
Medium shot = Green light.
Large shot = Red light.
Funnel = Slit.
Grading table = Prism (or optical grating).
Row of bins = Spectrum.
Individual bin = Spectral line.
Height of shot in a bin after a run = Intensity (brightness) of spectral line.

To correspond as closely as possible to the optical spectrum, the bins should be extremely narrow, very numerous, with invisible partitions.

The Spectrograph in Chemical Analysis *

By Theodore J. Zak

A spectrum is usually defined as light resolved into its component frequencies, as by a prism or grating. Chemical spectral analysis is based upon the fact that atoms and molecules under proper conditions of excitation absorb energy and later radiate that energy in the form of light which is

* From the *Yale Scientific Magazine,* Sheffield Scientific School, Vol. IX, No. 2, by permission.

characteristic of the emitting atoms and molecules. By passing light through a prism, it may be dispersed into its various colors to form a spectrum.

The instrument used to break up the light from a source into its constituent wavelengths and to provide a means of qualitative or quantitative study of the spectrum thus formed is called a spectrograph.

Basically all spectrographs consist of four parts: the slit, the lenses, the dispersing system, and the recording or observing system.

For practical excitation of most metals and materials the electric arc affords the simplest and most satisfactory means, its chief advantages being in sensitivity and speed. Due to high temperature of the electrodes greater density and concentration of the vapors evolved is made possible. If pure graphite rods are used as electrodes, the arc is usually operated at 220 volts and from 4 to 9 amperes. However, if a hotter or more vigorous source of energy is required, the condensed spark discharge may be used. The spark concentrates its energy at one particular point, while the arc covers a much greater area.

For analysis, regraphitized carbon electrodes are most commonly used. These electrodes usually contain small amounts of impurities such as silicon, vanadium, titanium, magnesium and calcium, but the amount of these elements present is generally so small that it does not interfere with the analysis. Arcing the electrodes just before using reduces the amount of impurities and increases the porosity. A photograph of the spectra of the electrodes alone beside that of a sample will indicate the impurities present in the electrodes. Thus if the density of a line in the sample spectrum is equal to or less than the density of a corresponding line in the electrode spectrum, then this particular element may be disregarded in the sample.

A hole about 8 mm deep is drilled in the lower electrode. If the sample to be examined is a powder, about 15 milligrams of it is placed in the hole, and the arc is struck. A quartz condensing lens serves to concentrate the light from the arc on the slit, and the electrodes and the lens are adjusted in such a way as to exclude the light from the incandescent carbon, whose strong continuous spectrum would be objectionable. The arc is kept running at the original voltage and amperage until the sample is completely volatilized. Usually for reference in location of lines an iron arc is photographed beside the unknown spectrum, and thus are produced side by side on the photographic plate a spectrum of the blank electrodes, one of the sample, and one or the iron arc as a reference.

The photographic plate is then developed, fixed, washed, and dried. Which lines are characteristic of a given element can now be determined by comparing the spectra with published maps or by use of tables. These lines may be marked as desired. One may also photograph side by side the spectrum of the sample given by the pure element that one desires and thus determine the presence or absence of the particular element in the sample.

The principle involved in the methods of quantitative analysis is the gradual weakening of the spectra of the elements when the amounts present in the light source are decreased. For example, a photograph might show four spectra where the percentages of zinc and copper remain constant, but the percentage of lead varies. These spectral photographs are obtained as follows: 16 grams of pure copper and 7.6 grams of pure zinc are dissolved in nitric acid and diluted to 100 cc, these being the proportions of copper and zinc used in making a 70–30 red brass. This solution is then divided into four equal parts. To numbers 1, 2, 3, and 4 are added respectively 0.1, 0.2, 0.4 and 1.2 grams of lead nitrate. One tenth of a cc of each of the solutions is placed in a drilled electrode, allowed to dry in an oven for 45 minutes, and then pictures of the spectra are taken. Thus the zinc and copper lines are of the same density in all the spectra, while the lead lines gradually diminish in density, sample 4 showing the strongest lead lines and sample 1 the weakest. If one has a sample of brass, a solution is made of the same concentration and 0.1 cc of it is arced and photographed under the same conditions which were maintained while preparing the standards. In examining the plate visually, if the spectral lines of lead in the unknown are of a density between those in samples 3 and 4, then one would conclude that 0.1 cc of sample contained between 1 and 3 milligrams of lead. Knowing the weight of sample taken and the volume of the resulting solution, one may calculate the approximate percentage of lead. For greater accuracy in determining the density of spectral lines a microphotometer is used.

In quantitative estimation the accuracy of the spectral method is fully as great as that of chemical methods where the element looked for is present in small amounts, but where large amounts of the element are present chemical methods are the more accurate.

The advantages of a spectral analysis to the chemist are its accuracy, sensitivity, speed, completeness, and the very small amount of sample required. One can detect minute amounts of the elements. As compared with the usual chemical methods, a qualitative analysis by spectral means is very rapid; from ½ to 1½ hour is usually required for a complete analysis, which includes photographing, developing, fixing the plate, and interpreting the emission spectra. The spectrum plate contains the record of all metallic constituents, while chemical analysis gives only those specifically looked for, and the spectral identification is very accurate. In chemical methods one might confuse one precipitate or reaction with another and thus obtain false results. Moreover, the absence of certain elements in quantities of more than 0.01 of 1 percent may be shown more conclusively spectroscopically than by the usual rapid chemical means.

A sample of 10 milligrams is ordinarily used in obtaining a spectrum, but smaller samples may be used if necessary. It would be extremely difficult to carry out a corresponding chemical analysis with such a small sample, yet in many cases only a very limited amount of material is available for analysis. And finally with a spectrum plate one has a permanent record which may be filed away for future reference.

In the chemical laboratory there are innumerable instances where spectral data would be of assistance in solving special problems. A preliminary qualitative analysis made spectrographically will reveal with few exceptions the chemical elements present in an unknown. In this way much time, which the chemical methods require in searching for the different elements of the various groups, is saved. The spectrograph can be used as a guide in devising suitable methods of analysis for unusual materials. The presence of an unexpected element may require special technic to avoid its interference in the determination of other materials. The proved absence of another element might permit a simplification of the method. Filtrates and precipitates are oftentimes much more rapidly and conveniently analyzed with a spectrograph, and materials bought on specifications which limit the amount of impurities may be compared with a standard.

The spectrograph is used in the classification and sorting of scrap metals. Metal stock in warehouses sometimes becomes mixed; here again the spectrograph can be applied. In industry the spectrograph may be used in distinguishing one's own product from a competitor's, as might be done with three common commercial aluminum alloys. Five spectra would be placed on the same photographic plate, including one of the black graphite electrodes, one of each alloy, and one of iron as a reference. The plate would indicate considerable magnesium in one alloy with only traces in the other two, one of which, however, would also show much copper and manganese. A further industrial application of the spectrograph lies in checking the quality of die castings, in which small amounts of tin, lead, and cadmium are particularly objectionable.

The following is a typical example of the spectrograph's usefulness. A section of half inch steel tube cut in half lengthwise and carefully labeled "Do not touch with fingers" was given to a chemical laboratory to find out whether sodium was present in the inside wall and, if present, how deep it penetrated. Using a triangular file, and holding the tube with a pair of pliers, five thousandths of an inch was filed off and a spectrographic photograph was taken of the filings. This was repeated five times, so that a depth of .025 inch was cut away. The spectrographic plate showed a considerable amount of sodium in the first spectrum, which decreased as the filing went deeper into the wall until it became negligible in the last spectrum. Thus the problem was answered: sodium was present in the inner wall, and it penetrated to a depth of not more than .025 inch.

The above are only a few instances where the spectrograph may be applied. At the present time chemical spectroscopy is in its infancy but chemists are rapidly realizing that the spectrograph is a valuable and indispensable tool.

A Concave Grating Spectrograph *

By R. M. Watrous, M.D.

The concave grating spectrograph is undoubtedly the simplest of all types for the amateur to construct because it has only one optical surface, requires no collimating or objective lenses, and can be constructed to give almost any desired amount of dispersion. The essential optical part can be bought for $4.50 and up; the rest of the instrument for the most part can be made of wood

* From *Scientific American*, 1942 July, by permission.

and scrap brass, and does not require elaborate machining. Scientific supply houses, such as the Central Scientific Co., Chicago, list in their catalogues a variety of replica gratings made by taking collodion impressions of famous gratings ruled on glass. These are offered in three grades at three sets of prices, depending on the degree of faithfulness with which the original rulings are reproduced. The medium grade has been found to give amply good performance in the instrument to be described. Replica gratings can be obtained mounted on silvered spherical concave mirrors of various focal lengths, and one of these is the only optical part needed for a concave grating spectrograph.

The concave grating spectrograph may have various forms, but all are dictated by the optical principle laid down by Rowland, which states that the

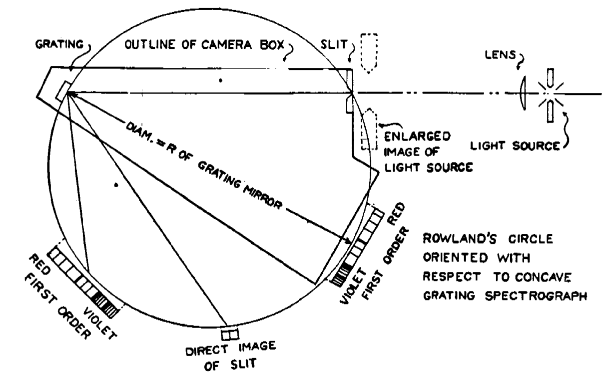


Figure 1

Drawings by the author

slit, the grating, and the spectrum must all three lie on the circumference of a circle whose diameter is equal to the radius of curvature of the mirror on which the grating is mounted. The mirror and the spectrum must lie at opposite ends of one diameter of the circle, in order to have images of the slit in focus, so the only possible variations in design must be obtained by changing the location of the slit along the circumference of the circle. In practice, the parts are arranged as shown in Figure 1.

In order to understand how images are formed by a concave grating, it is worth while to imagine the mirror on which the replica is mounted set up facing the observer as for a Foucault test, using a slit at the center of curvature as the source of light. Under such circumstances, the image of the slit will be cast back upon it, and a percentage of the light striking the mirror will be returned. However, the grating will cause some of the light to be diffracted with the result that varicolored images of the slit will be formed both to the right and to the left of the direct image. Thus there are two first-order spectra. To the right and left of these respectively will be another set of colored images forming the second-order spectra, and beyond these will be third-, fourth-, and *n*th-order spectra, each fainter and more spread out than the last. If the slit be now moved to one side sufficiently, and also be brought closer to the mirror, to preserve the relationships of Rowland's circle, the direct image of the slit will move in the opposite direction, as will all the spectra, until a position is reached in which the images will lie in the positions shown in the figure. By moving the slit still farther, the second-order spectrum could be brought opposite the mirror.

Having determined the dimensions required to secure the relationship shown in the figure with any given concave grating, it is necessary only to construct a box to support the parts and exclude light, and one has a spectrograph. A film holder may be made, to support films at the point where the spectrum comes to focus, or a telescope eyepiece may be supported at this point for direct observation. With such an instrument, clear spectrograms may be obtained 8 inches long, showing hundreds of details such as Fraunhofer lines. The light obtained by sparking two iron nails across the terminals of a storage battery will give a beautiful line spectrum of iron. Light passed through solutions of hemoglobin, dyes, chlorophyll, and others, will show characteristic absorption bands. Bunsen's famous experiment with the sodium flame can be performed; and so on.

In choosing a grating, a few facts should be kept in mind. The degree of dispersion (and thus the length of the first-order spectrum) is proportional to the number of lines per inch in the grating and to the focal length of the mirror. The resolving power, however, depends on the area of the grating and the accuracy of the ruling. The spectrograph shown (Figure 2) contains a medium grade grating of about 40-inch radius of curvature, with 14,500 lines to the inch and a grating area of about 2 by 3 centimeters.

The box is made of plywood, painted black inside, and with light baffles located at strategic points. The adjustable slit mechanism is on the left. The sliding adjustment for the film holder is on the right, actuated by the two vertical screws. In Figure 2 the film holder has been removed and is resting on top of these screws, its slide pulled two thirds of the way out to show how it is loaded. The main body of the camera extends into the background, with a small square porthole in the far end to give access to the adjustments of the grating mount.

The slit of a spectroscope is one of the essential parts, since every detail of the spectrum is actually an image of the slit. Its edges should be as smooth and as parallel as the maker's skill can contrive, and one may lavish as much or as little care on it as he wishes. For ordinary work, a slit 0.002 to 0.003 inch in width is suitable, and there is very little actual use for an adjustable width. Provision should be made for rotating the slit mounting to line it up parallel with the ruling of the grating for best definition, and it should be mounted in a draw tube so that its distance from the mirror can be varied slightly for focus.

The jaws of the slit may be made of brass and should be filed to a chisel edge and then sharpened like a chisel on a flat piece of plate glass, using finishing emery. After the edge is sharp, it may be placed on a very clean,

smooth piece of plate glass and gently pressed down. This will smooth out the "saw" edge and give a perfectly straight line. The two jaws should then be placed in their channels and closed gently together in front of a strong light. The most difficult part of an adjustable slit to make is the parallel channels in which the jaws are to slide. Not having a milling machine, I built these up out of strip brass.

Thirty-five millimeter film is very useful for making spectrograms and a holder may readily be designed to accommodate strips long enough to take in the full length of the spectrum. The film should be held in a curve conforming to Rowland's circle. Though it adds considerably to the problems of construction, a slide which permits the film holder to be moved at right angles to the length of the spectrum in the same plane will prove well worth while, since it allows up to ten spectra to be made on one film, with all the advantages of

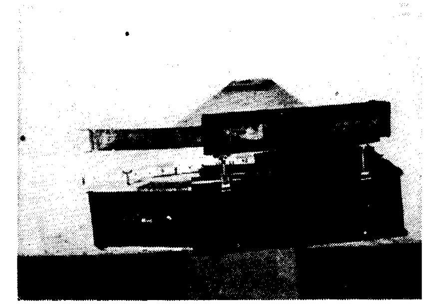


FIGURE 2

being lined up for comparison with one another. With such an arrangement a narrow slit-like mask should be placed just in front of the focal plane so that each spectrum occupies a strip about 2 mm wide running the length of the film.

The grating mount, as all telescope makers will realize, must be adjustable as to tilt in two dimensions, and it must have an adjustment for rotation about the mirror axis, in order to line up the rulings in a vertical position.

Light sources are many and varied, but the ordinary incandescent filament lamp gives a disappointing spectrum. Sunlight, with its thousands of Fraunhofer lines, furnishes material for many hours of study, but one must secure the co-operation of some patient soul to wield a mirror in order to direct the light into the slit, or else make a heliostat. If photographs are made, of course, they can be studied at any time.

Carbon arcs give fine line spectra, and are excellent for collimating the instrument. Cored projection carbons, $\frac{5}{16}$-inch size, will operate well on ordinary house current if the arc is placed in series with a cheap heating element or electric iron drawing about 500 watts. If the carbons are removed from thi circuit and replaced by iron nails, copper wires, aluminum, brass, nickel, or lead rods, light can be produced by making and breaking the contact, which will give beautiful bright-line arc spectra of the metals. These flashes are too fleeting to study visually but can be recorded on film and the lines can be identified with the aid of a table of wavelengths.

If the experimenter has a small transformer, such as is used for neon signs, he can obtain spark spectra of metals by causing the spark to jump between electrodes of the proper material. In order to obtain emission of lines, however, a condenser must be placed across the secondary of the transformer. The

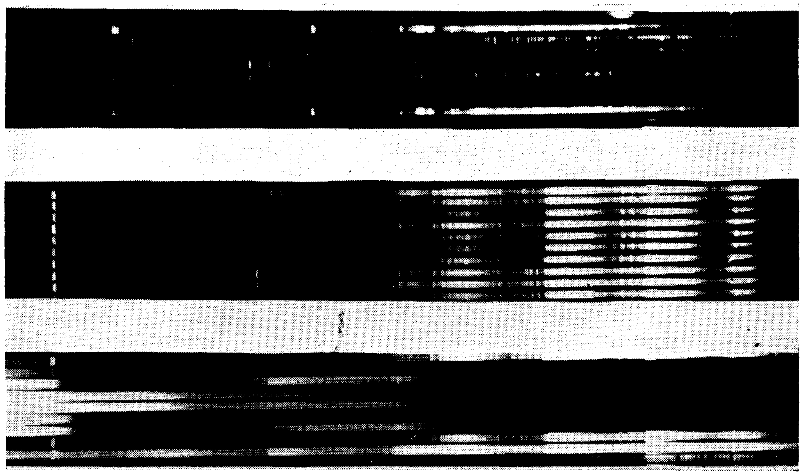


FIGURE 3

writer found that a home-made, one quart Leyden jar served this purpose very well, though a more efficient and less bulky condenser would be preferable.

The light from neon signs, fluorescent lights, and sodium vapor lamps will furnish interesting material for study and will also challenge the ingenuity of the experimenter to find some way of making it enter the instrument. On one occasion I balanced my spectrograph, which is about the size and shape of a baby's coffin, across the back seat of my car, while my wife sighted it like a rifle at a sodium vapor lamp and I held a condensing lens so as to cast an image on the slit. This was on a busy highway, but fortunately the stunt took place at night!

Figure 3 shows three contact prints made from portions of negatives obtained in the instrument. They extend from the orange to the violet. Violet is on the right.

Top: Arc and spark spectra of metals; from top to bottom: aluminum arc;

15,000-volt condensed spark between Al electrodes; iron arc; spark between iron electrodes; copper arc; copper spark; nickel arc; nickel spark; spark between platinum electrodes.

Middle: Series of exposures made with carbon arc for purpose of focusing slit.

Bottom: Absorption spectra of hemoglobin derivatives: carbon arc; next two, light from incandescent portion of carbon arc passed through hemoglobin solutions; next two, same through methemoglobin solutions; next two, same through carbon-monoxide-hemoglobin (note shifting of the two dark bands to the right); carbon arc.

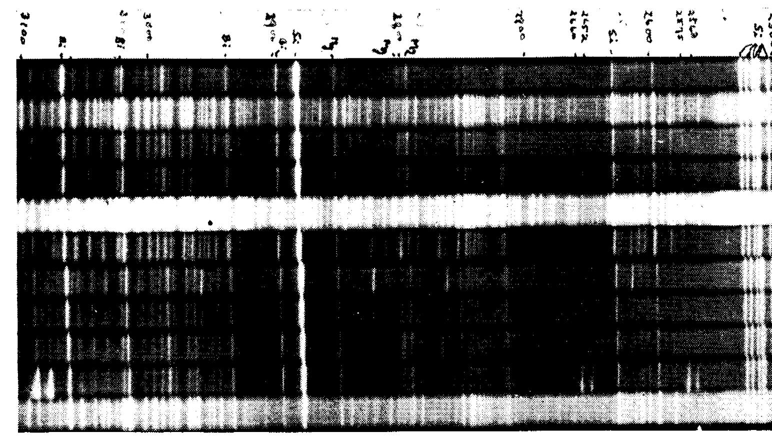


FIGURE 4

The two D lines of sodium are especially prominent in most of the negatives made with light from the carbon arc. They appear near the left margin in the middle set of spectrograms, and serve as convenient landmarks.

The spectrograms in Figure 4 give a better idea of the refined capabilities of such an instrument than those in Figure 3. The spectrogram is enlarged four times from a portion of film on which are registered ultraviolet spectra extending over that part of the ultraviolet from wavelength 3100 angstroms down to 2500 angstroms. The light which made these lines is completely invisible to the eye.

The top spectrogram was made with light from an arc between ordinary cored carbons such as are used for some kinds of lantern slide projectors. Those below it were obtained by melting bits of common metals (tin can strip, tin foil, solder, galvanized iron, brass, copper, sterling silver, silver solder, aluminum, iron) in the heat of the arc, thus causing them to vaporize and emit their characteristic wavelengths. Some of these metals did not remain in the arc long enough to record their spectra.

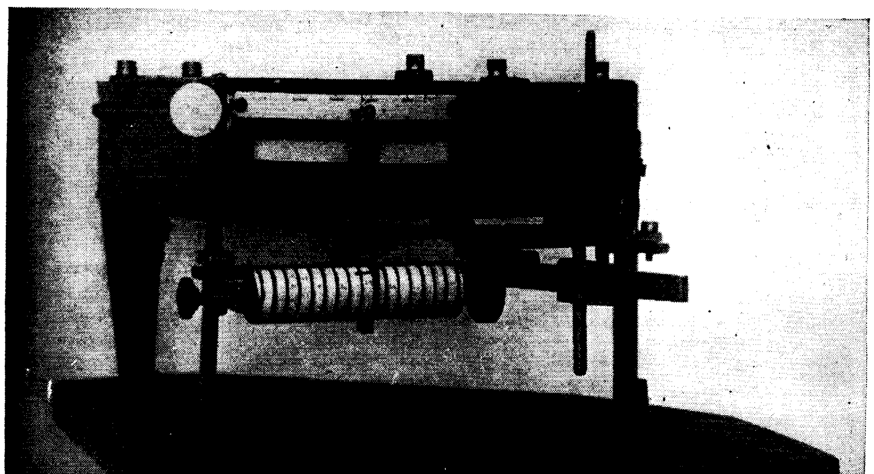
Since the carbons used were not of the high degree of purity required for spectrographic analysis, the lines of the elements in the core (silicon, bismuth, and magnesium) appear in all of the spectra, and are indicated at the top by their chemical symbols. The other numbers written across the top refer to the wavelengths in angstroms.

Brode's "Chemical Spectroscopy" is a fine technical work with 120-page tables of wavelengths and other things but no information on building spectroscopes. The old maestro of spectroscopy was Baly, whose 3-volume "Spectroscopy" was published in 1912, but this, too, is pretty technical and is no longer in print.

A Spectrograph *

By F. P. Smith

The concave grating type is the easiest, also the most practicable to build. A very good slit can be made without machine tools, the practice it gives in filing also being of value.



In the illustration the screw that is used to oscillate the cylinder, or drum, is grooved and the groove moves the eyepiece across the spectrum as the handscrew is turned. The spiral strip on the drum is calibrated in angstrom units. It also carries the symbols of the principal lines of the elements. Thus,

* From *Scientific American*, 1942 August, by permission.

if 15 or 20 elements are present, the user gets a line on the cross-hair and then refers to the drum.

The camera part is on the extreme right. The round white spot is the handscrew that is used to oscillate the grating.

I have followed spectroscopy as a hobby for 16 years and found that it contains unlimited fascination.

A Grating Spectrograph for Use in Qualitative Analysis *

By William S. von Arx

There is a new design of grating spectrograph manufactured by Adam Hilger Ltd.,[1] of London, under the name "Technal," and, while no less expensive than other good grating instruments, it has exceptional properties of ruggedness and simple design which are so inherent as to be preserved even when home-made by relatively inexpert hands. Home-made instruments are usually the result of whatever happens to be available, plus a few deliberately purchased parts. For this reason no two are ever quite alike. But, having the mechanical principles well in mind, it is possible to build a modest version of the "Technal" spectrograph in about two weeks of evenings. Its cost will vary, of course, depending upon the material at hand and the degree of refinement to which the design of the instrument is carried. But in no case should the cost exceed $50.

The Technal mounting is the most recent of the "minimum astigmatism" mountings for the concave grating. Others are the Wadsworth and the Eagle mountings. Both of these are composed of relatively delicate mechanical and optical parts, while the "Technal" is not only simple to understand and operate but rugged enough to withstand almost any kind of ordinary abuse.

First, let it be made clear why the concave grating is preferable to the more familiar prism as a dispersing medium. Prisms introduce irrational dispersion —non-uniform separation of equal wavelength intervals is different spectral ranges—which makes the interpretation of spectrograms unnecessarily difficult for the beginner. Furthermore, the prismatic instrument must always contain three component parts—the collimator, prism, and camera, each of which involves at least one pair of optical surfaces. For analysis in the ultraviolet range, these parts must be made of quartz, which is very expensive. The grating spectrograph, on the other hand, not only produces linear dispersion but may contain no lenses whatever and only one spherical reflecting surface if the concave grating is employed. With these, an aluminized reflecting surface is all that is required for efficient operation in the ultraviolet. This simplicity carries a twofold advantage; it reduces the initial cost of the instrument and makes it easier to keep in adjustment. Another advantage in the use of grat

* From *Journal of Chemical Education*, Volume 19, 1942, September, by permission
[1] Later Hilger and Watts Ltd., 98 St. Pancreas Way, Camden Rd., London, N.W. 1 England.

ing dispersion is the wide range of dispersions available in the higher orders of spectra. While the intensity of these higher orders is usually considerably less than that of the first order, the high intensity of the carbon arc, which is almost invariably used for qualitative analysis of non-conducting samples, allows them to be used for more precise analysis of the complex spectra characteristic of the transition group of elements. The ultraviolet range of the second order spectrum overlaps the visible range of the first order in grating dispersion, but when the first order is being photographed the ultraviolet of the second order may be filtered out completely by means of a plane-parallel strip of soda glass just before the plate at this point. The concave grating does possess a few disadvantages, the worst of these being astigmatism. But this can be effectively controlled either by means of properly designed slit illumination systems, or by employing the minimum astigmatism mountings, of which the "Technal" is an example. These reduce the stigmatic error to such a small figure that it becomes unimportant in the normal working ranges.

The "Technal" design has no inventor's name associated with it, but J. H. Dowell, of Adam Hilger, Ltd., has described the mounting and the Hilger interpretation of its design [2] which he credits to Cotton [3] and Richards.[4]

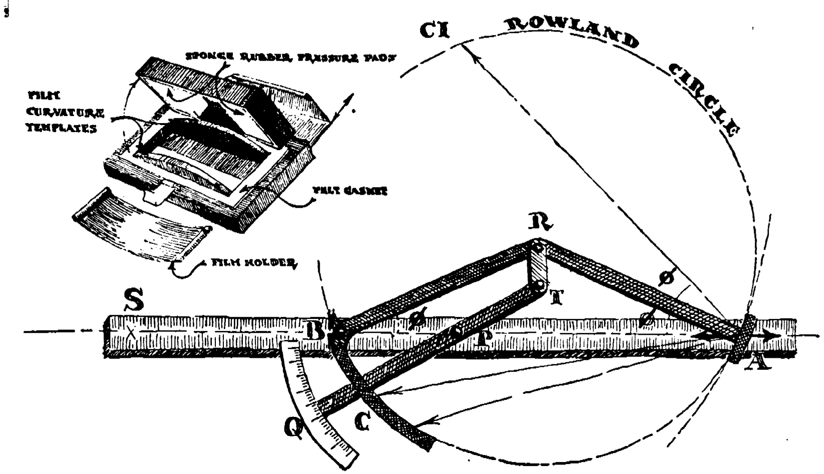
The mechanism involves only three levers of fixed length, a pivoting hinge, and a short track along which the grating moves under control of the lever system. The arrangement of parts is shown diagrammatically in the main sketch, the grating being at A, the slit at B, and the plate at C. The line BA represents the center line of the spectrograph bed and the levers BR and AR are in length one half the radius of curvature of the grating and have the grating and slit-plate elements rigidly fixed to their ends. Where they meet at R they are pinned together so as to articulate. A track which is parallel to the bed BA is placed under A, and is long enough to allow the grating element on the radius arm AR to travel along the bed BA in the direction of the double-ended arrow for a few inches.

It is evident, since BR and AR are radii of the Rowland circle of the grating, that by moving the joint R toward or away from the line of the bed AB, the range of wavelengths recorded on the plate C will change. Furthermore, the parts will always remain on the circumference of the Rowland circle and will therefore be in correct focal relation to each other at all times. If a light source is located at S on the line of the bed AB prolonged, the incoming light ray must always fall fully upon the grating at A no matter what wavelength range is being photographed. If R is moved away from the bed it will be found that the plate will record the longer wavelengths or higher orders of dispersion of the grating since the central image CI of the slit is on the opposite side of the radius arm AR at an angle 2ϕ with the bed. The angles ϕ are all equal, as is evident from the geometry of the mechanism. They usually have values ranging from 0 to perhaps 10 or 12 degrees.

The angles ϕ are varied by moving the joint R from outside the instrument

[2] Dowell, *J. Sci. Instruments* 17, 208 (1940)
[3] Cotton, *Comptes rendus* 186, 192 (1938)
[4] Richards, *Proc. Am. Philosophical Society* 51, 554–563 (1912)

by means of the lever QPT, which is pivoted on the bed of the instrument at P and connected with the joint R by a short toggle RT. The pivot is somewhat nearer T than Q in order to provide a small mechanical advantage and greater precision of motion of R. The outer end Q of the lever sweeps a scale upon which the wavelength ranges for each setting are marked. Not more than half a dozen standard settings need be marked upon the scale. They may be determined by experiment after the instrument is completed and in final adjustment. It is evident that, once adjusted, the entire optical system is completely controlled by the motion of the lever QPT and with complete assurance that all optical parts are properly oriented with respect to each other



for perfect focus. Indeed it is difficult to make them behave otherwise. It is this feature which makes the "Technal" design so superior for student use.

As for astigmatism: All images formed by a concave spherical surface suffer astigmatic distortion except that one image which falls exactly in line with the light source. Astigmatism increases slowly at first as one travels from this point in any direction in the focal plane, but increases rapidly beyond angular departures which are in excess of a very few degrees. Those lines nearest the slit will be most nearly stigmatic and those farther away will show increasing distortion. It is for this reason that the slit in the "Technal" mounting is placed as close to the ultraviolet end of the plate as possible. Since the far ultraviolet sensitivity of plates is always somewhat lower than that of the near ultraviolet and visible blue it is desirable that no light should be wasted in that region. Ideally, the slit should be placed in the very center of the plate, but this is difficult mechanically and would cause great inconvenience in operation.

The "Technal" arrangement has proved to be quite satisfactory, even without special precautions to stigmatize the optical system by means of auxiliary lenses or mirrors in front of the slit. Should increased stigmatism be necessary, however, the methods of Sirks [5] and Baly [6] may be employed.

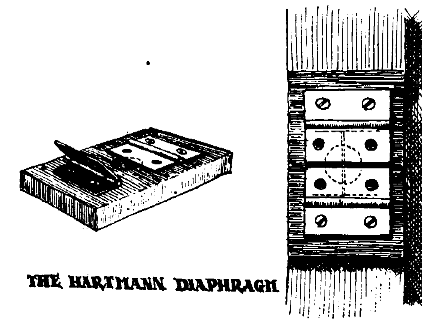
When the carbon arc is used as the light source it has been found that a quartz lens of 10 to 15 cm focal length focused to project an enlarged image of the gas column on the slit renders the incident light sufficiently parallel for a Hartmann diaphram or rotating logarithmic sector to be used in front of the slit.

For spectrochemical analyses of compounds containing iron or other elements of the transition group which have exceedingly complex spectra, two minimum specifications must be observed regarding the dimensions of the optical system of the spectrograph: (1) dispersion of at least 16 angstroms per mm and (2) sufficient resolving power to separate completely two lines of equal intensity not more than 0.4 angstroms apart. In grating instruments this requires a focal length of about one meter, 15,000 lines to the inch, and a ruled surface at least 30 mm wide. The Central Scientific Company, of Chicago, sells a Wallace replica grating having these minimum specifications for a little more than ten dollars (1939). These gratings are of fairly good quality initially but may be improved by changing the shape of the factory-made mask to be somewhat longer, thereby exposing more ruled surface and increasing the resolving power, and somewhat narrower, in order to compensate for the irregularities in the collodion replica. The precise shape of the mask must be determined by experiment. It is a long and exasperating job but eminently rewarding in the end.

Construction: The slit and the plateholder (inset sketch) are the most difficult parts of the instrument to construct and should be given double their share of careful planning and workmanship. A fixed slit of moderately narrow width is to be recommended. The plate must be curved to the circumference of a circle whose radius is one half the radius of curvature of the grating—the Rowland circle. It is more than one can expect of glass plates to bend to fit the circumference of a half-meter circle. The "plates" may be strips of 35-mm motion picture film if it is expected that only one or two samples will be run at a time; or 8 by 10-inch cut film sliced down the middle to the standard spectrographic size 4 by 10 if more extensive work is anticipated. On these 4 by 10-inch plates it is possible to record at least 16 well-separated spectra with their iron comparisons. The spectra need not be more than three millimeters high if no comparison spectra are juxtaposed, but should be half again as high with comparison spectra, so that about one millimeter of the end of each line can interfinger with the comparison lines. This simple expedient increases the accuracy of plate measurement, since lines of nearly the same wavelength are more easily classified as coincident or separate.

The astigmatism of gratings causes the ends of the spectral lines to be ragged in appearance, the brightest line being longest. In order to conserve plate space and trim up the spectra, it is necessary to build an extra slit just in front of the plate in its holder. This slit is at right angles to the principal slit of the instrument and is preferably constructed to have variable width. The slit's function is simply to limit the height of the lines and make their outer terminations sharp. A pair of brass-edged foot rulers is admirable for the purpose. They may be made adjustable by coupling the two at their ends in the manner of the navigator's parallel rule.

The light-tight housing around the optical parts of the instrument may be made of sheet metal or of plywood screwed to a light wooden frame. The housing should have a door or hatch in it near the grating end of the case so that the grating is accessible for adjustment whenever necessary. A simple flap shutter should be placed in front of the slit. The plateholder motion scale will be found to be more useful if it is graduated in metric units. The metric scale of a 6-inch celluloid pocket ruler, glued to the plateholder track, serves very well.



THE HARTMANN DIAPHRAGM

The design of the bellows between the light-tight housing and the articulating plateholder track presents something of a problem. Spectrograph bellows are usually of such an odd size and shape that they must be specially made. Bellows cloth costs about one dollar per yard. Bellows may be installed in the usual accordion pleat fashion built up of two layers of bellows cloth with cardboard stiffening pieces cemented between—rubber cement is recommended—or, since the span is always very short, simply cut to fit the gap and allowed to fold as it will without reinforcement inside. The latter is quite satisfactory for small instruments, the natural stiffness of the cloth itself being sufficient.

A rack and pinion control of the plateholder motion is a convenience which may be eliminated without impairing the efficiency or accuracy of the instrument.

The Hartmann diaphram has been mentioned. For accurate comparison of two samples this device is absolutely essential. It may be constructed quite simply by means of two small brass hinges screwed to a panel with a hole in it just before the slit. When both hinges are opened flat upon the panel their

[5] Sirks, *Astronomy and Astrophysics*, 13, 763 (1894).
[6] Baly, "Spectroscopy," Longmans, New York City, 1924, Vol. 1, pp. 165 ff.

leaves do not quite touch. Thus when two samples are exposed with one hinge open at a time, their spectra will overlap the same amount by which the hinges do not touch. The entire purpose of this arangement is to permit two spectra to be photographed side by side without mechanical motion of any part of the spectrograph between exposures. This assures perfect optical juxtaposition so that if two lines continue unbroken across both spectra one may be sure they have the same wavelength within the limits of error of the optical system.

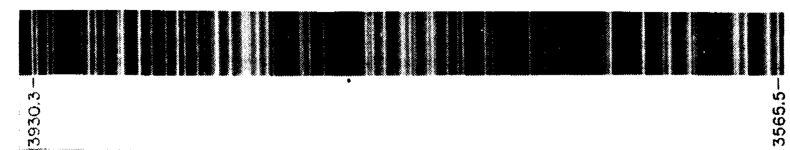
When the inner mechanism of the instrument is complete, the entire inside of the case and the parts enclosed should be painted dead black. Ordinary blackboard paint is suitable, for it contains enough varnish to stick equally well to metal and wood. Since the instrument is likely to be used in a dimly lighted room, the outside of the instrument is best painted a light gray so that it is more easily seen. It is convenient to mark the rulings on the plateholder motion scale with zinc silicate paint to which a trace of a uranium salt has been added. A dot of the same on the plateholder makes it easier to set the plateholder without turning on bright lights in the room. Should the phosphorescent paint be too dim for ready visibility a small argon night light may be used to excite the fluorescence temporarily.

Recommendations for Use of the Instrument: Since the purpose of the spectrograph is to check analyses made by the wet method it is suggested that the method of coincidences be used. This method employs the Hartmann diaphram by exposing the sample first, and then, after reversing the hinges, the element which is thought to be present. If the element is present in the sample the lines of the element will be continuous across both spectra. This procedure is very accurate and requires a minimum of physical and mathematical knowledge.

An alternative method may be desirable for making complete spectrochemical analyses. This method employs the iron comparison spectrum which is photographed, by means of the Hartmann diaphram, in registry with the spectrum of the unknown. This pair of spectra may then be compared with a series of negatives of single elements, each of which has an iron comparison spectrum in registry beneath it. Since the iron spectrum is common to all, it is possible to perform an analysis by superimposing the spectra of the elements upon the spectrum of the unknown in such a way that the iron spectra on each coincide. Once registry is established the lines of the element will coincide with those in the unknown if the element is present in the unknown.

For advanced students, it may be desirable to perform the analysis by measuring the wavelengths of the lines in the spectrum of the unknown by interpolation from the iron comparison spectrum, and looking up the elements in a set of reliable wavelength tables such as Kayser's, the "Handbook of Chemistry and Physics," or M.I.T. tables. This is a time-consuming process even for an experienced spectrographer, hence the sample should contain only the simplest components to begin with, such as a feldspar (Na, Ca, Al-silicate) or a mixture of alkali salts.

It is a common misapprehension that the spectrographic test is the ultimate in sensitivity for all the elements. In order to acquaint the student with the variable sensitivity of spectrochemical tests in different portions of the periodic table it is instructive to let him take spectra of several elements throughout the periodic table. Tests for the alkali metals are exceedingly sensitive; for the transition elements fairly sensitive; and for the amphoteric elements rather insensitive. The electronegative elements can be recorded only under special circumstances in the carbon arc. Fluorine, for example, can be recorded only when calcium is present in fair abundance, at which time it will yield a fairly strong CaF band head in the near ultraviolet. The noble gases, of course, yield emission spectra only when excited in high voltage discharge tubes under reduced pressure. Despite these limitations, the spectrograph will detect satisfactorily more than two thirds of the elements in the periodic table.



A short segment of the iron spark spectrum made with the Technal spectograph, enlarged from about one tenth of the original ten-inch-long negative which covers the visible and near ultraviolet wavelengths.

[Editor's Note: Owen Gingerich, of Goshen, Indiana, who began making telescopes at the age of 15, later majored in chemistry at Goshen College and there discovered a debilitated home-made spectrograph that had been made and left behind by an earlier student. He dusted it off and, under the auspices of the science department of the college, undertook its rehabilitation. The little problems he faced were much the same as those that any tyro spectrograph maker would encounter, hence he was invited to record here some of the practical solutions he reached before he came to know any more about spectrographs and thus lost the tyro point of view.]

Notes on a Spectrograph

By Owen Gingerich

The Paschen-Runge mounting, which is today one of the most poular grating arrangements, is based on the Rowland circle. In this plan the slit, concave grating, and the film are all placed on a circle whose diameter is equal to the radius of curvature of the grating. To change the range photographed only the plateholder need be moved. When ordering replica gratings the focal length listed is the conjugate focal length, and is identical to the radius of curvature of the grating.

The instrument described here was constructed by an amateur in the late '30s. Unfortunately, it was built of wood, and changes in humidity, also shocks, disturb its best operation. The need for rigidity must be stressed as rigorously when building spectrograph mountings as in telescope mountings. It is a source of annoyance to find only six strips of spectrogram across a film instead of the nine photographed, because the grating has shifted.

A series of equally spaced bolts are set radially outward from in the top and bottom of the frame along the circumference of the Rowland circle between the slit and the slit image. Curved metal sections 6 inches high and of differing lengths, with corresponding holes, are bolted around the side where the spectra fall. It is a simple matter to remove any desired section and rearrange the others to make room for the plate in any region of the spectrum. In practice only two regions are used: the first order, from 24 to 14 inches to the left of the normal, and a part of the second order, from 14 to 4 inches to the left of the normal. The latter section covers the region from 3500 to 5500A.

The plateholder itself provides place for a 10-inch section of 35 mm film. The film is laid in place from the back of the spectrograph, through a light-proof door—10 inches of door open up and the film is laid in. A long black shutter is provided directly in front of the film, running in two grooves. It may be removed lengthwise through a slot after the holder has been bolted in place. In front of the focal plane shutter is a metal stop, with an opening about 3 mm wide running lengthwise. The stop may be racked up and down before the film by a control on the plateholder outside. Although this has caused no difficulty in qualitative work, provision should be made so that the film itself may be racked up and down instead, permitting the same section of grating to be used for each exposure. Otherwise the upper and lower strips across the film will be dimmer than the central strips.

Before any attempts are made to obtain accurate alinement in a spectrograph the slit width should be adjusted. For this and succeeding adjustments a source having many well-distributed lines is needed, preferably an iron arc. A Ramsden 1-inch or ½-inch eyepiece may be used to determine the condition of the lines at the focal plane. The slit should be closed to give the finest sharp line possible.

The grating must then be made normal. When the Rowland circle is laid out, the line half way between the slit and the slit image should be accurately marked. A slit or pinhole source of light should be placed on the line at the circumference, and the grating turned on its vertical axis until the image coincides with the source.

Next, the grating must be turned clockwise or counterclockwise on its normal axis until the strip of spectra is horizontal from one end to the other. The grating can then be tilted on its horizontal axis until the strip of spectra has the desired height. However, the slit and rulings must be exactly parallel, otherwise astigmatism will result. In turning the grating, the slit and rulings may not agree, so the slit must now be turned. The easiest way to check this alinement is again with the Ramsden eyepiece. If the slit is at a slight angle, the lines will be wider and may present a stairway effect at the ends.

The final adjustment is the most sensitive, that of focus. Here the familiar

knife-edge test is used. The knife-edge is fixed on the focal plane, and one of the lines is used as the source. If the shadows move in from the left, the slit is of course moved inward. It is well to test several times at separated points along the circumference of the Rowland circle.

Further adjustments may be made after photographs have been secured.

Photography: Since the replica grating rather than the film is the limiting factor, the amateur will not need to secure special spectrographic film or developer. It is, however, necessary for the film to be panchromatic and have a reasonably constant color sensitivity for the range used. Kodak Plus X is a satisfactory film from every standpoint. Microfilm was tried experimentally because of its high resolving power, but was found to be too slow.

With a 105 cm replica and arc source the exposure time is around seven seconds. This of course varied under different operating conditions. Fraunhofer line spectra required 40 seconds but three half-silvered mirrors were used to place the image. Photographs of discharge tubes require several hours.

Once the film has been exposed, speed in processing it is the motto. Although D-72 developer has been recommended, D-11 works faster and produces satisfactory results. The D-11 is made especially for high contrast line films, in which no intermediate shading is required. Five minutes are required to develop the film in D-11. Next the film is placed in a short-stop solution, which is primarily water made slightly acidic with acetic acid. After one half minute the film is transferred to a solution of hypo. Materials for both the short-stop solution and hypo can be obtained at any photo supply store. Needless to say, this complete process must take place in total darkness. After the film has been agitated in the hypo for 5 to 10 minutes, it may be taken to a light place and examined. If the film is to be kept for reference, it should be washed in water for 30 minutes.

Special problem of photography: In order to obtain reliable results on unknowns, the region about the arc and spectrograph must be kept spotlessly clean. A little calcium metal dropped near our arc left persistent lines of that element on films for several weeks. Much confusion will be saved if accurate records are kept of the position of the elements or unknowns on a film. If several films are being processed simultaneously, the films should be marked with punches along its perforations.

For electrodes, sticks of spectrographic carbon may be obtained from science supply houses. Ordinary carbon electrodes should be avoided since most of these are deliberately stuffed with impurities to make them bright. The electrodes should be $\frac{3}{16}$ or ¼-inch in diameter. A ⅛-inch hole is scraped in one end to hold the material.

An iron spectrum is usually placed across the film in several places, to be used as a reference spectrum. Excellent photographs of the iron spectrum, together with tables of lines of other elements, may be found in "Chemical Spectroscopy" by Wallace Brode (John Wiley and Sons, New York).

The arc itself may be built in many ways. It should provide clamps for iron or carbon electrodes, so that the gap is about ¼-inch. This gap should be adjustable during operation, and provision must be made to strike the arc. Direct current of 80 to 140 volts at 2 to 4 amperes must be provided, with a heavy rheostat in the line.

Metal chunks placed in the arc will often glow after a few seconds of current. This will give rise to continuous spectra, which will fog the background unless the center of the arc is focused very carefully on the slit.

Some metals are difficult to obtain because of their low melting points. Tin, bismuth and phosphorus are particularly guilty. Pure sodium and potassium, on the other hand, cause no special trouble.

In photographing compounds, usually only one element shows. In chlorides (or other halides) the chlorine vaporizes and the metal spectrum remains. But in many compounds such as oxides the molecule does not disintegrate but gives rise to a molecular or band spectrum. This occurs in the carbon or graphite arcs when the C_2 molecule is formed, making a band spectrum. This is why the carbon electrodes are usually photographed pure before the unknown is added.

Identification of unknowns may be vastly simplified by preparing master films of 15 of the most common elements. By holding the film against the masters one after another, it is possible to identify several elements in a few minutes. Thus from arc to report only 30 to 40 minutes will have elapsed.

Slit for Spectroscopes or Other Optical Instruments *

By John Strong

Many types of slits have been used for optical instruments. (See H. Kayser, "Handbuch der Spektroscopie," Vol. 1, p. 532). Among them one bilateral slit which we may term the parallelogram slit, and which is diagrammatically illustrated in Figure 1, left, *a*, has several noteworthy features. When it is skillfully constructed this slit is both simple and effective. The opening of the parallelogram slit exhibits an adverse non-uniform relationship to the amount of turn of the adjusting screw: The slit opening changes most rapidly when the slit is nearly closed whereas we would prefer to have a more delicate control, that the slit opening change slowly when the slit is nearly closed and rapidly when it is nearly open. Figure 1, left, *b*, represents diagrammatically the principle of the parallelogram slit adapted to achieve this desired end and Figure 1, right, illustrates how we apply this principle in practice.

Figure 1, right, is a sketch by Mr. R. W. Porter drawn from one of the slits of a new spectrometer under construction here. The cover plate, with the slot for illuminating the slit, is shown turned to one side. This plate is secured by screws in the four corners while the slit as a whole is fastened to the spectrometer by four other screws, two on the right side and two on the left.

* From *Review of Scientific Instruments*, Volume 12, p. 213, by permission.

The micrometer screw displaces the slit jaw assemblies equally in a direction parallel to the slit and, by virtue of their 0.006-inch clock-spring mountings, this displacement causes the slit jaw assemblies to separate and the slit to open. Two helical springs locate the jaw assemblies definitely against the hardened end of the micrometer screw. The carefully worked slit jaws are adjustably fastened to the jaw assemblies so that the jaws will close exactly.

The advantages of this type of slit over other types are: that the jaws cannot possibly be jammed; that the slit opening is delicately controllable when the slit is narrow; and the spring mounting, as contrasted with mounting in ways, provides a definitely reproducible mechanical system. Disadvantages are: the non-uniform relation between micrometer screw setting and slit opening and certain limitations on compactness of construction. The slit is relatively easy to construct in such a manner as to yield high accuracy.

The slit opening is given approximately by the expression $S = 2L$ [1—cos (M/L)] where L is the free length of the clock springs and M is the displacement of the micrometer screw from the closed position. For the slits already constructed $L = 1$ cm and $M = 3$mm, giving S approximately 1 mm. The slit jaws are 24 mm long while the useful length of slit is 12 mm. The over-all dimensions of the slit exclusive of the micrometer head are 3½ by 3 by ¾ inches.

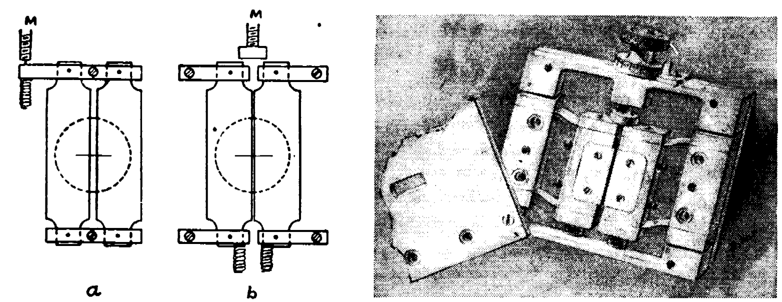


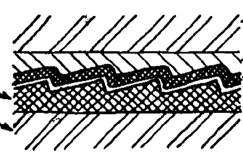
Figure 1
Drawings courtesy *The Review of Scientific Instruments*

[Editor's Note: After the preceding description was published in the *Review of Scientific Instruments* (New York) Strong discovered that a slit "substantially the same" had been described a decade before in the *Journal of Scientific Instruments* (London) 10,376–377, 1933, by J. E. Sears of the National Physical Laboratory (Britain's bureau of standards) and hastened to acknowledge the priority (*Review of Scientific Instruments,* 13,370). Strong writes, "No plagiarism was involved, as the journal in which Sears published was not then available to me. Please credit Sears abundantly. The slit is a little hard to build but a fine one to use."]

[Editor's Note: In 1953, as this book goes to press, it is easy to buy replica gratings, difficult to obtain originals. Replicas may be had from Laboratory Specialties Inc., Wabash, Ind., Gaertner Scientific Corp., 1201 Wrightwood Ave., Chicago, Ill., W. M. Welch Mfg. Co., 1515 Sedgwick St., Chicago, Ill., Central Scientific Co., 1700 Irving Park Road, Chicago 13, Ill, and probably others.

Many of these replicas are made by basic methods or private variations on them described by Robert James Wallace in *The Astrophysical Journal,* Vol. 22 (1905) p. 123. There he said that T. Thorp of England in 1900 was the first to describe a presentable replica of considerable efficiency. Over the original grating he flowed a film of high-grade oil and then a celluloid solution which he left to dry. He then peeled off the thin tough film and mounted it face up on glass with gelatin and glycerin, lowering the film gently and gradually into contact. On the same page Wallace describes his own method. He flowed especially prepared collodion over the grating, allowed it to dry, stripped off the resulting film and mounted it on gelatin-coated glass. In the same journal, Vol. 31 (1910) pp. 171–4, J. A. Anderson describes another method.

Most of the replicas made by the collodion method are mounted flat, hence a condensing lens must be included in the optical train to focus the beam. Since much of the interest of the spectrographer is in the ultraviolet, and since a glass condensing lens is opaque in that range, the condensing lens must be crystal quartz and a quartz lens is costly.



In 1935 the Perkin-Elmer Corporation, Norwalk, Conn., developed a high-grade (and correspondingly expensive—about $95 in 1950) concave replica of 1 meter radius of curvature, not blazed, with ruled area 2 by 2½ inches, 15,000 lines an inch. These are made as shown in Roger Hayward's drawing. At the bottom is a glass support ½ by 3¾ inches, and on it is the aluminum film in which the original grating was ruled. The grating is greased and given an evaporated aluminum film. A liquid plastic fill of Laminac is then added. The supporting mirror is placed on this and the plastic is polymerized by heat. The replica unit is then parted from the original grating at the level of the grease.

There is sometimes confusion about fl of a concave grating. If uncertain, draw a circle (which will be Rowland circle of some types of mounting), inscribe a diameter (which will be a tie rod). Place grating at one end of rod, photographic plate at other. Using rod as hypotenuse, inscribe right angle triangles representing various spectral positions. Place slit at angle opposite hypotenuse. Set-up now corresponds to k-e test: slit = pinhole, grating = mirror, plate = eye. Confusion sometimes follows from too simple assumption that curve of grating fits Rowland circle, whereas its circle has double that circle's radius, and grating is tangent to it, not coincident. Thus a grating with 1 meter rc has 1 meter fl.

A trick way to stretch a short-focus concave grating and multiply dispersion, provided the grating is blazed (grooves so shaped in cross-section that the light reflected from them coincides with the diffracted light, the effect being to concentrate much of the light in one part of one order) is to set two flats in a V, or a 90° prism, on the Rowland circle so that they reflect a part of the spectrum back to the grating, which then sends this part to the plate. Thus the grating has been used to disperse the light twice and is said to be double-passed. By adding more V mirror pairs you can do it again and again so long as there's enough light, getting spectra equivalent to very high orders as regards dispersion, resolution also. It is the principle of the Littrow spectroscope, where a prism is used and a single mirror returns the light through the prism. The method was coming into considerable use after about 1950 and has been described by Jenkins and Alvarez in the *Journal of the Optical Society of America,* 1952, Oct., 699–705, and in a subsequent paper by Fastie and Sinton.

Postwar, the building of a special type of industrial spectrograph, the direct-reading spectrometer, has become such big business that the informed amateur should know what goes on even though he may never build one. Dieke, Crosswhite, and others saw by 1945 that means were available for obtaining quantitative analyses of metals and biological products during the actual stages of production more quickly than by making spectrograms photographically and determining the density of the lines, not to speak of wet analysis, still slower. Suppose you are making alloy steels and it is important to know the composition of the molten metal mixture before you pour it, to be sure the alloying ingredients are in correct proportion. Your men at the furnace take samples, mold them into electrodes, plop them into a pneumatic tube and in seconds they are in the adjacent laboratory being burned in the arc of a direct-reading spectrometer. Fixed along the Rowland circle at the positions of the element lines of a dozen or score of elements in the melt are electronic photomultiplier tubes that convert light into electricity. The respective currents are amplified and actuate indicators that read directly in percentages of each metal. It does not require a physicist or chemist to read a recorder and flash the percentages to the furnace operators. Within 3 to 6 minutes these workers know the analysis and can decide, before the melt has passed the critical temperature, which alloying materials to add and how much. This goes on routinely in hundreds of plants that manufacture a wide variety of products. A spectrometer for this kind of work is as large as a grand piano and, with the accessory apparatus, recorder, etc., will fill a room and cost tens of thousands of dollars. Even so, the gratings needed are small. For example, those ruled by Applied Research Laboratories, Glendale, Calif., which operates four ruling engines, are 1 by 2 inches or 1¼ by 2½ inches, with 24,400 to 36,600 grooves to the inch and are concave with 1½ or 2 meters fl. The Baird Associates, Cambridge, Mass., the Bausch & Lomb Optical Co., Rochester, N. Y., the

Jarrell-Ash Co., Boston, Mass., the Gaertner Scientific Co., Chicago, and probably others manufacture these specialized industrial electrometers.

F. Twyman, "Metal Spectroscopy," Charles Griffin and Co., Ltd., 42 Drury Lane WC 2, London, 1951, contains data on industrial spectroscopy.

The construction of a Wadsworth-mounted grating spectrograph with 6-inch 14,400-line Johns Hopkins grating of 22-foot radius of curvature was briefly outlined by R. L. Purbrick of Willamette University, Salem, Oregon, in the *American Journal of Physics* (57 E. 55th St., New York 22) 1953 April, pp. 241–243.

In 1953, as this book went to press, it had been difficult to obtain an original grating except as a part of an entire spectrograph costing thousands of dollars, mainly because the manufacturers of spectrographs, mainly the industrial type, were absorbing the whole production. Asked whether this would be a permanent policy one manufacturer of industrial spectrographs and of the gratings used in them replied that it should not be long before sufficient gratings will be ruled to supply all those who desire them. There is no "conspiracy" to deprive amateurs of gratings, nor will the spectrograph manufacturers lie awake many nights over amateur "competition."

The peculiar nature of the problem of ruling original gratings was described at length in *Scientific American,* 1952 June, pp. 45–54 and 90–95, also in July pp. 84–87 and in August pp. 77–79.]

A Null Test for Paraboloids

By H. E. Dall *

The Foucault or Ronchi test applied at the center of curvature is probably still the most commonly used method of testing paraboloids for astronomical mirrors. That this is so is more due to the convenience and simplicity of the set-up than to the ease of interpretation of the results. While no particular difficulty of interpretation of zonal measurement of the parabolic shadows is experienced for mirrors of aperture ratio $f/8$ upward, the test becomes increasingly difficult for short focus mirrors from $f/7$ to $f/3$. Zonal errors of appreciable magnitude may remain undetected, and in particular the outer zones are frequently found to be faulty even though the knife-edge shift r^2/R between the center and outer zone is correct. It is just these outer zones which contribute so greatly to the formation of the final image, and if a short focus mirror is to equal in performance its longer focus counterpart, it is essential that the grading of curvature in these zones be correct to a close tolerance. Hence the need, felt even by the most experienced mirror maker, for changing to a null method of testing.

Where equipment is available this need is fulfilled by the well-known autocollimation null test utilizing a large flat mirror and a smaller flat or prism for deflecting the beam to a convenient viewpoint. A large silvered flat of high quality is not always available and, even if it is, the test rig is sensitive to careful squaring on, thus that test cannot be compared in simplicity with a test made at the center of curvature.

The method shown diagrammatically in Figure 1 is carried out near the center of curvature with a simple rig consisting of a plano-convex lens spaced apart from an illuminated pinhole, the light from which is made approximately monochromatic with a red filter. The spacing of these is best done with a piece of tube which in use is directed to the mirror. The knife-edge is applied in the ordinary way to the pinhole image which should be located as close as possible to the center of curvature of the mirror. The aberration of the lens is opposite in sign to, and of the same character (within limits) as the aberration (r^2/R) of a paraboloidal mirror with the pinhole near the center of curvature, hence they can be made to nullify as in this test.

The principal requirement in applying the test is to space the lens correctly from the pinhole at a distance appropriate to the lens in use, and the data to enable this to be done are given with sufficient simplicity for the less mathematically minded to follow. A perfectly regular paraboloid will give a null test, i.e., will darken uniformly over the entire disk as the knife-edge cuts across the pinhole image at focus. Defective zones show up clearly and are identified with the same certainty and precision as in the case of a spherical mirror tested at the center of curvature in the normal manner.

---

* From *The Journal of the British Astronomical Association,* Vol. 57, No. 5, 1947 November, by permission. Revised 1952 December by the author.

The only addition to the normal Foucault testing equipment required by the new test is a red filter and a plano-convex lens and holder. The filter is required owing to the dispersion of the simple plano-convex lens. The latter, being of crown glass, has a very low dispersion at the red end of the spectrum, hence a simple red gelatin filter of the type "Tricolor Red" is highly economic of visual light while being sufficiently monochromatic for the purpose, and is sold in most photographic stores. Ruby glass will also serve but will pass barely 10 percent of the visual light compared with some 30 percent of the Tricolor Red. Colored glass, gelatine or cellophane film of the bright red type will generally function quite well. A small piece of the filter material is placed in the lamp, preferably between lamp and pinhole. The writer has used a monochromator giving one percent spectral purity, but finds no appreciable gain in sensitivity compared with the simple red filter when used

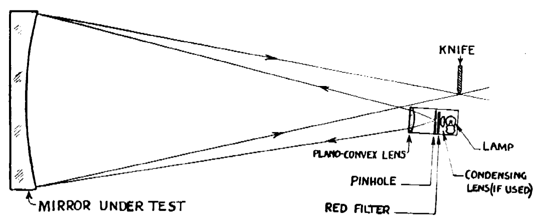


FIGURE 1

with lenses up to 12-inch focal length. Lenses of longer focus than this would be required for only the largest sizes of mirrors outside the usual amateur's range, and these would perhaps need and warrant a higher degree of monochromatism. The plano-convex lens is used with its plane side toward the mirror under test. This is the direction of maximum aberration for which the data given are calculated.

It is necessary for the optical axis of the lens to be alined within a degree or two of the center of the mirror. Sighting along the tube of the holder will generally insure this. Serious errors of alinement or centering will result in astigmatic effects in which the knife-edge shadow fails to advance parallel to the knife-edge movement. A similar type of error also results from too great a lateral separation between pinhole and knife-edge. This should be arranged if possible not to exceed two percent of the focal length of the mirror, and the use of small diameter housings for spotlight torch (flashlight) type bulbs is strongly recommended for all mirror testing. Alternatively, use can be made of prisms or beam splitters to reduce the separation.

All types of optical testing are facilitated by the use of brilliantly illuminated pinholes, perhaps more so with the null test, owing to the losses in the red filter. The use of a short focus condensing lens inside the pinhole is recommended, although not essential; moreover a short vertical slit may be

used instead of a pinhole, although the writer has preference for the latter. If a slit is employed its length should not be greater than 0.03 inch. The pinhole diameter or slit width recommended is from 0.001 inch to 0.002 inch, the smaller size for preference.

The plano-convex compensator lens should have a focal length between 1/5 and 1/20 of that of the mirror being tested. This is a long range to choose from, and many amateurs will find a suitable one in their stock of lenses. If the mirror is of wide angle from $f/4$ to $f/6$, preference should be given to lenses at the longer focus end of the range, say with foci half the mirror

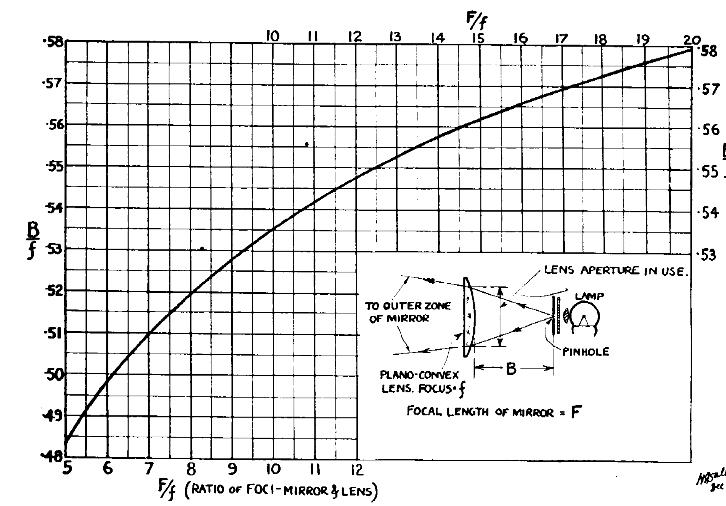


FIGURE 2

diameter. The field lens of a low-power Huygenian microscope eyepiece will often supply the need for mirrors up to 10 inches. To take an example, if a 12-inch diameter 60-inch focus ($f/5$) paraboloid is to be tested, a 6-inch focus lens would be quite suitable. For this lens F/f would be $60/6 = 10$. (The precise focus f should be measured as closely as possible, remembering that this is the distance from the vertex of the lens curved surface to the screen when the image of a distant object is formed on that side. Allowance should be made for the considerable aberration by stopping the lens down to, say $f/10$ or, if used without a stop, by measuring the maximum distance at which a sharp image can just be recognized inside the aberrational halo.)

Next refer to the curve, Figure 2, to find the ratio of the pinhole-lens separation B to the focal length f of the lens. This is shown plotted against the ratio of the foci of mirror and lens. In the example quoted the latter ratio is 10. Hence from the curve the B/f ratio is found to be 0.535. The distance B is thus $0.535f = 3.21$ inches. The utilized aperture of the lens is a little more than B divided by the f number of the mirror; in this example approximately 0.72 inch, and the lens should thus not be less than ¾ inch diameter. It can be larger without affecting the test. The curve is calculated for the range of focal ratios and lens foci mentioned, which is a region in which the higher order aberrations are small or negligible. The curves were obtained by rigorous ray tracing for a glass of refractive index 1.52 and a reasonable lens thickness. Departures of normal crown glass from this assumed value will not seriously affect the result. The lens chosen is fitted in a holder, which is preferably a tubular extension from the test lamp, and carefully measured to give the required separation between vertex of curved surface of the lens and the pinhole. The test rig is then ready for use and, upon adjusting its axial position so that the pinhole image comes as close as possible to the center of curvature of the mirror (distance R from the mirror), a null test should be obtained with the knife-edge if the mirror is perfect.

A few further examples are given in Table 1, some of which may fit individual requirements and obviate the necessity for further calculation for those less practiced with slide rule or logs.

If the mirror is regular but overcorrected, it will appear to have the usual paraboloidal shadings though less deep than if no compensating lens is used. A regular undercorrected mirror will appear with the shadings characteristic of an oblate figure tested by standard methods. Zones which depart from the paraboloid will show up clearly as shaded rings, and can be interpreted for further action in the usual way.

TABLE 1

Mirror aperture D	f-number of Mirror	Suitable focus of lens $= f$	Distance B	Minimum diameter of lens
6″	f/5	3.0″	1.605″	.4″
6″	f/6	3.0″	1.64″	.4″
8″	f/4	4.0″	2.075″	.65″
8″	f/5	4.0″	2.14″	.5″
8″	f/6	4.0″	2.19″	.5″
10″	f/6	5.0″	2.74″	.6″
12″	f/4	6.0″	3.115″	1.0″
12″	f/6	6.0″	3.28″	.7″
18″	f/5	10.0″	5.28″	1.2″

[EDITOR'S NOTE: The following is from a later personal communication from Dall: "George Hole, a British Astronomical Association member whose profession is telescope making, has just finished a 24-inch $f/5$ mirror for his own use. Being well equipped he was able to test the mirror both by autocollimation and by null test. He found such good agreement that all main figuring was done by null test, it being so greatly simpler than the other. Despite a warning that higher order aberrations should begin to affect the nullity at $f/5$ on a 24-inch with the lens used for testing, he said the tests by the two methods were indistinguishable."]

THERMAL EFFECTS OF OBSERVATORY PAINTS *

By H. E. DALL

Little information appears to exist on the subject of the most suitable surface treatment of observatories for the purpose of reducing undesirable thermal effects. From general considerations it seemed that the choice was practically limited to two paints, white and aluminum, but it appeared to be worth while to carry out some simple tests to determine which of the two was the better. The results of these tests proved to be quite interesting, and were in fact somewhat surprising to me until the reasons were studied more closely.

Two stout cardboard boxes of identical size were used for the first test. Both were ventilated to a small extent and comparable with an observatory. Box A was painted with aluminum paint and box W with white-lead paint. These were placed on pedestals in exposed positions in the open air, and a yard or so apart. Each contained an identical maximum and minimum thermometer, and readings were taken daily over a period of some eight weeks, commencing in late spring. Occasionally the thermometers were interchanged to eliminate systematic errors. In addition, two large metal boxes were coated with the same high-grade paint and similar tests made with and without ventilation.

The character of all the tests was identical—showing conclusively that the aluminum-painted boxes maintained a higher temperature *both by night and by day* than the white boxes.[1] Table 1 shows a typical series of readings, including notes on the weather. As was expected, the greatest difference between A and W occurred on days and nights with least cloud and least wind. Strong winds, even with clear skies, result in convection effects swamping those of radiation, and both boxes attain closely atmospheric temperature.

The difference is quite sufficient in amount to justify the tests and to warrant careful consideration as to the most suitable paint for the purpose in view. If the observatory is to be used primarily *for solar or other daylight observations, the benefit of white paint will be most marked,* and convection-current troubles will be reduced to a minimum. If, on the other hand, night observations are principally intended, then aluminum paint is far superior to white. All temperature gradients within the observatory will be lessened;

* From *The Journal of the British Astronomical Association,* 48 (1938) by permission.

[1] For the results of other experiments on the effects of paint in sunshine, see letters by H. R. Beckett and H. Spencer Jones, *The Observatory* (Oxford), 1936, 59, 14 and 17

TABLE 1—*TYPICAL TEMPERATURE READINGS (° F.) IN BOXES W AND A*

Date	White (W)		Aluminium (A)		Remarks Weather and State of Boxes at 11 P.M.
	Max.	Min.	Max.	Min.	
17/6	63	40	69	42	Mixed weather. (A) quite dry. (W) heavily dewed.
20/6	69	44	75	47	Mixed, showery. Both wet after shower.
27/6	79	47	82	47	Metal boxes. Cloudy night. Fitful sunshine. Both dry.
23/6	72	44	76	47	Metal boxes. Clear—cool winds. (A) quite dry. (W) heavily dewed.
30/6	65	38	66	39	Clear at night, but dry. Cold and very windy. Both dry.
21/6	74	36	79	41	Fairly clear day and night. (A) dry. (W) wet.
7 days from 8/8	84	51	92	56	Variable week—clear on several days. (A) dry. (W) twice wet.

performance should be quite noticeably improved. Dewing of the optical surfaces will probably be eliminated and external dewing much reduced.

My first impression before the tests was that white paint, having a visibly higher reflection coefficient than aluminum paint, would be cooler by day and warmer by night. This reasoning was fallacious, because it ignored the large variation of reflectivity and emissivity with the wavelengths of the radiation.

The temperature attained by an object in an exposed position is that at which equilibrium is reached between the heat lost and the heat received.

Apart from the effects of conduction and convection, the heat radiated from the object depends on the emissivity of its surface at the particular wavelengths corresponding to its temperature. Similarly the heat received depends on the absorptive power at the wavelengths of the arriving radiations.

The emissivity of white paint at the wavelengths corresponding to atmospheric temperature is indistinguishable from that of black paint, i.e. *approximately 95 percent (reflective power = 5 percent).* A good grade of leafed aluminum paint has the relatively low emissivity of 45–50 percent under similar conditions.

The absorptive powers of the two paints for radiations from the high temperature sources of daylight are approximately 15 percent and 30 percent respectively. It is thus easy to see why the *A* box becomes higher in temperature than the *W* box when exposed to solar radiation. At night, *if the sky is clear,* the effective temperature of the sky will be considerably lower than that of the exposed object, therefore if it is coated with the highly emissive white paint it will attain a lower equalizing temperature than the slowly emitting aluminum-painted object. Metallic aluminum emits considerably more slowly still, and should in consequence be even warmer.

Condensation occurs on the object if its temperature falls below the dew-point, and, as the falling gradient of air temperature at night often results in its being saturated, the white-painted object falling *below* air temperature becomes wet with dew, while the aluminum-painted object remains dry. The notes in the table indicate that this condition was observed frequently, and would imply that the surface of box *A* did not fall appreciably below atmospheric temperature. From the point of view of reduced convection currents this is very advantageous for an observatory used at night. If the surface is hygroscopic (and this appeared to be the case with the white-painted surface) there is the further objection to the formation of dew that additional heat is abstracted by subsequent evaporation, and the danger of dew on the optical surfaces is increased.

Aluminum paint should, for best results, be mixed just prior to use, as true "leafing" or interlacing of the scale-like powder does not occur more than 48 hours after mixing, and emissivity would increase due to the greater thickness of medium above the metal.

Interior painting: Radiation escaping from the aperture in the dome is practically black-body radiation corresponding to inside wall temperature, even if the emissivity of the walls is as low as 50 percent. Similarly the color of the interior walls has practically no effect when sky or solar radiation enters the aperture. The interior walls may therefore be painted without regard to thermal effects. An observer highly sensitive to feeble extraneous light would prefer a black interior, but otherwise a light color would be preferable to assist illumination. It is, however, desirable to coat with white paint any part of the instrument subject to direct solar rays through the aperture, or, if night observation is more important, with aluminum paint.

Optical Flats

By R. E. English
E & W Optical Company *

The methods employed in grinding, polishing, and correcting an optical flat are very much the same as those followed in making any fine optical surface.

The material for the flat should be selected for its stability, with as low an average coefficient of linear expansion as possible. P. K. Devers, General Electric Co., in the *Magazine of Light*, June 1943, gives us the following values of this property:

Clear fused quartz	5.5×10^{-7}
Corning Vycor Brand glass	7.5×10^{-7}
Crystal quartz (axis I)	169×10^{-7}
Crystal quartz (axis II)	96×10^{-7}
Pyrex	33×10^{-7}
Corning lead glass No. 001	90×10^{-7}
Corning lime glass No. 008	92×10^{-7}

From the above table it is evident that only one other material even approaches the quality of clear fused quartz. I have made some telescope diagonals from the Corning Works' Vycor Brand glass, which seemed nearly as constant in size and shape as fused quartz.

The following is a list of minimum thickness of material used in making flats: 2 inches diameter, ⅝ inch thick; 3 inches diameter, ¾ inch thick; 4 inches diameter, ⅞ inch thick; 5 inches diameter, 1 inch thick; 6 inches or larger, ⅕ diameter.

The grinding, edging and polishing of the back surface are too familiar to need description here. All these operations should be completed before attempting to correct the true surface so that none of the surfaces need be disturbed after the flat is corrected. A good series of abrasives should be used. Numbers 80, 120, 220 Carbo, 400 and 900 emery, make a good series. If the blanks are nearly flat some of the coarser grades may be eliminated. The Carborundum Company's No. 50 Aloxite Optical Finishing Powder is a very good abrasive for the final grind.

The true surface may be ground nearly flat with two other disks by the familiar 1–2–3 method. This will produce a finer grind in the centers than at the edges and will usually slightly turn down the edge. A better grind may be produced on a cast-iron tool grooved so that it is covered with facets about 1 inch square. The grooves will prevent the coarser grains from being

* Minneapolis 14, Minnesota

pushed to the outside edge of the tool. They will stay in the center of the tool and break down into finer grains, producing a very fine grind. The cast-iron grinding tool should be about 1½ times the diameter of the work upon it.

By grinding off center the correct distance the tool can be kept flat. With the proper adjustments the tool will wear down evenly all over and stay flat. If the work tends to finish concave it should be moved nearer the center or ground with a shorter stroke. A convex disk should be ground with a longer stroke or farther off center. A little experimenting will determine the correct stroke and position and only slight further adjustments will be necessary. After a few minutes of polishing the surface can be tested to determine whether it is near enough to be easily corrected.

The process of correcting the flat can begin at the start of the polishing. I use a Hindle-type polishing machine. For small work up to 8 inches in diameter the lap revolves at 5 rpm and the stroke is 50 per minute.

I have never been able to make flats smaller than 3 inches in diameter without having them rock and turn down the edge. To avoid this they are cemented into a ring 5 inches in diameter and 1 inch thick. This ring may be glass, Pyrex, granite, or perhaps some other material. It is perforated at the center with a hole about one eighth inch larger than the disk that it is to hold. Care is exercised to avoid any pressure on the flat when it is being worked. It is first coated on the back with soft pitch and then placed face downward on a surface plate. The ring is then placed around it and the space between the ring and the blank is packed with a strand of candle wick. The hole is then filled in with dental plaster.

When the plaster has set, the ring is taken off the surface plate and the space between the ring and the blank is filled with melted beeswax. The wax is slightly undercut to prevent any wax from rubbing off on the lap when polishing. The assembly is then ground and polished in the same manner as a 5-inch disk.

For the polishing and correcting I use only two laps. One, the same size as the work, is used for correcting a convex flat and one, slightly larger, is used for a concave disk. I have never been able to use a lap having an irregular pattern nor one having channels of varying width without producing a rough surface. Any surface can be corrected with laps having regular facets and uniform, well trimmed channels except astigmatic ones. For these and for scratches I regrind at once instead of struggling with them. If the laps are properly made and operated they will produce smooth curves and neither zones nor irregular curves on the work.

A cast-iron disk makes an excellent tool on which to pour the pitch. The disk should be leveled with a spirit level in order that the coat of pitch will be uniform in thickness. A strip of gummed paper around the edge will keep it from flowing out thinner at the edge. The hardness of the pitch seems to be the one thing about which no two lens polishers will agree. For that reason every polisher pours his own. If the lap is too soft the channels will close too rapidly and it will not hold a regular curve. If it is too hard it will not hold the rouge particles and will polish slowly. Dust falling on it will not sink into it and will scratch the work. If it does not flow fast enough it will not follow the work and will produce zones. It should be soft enough so that it will require trimming the channels every hour or two in order to keep them nice and even.

I use optical pitch softened with pine tar until it meets the following tests for hardness. A small sample is allowed to drip onto a sheet of wet glass. When this is still soft it is removed and rolled between the palms into a rod about ⅛ inch in diameter. This rod is cooled in cold running water. It can then be bent slowly without breaking but will break if bent rapidly. It can be bitten without shattering.

The pitch lap is poured about ⅛ inch thick so that the channels can be cut entirely through to the iron disk. They are first marked off with an awl and a straightedge so that the facets will be uniform in size and about 1 inch square. They are cut with a razor blade, using short rapid strokes. Their edges are straight and they are uniform in width.

It is important to use a fine red rouge. Notice has been given to polishing compounds which will shorten the polishing time. I have tried many of them but have not found any that work as well for me as fine red rouge. A rouge that produces sleeks is too coarse for the finest optical polishing.

The polishing action of the laps is determined by the following conditions:

1. Size of the laps.
2. Hardness of the pitch.
3. Length of the stroke.
4. Weight of the work.
5. Distance off center.

The last three of these conditions can be better controlled on a machine than when polishing by hand.

On a lap no larger than the work the center will polish faster than the edge. A lap an inch or so larger than the work will polish the edge faster than the center. This gives us a way to polish the disk flat simply by choosing the lap on which it will be corrected.

The hardness of the pitch and the weight upon the work are dependent upon each other. The hardness of the pitch varies considerably with the temperature and the weight must be adjusted to correspond. If the weight is too heavy the edge of the work will turn down, and if it is too light the pitch will not flow enough to produce a smooth curve and zones will develop.

The length of the stroke is usually about one third diameter. If the stroke is too long the center and the edge of the work will polish faster than the intermediate zone, producing a figure resembling a bird in flight (Figure 1). We call it the "bird." It is corrected by using a much shorter stroke, which will produce the opposite effect.

Usually the work is polished directly over the center of the lap. If a zone starts to develop it can be corrected by moving to a slightly different position on the lap. A turned down edge can be brought up by slightly overhanging the work.

Testing: Nearly every kind of light will produce interference fringes. Daylight and tungsten will produce red and green lines which are hard to see. Fluorescent light fringes show more contrast but are not good. Sodium light is good but a sodium lamp is expensive. Salt sprinkled on a flame will produce sodium light but this is too difficult to manipulate. A neon glow lamp is cheap but does not produce much light. The lamps best suited for the job are mercury vapor with a No. 77 Green Line filter and helium filled tubing. Helium tubing is most commonly used. These lamps can be made by any sign company. They are cheap and economical to operate. The light from the tubing should be well diffused by a sheet of flashed opal glass which may be purchased from the Pittsburgh Plate Glass Company, Grant Building, Pittsburgh, Pa., or any other window glass manufacturer.

For ordinary testing the lamp is arranged so that the light falling on the flats is reflected back to the eye. There is a slight error in this method because the angle of reflection is not the same from all points on the two surfaces. The error is proportional to the thickness of the air film between the flats and inversely proportional to the distance of this film from the observer's eye. To be correct, the thickness of this film should be measured on a line perpendicular to its surface.

This error of observation may be demonstrated in the following way:

Take two 8-inch flats and place them together with three small pieces of cellophane between them near the edges so that they will be separated by .001 inch. Place the eye at *A*, 10 inches above the nearest (Figure 1, left). What we actually measure are the distances *BC, DE, FG, HI, JK, LM, NO, PQ,* and *RS*. These distances are easily computed, each being $\frac{1}{10,000}$ of the hypotenuse of a right triangle. They are shown in Table 1. It is evident that

TABLE 1

BC	.001000	*LM*	.001118
DE	.001005	*NO*	.001166
FG	.001020	*PQ*	.001221
HI	.001044	*RS*	.001281
JK	.001077		

if the terminal digits of these dimensions could be plotted in a straight line *JK* in the middle would be one half the sum of *BC* and *RS* at the ends, but they cannot. *JK* is .000063 inch less than that amount. To demonstrate this, let us put these dimensions on cross section paper (Figure 1, right). They make a curve whose center is .00063 inch from the center of the chord.

So this is our error, and the fringes would show nearly three wavelengths concave. By reducing the air film to .0001 inch and increasing the viewing distance to 100 inches the viewing error may be reduced to .00000063 inch. The error may be eliminated entirely by an arrangement that will view each part of the flat on a line perpendicular to its surface.

An interferometer is sometimes used that views only about a square inch of the surface at a time. It is equipped with a mechanism that moves the flats across the field of vision in a straight line. Thus every part of the flat is observed from the same position normal to its surface.

Another arrangement is shown in Figure 2, left. Light from the helium-filled tubing is diffused by the sheet of opal glass and reflected vertically downward upon the flats. The reflected beam from the flats passes upward through the plate glass and is reflected horizontally into the eye by the plate glass back-silvered mirror at the top. The movable straightedge is illuminated by the light from the opal glass which passes upward through the plate glass.

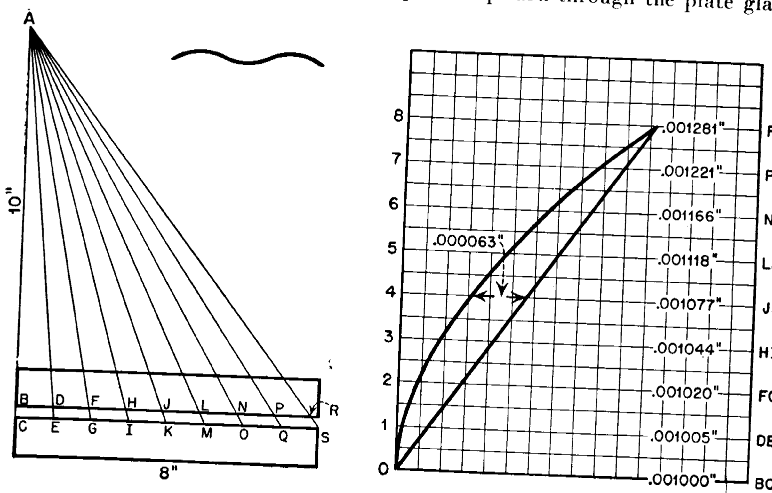


FIGURE 1

Drawings by J. F. Odenbach, after the author

Its image is reflected from the top of this plate glass, and again from the mirror above to the eye, so that it appears as if it were placed upon the flats.

The flats are turned so that the fringes are in alinement with the straightedge and the eye is alined with the straightedge and its image. By raising and lowering the eye the flats are viewed vertically across their diameter. The errors of observation are thus eliminated and any deviations from a straight line are easily observed.

To obtain the greatest accuracy of measurement the flats should be so nearly parallel that only two or three fringes appear. They can be so placed that one fringe covers the entire surface. It will appear as a solid color across the entire surface. I do not find this position as satisfactory as gaging the straightness of a fringe across the center of the flats. When I am unable to

observe any deviation from a straight line, the National Bureau of Standards will report the flats as being within 1/100 wave of light.

The flats being tested must be perfectly clean and free from dust. If they are taken off a polishing lap all they need is rinsing and wiping with a clean cloth. If the surfaces are touched with the hand they will acquire a slight film that may affect the reading. Sliding them on each other will almost always scratch them. A light tap with the end of the finger on the edge opposite the point of contact will usually decrease the number of fringes.

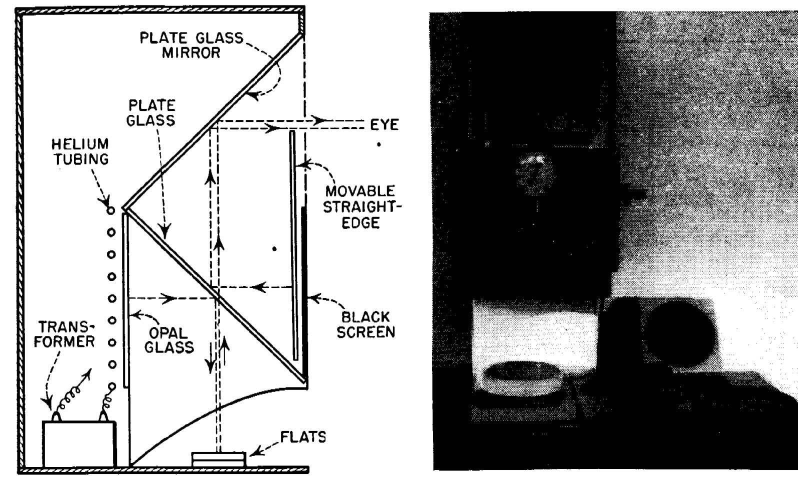
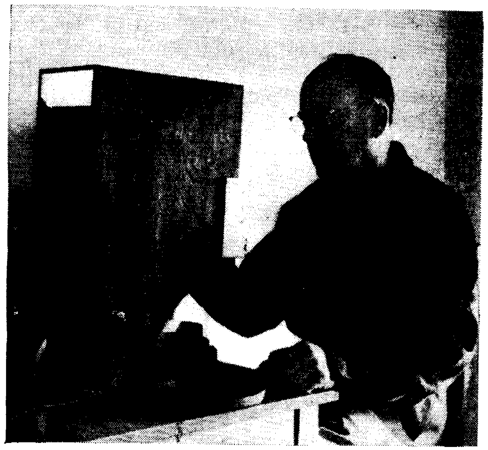


FIGURE 2

Inability to obtain a good separation of the fringes is indication that the surfaces are not clean or free from dust.

In the instrument shown in Figure 2, right, the straightedge and a dial indicator are both mounted on a block which can be moved horizontally by means of a worm with its knob at the right. Under the dial indicator is an inclined plane which can also be moved horizontally by means of a rack on the bottom of its way geared to a pinion on its mounting. The inclined plane is placed so that the dial indicator will read 0 when its gaging point is at the fulcrum of the plane. Its pitch can be regulated by the elevating screw so that the indicating hand will make exactly one revolution when the straightedge is moved from one fringe to the next. The graduations on the indicator will then read in 1/100 of one fringe.

If the measurements are required in inches, the inclined plane is set so that the hand will make 1.6 revolution when the straightedge is moved from one fringe to the next, and then each graduation will indicate 0.0000001 inch. With helium light the edge of the fringe cannot be determined with that degree of accuracy. About 1/50 of a fringe or two graduations on the dial indicator is the limit that can be detected with certainty.



Lens Production

By F. B. Ferson and Peter Lenart, Jr.
The Ferson Optical Company *

Most lens production methods are of relatively ancient origin. The general principles have not been changed with the advent of new tools. In order to present some of the new tools we will undoubtedly cover ground more ably covered by others. Nevertheless these will be included for the sake of continuity.

Lens Generating

In the past, the principal deterrent to the rapid production of optics and the most tedious to the optician who wishes to attain to the fine points of figuring precise surfaces has been the removal of surplus glass. To accomplish this, two great improvements have been developed. Without them the enormous lens production of World War II in all likelihood would not have been possible. One is the use of molded blanks, the other is the perfection of the diamond lens generator.

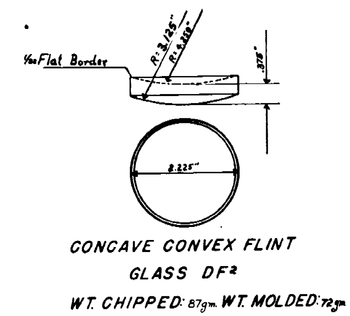


Figure 1

Modern optical glass manufacturing concerns can provide molded blanks within almost any reasonable specifications and in quantity. Figure 1 is an example of the specifications for one such blank. This blank has an overplus of glass in every dimension, so that the desired curves, thickness, and diameter may be reached without, in most cases, leaving in the glass any surface defects from molding operations. The amount of overplus of glass is calculated from experience and is small compared to flat disks of the material.

To form such blanks pieces of the proper weight are first sawed from

* Biloxi, Mississippi

larger pieces of optical glass of the required type. These small pieces are next laid in the entrance of a slumping oven where they receive enough heat to soften them. When they are soft enough to be paddled into a heated iron mold the operator lifts them with a small iron paddle, drops the piece into the mold and gives it a pat. The glass takes the shape of the mold, not of the paddle. There are, of course, molding machines with proper plungers having foot controls, which are capable of performing the same operation. On being pressed into the mold the glass cools rapidly and is dropped from it into a receptacle. The lens blanks are then placed in an annealing oven. The annealing oven again softens the glass (of course, under heat controls) to a temperature above the critical point, and the heat is then bled away at a predetermined rate that will provide relatively strain-free glass.

For small lenses this is now a routine task of the manufacturers, but for large objects having very exacting requirements in the direction of annealing special cycles must be determined and followed by the scientists in the optical glass manufacturing plants.

The molded blanks so received by the optician may have defects that will cause their rejection. These are: (1) feathers—material from the mold coating introduced into the interior of the glass; (2) stones, bubbles, seeds and straie from improper preliminary inspection; (3) improper annealing; (4) fractures from handling. These defects should be discovered as quickly as possible in order not to waste effort of production on worthless glass. A reasonable rejection percentage is customarily established.

Since the birth of the optical glass industry in the United States, which took place during the period just preceding World War I, glass molding has made strides in step with increased volume of production. Prior to that time the use of slab glass, the only form then available, presented even more tedious steps for the optician, and for obvious reasons.

The second step in rapid production came with the use of industrial diamond grits in curve production. The time of beginning of the use of diamonds was also during World War I. So far as we know, the first effort in this country to adapt diamond grits in lens (or prism) production was by Capt. J. W. Hamm, who used a milling machine, on the arbor of which he placed a small copper cylinder into which he had rolled diamond grits. The glass was fed under the roller by movement of the mill table to which it was clamped. A proper coolant was used. The rough slab was then milled to practically parallel thickness. The term "diamond milling," which is still sometimes used in the industry, had its beginning in connection with that machine. Col. F. E. Wright reports this effort in Ordnance Document 2037, "The Manufacture of Optical Glass and of Optical Systems," now out of print. Diamond milling rapidly removed the surplus glass and was as effective as the described method of fixing the grits in the copper cylinder could be. It did not, however, provide a means of milling or "generating" a curve.

Prior to World War II the American Optical Company developed the use of a machine composed of Delta drill press heads, one of which was inverted and fixed, the other tiltable about it, so that an annular diamond ring tool

of slightly larger diameter than the lens to be produced would either grind first at the edge to produce a convex surface, or at the center to produce a concave surface. The principle of this diamond cup wheel is shown in Figure 2. The spindles rotate rather rapidly in opposite directions. On top of the fixed spindle a cup chuck having the required diameter is used to hold the lens. This first development of present lens generators made use of annular ring tools of soft brass into which diamond grits were rolled by hardened steel rollers. The basic principle of these machines was freely given to all other lens makers by the American Optical Company for use in wartime lens production.

The next important step in curve generation requires a digression. Old-time druggists made pills in a pill mold by compressing powders with sufficient

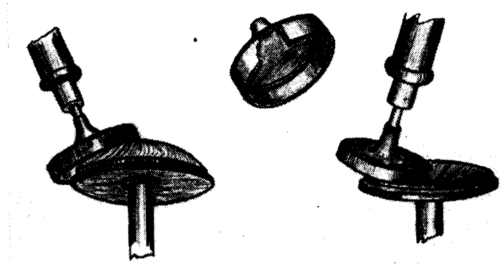


FIGURE 2

Principle of the diamond cup wheel. Left: Position for convex surfaces. Right: Position for concave surfaces. Center: The annular ring tool with diamond cutting surface.

pressure. The powders cohered firmly enough for normal usage. Not many years ago some brilliant mind, the owner unknown to the authors, conceived the idea of pressing metal powders and then sintering them to form sturdy machine bearings and other shapes. This is the basis of powder metallurgy. After sintering, the powders act as a solid metal, though it is usually porous. Powder metallurgy came into the lens picture when it was conceived that diamond grits could be mixed in certain concentrations with the metal powders and after sintering would be held more satisfactorily than by pressing small amounts of diamond into the surface of a soft metal, for here the grits came loose and the tool had a short life. With powder metallurgy the depth of the diamond concentration on the surface of the cutting edge could be made according to desire. The tools thus formed wear but slowly in comparison to the enormous amount of work to which they may be subjected, whereas in the earlier type of tool the grits pressed into soft metal did not maintain an even height and deeper scoring of the glass resulted.

For the cup wheel tools [1] for lens work the diamond grits and powdered metal, normally copper or a bronze with high copper content, is placed in a mold, a ring of bronze is placed on top, and pressure is applied. This causes the powdered metal to adhere to the ring and become a part of it when sintered. The ring is then attached by means of sweat soldering to an adapter, usually bored to a taper, which fits the spindle of the lens generator.

In addition to metal-bonded tools there are also resinoid-bonded and vitrified-bonded diamond tools. Resinoid-bonded straight wheels are often used in lens edging and centering operations since they are not likely to cause even slight chipping of sharp edges. Seldom are they used for curve generation.

Since the early adaptation of drill press heads to curve generating machines other special machines have been put on the market that are generally more effective. One of these is the Peck generator [2] which reverses the principle of the fixed lower spindle. The upper spindle is fixed. The lower spindle tilts and there are ways on which it travels so that the diamond cup wheel may be set accurately at the center of the lens.

The upper spindle has a certain amount of vertical travel in the fixed position. When the lens blank is inserted in its holder the upper spindle carrying the diamond tool is lowered to the lens and the machine is started. A small weight on a lever arm drives the diamond tool against the glass until a stop is reached.

It is possible for two such machines to be attended by one attendant. The glass is set into one while the other is generating the curve. We once witnessed the operation of two machines by a lady who very happily generated the curves on 700 lenses in one day, all the while singing "Don't Fence Me In."

Another modern machine is the Diamonnett [3] (Figure 3). This machine is believed to have superior engineering both for precision and ophthalmic lens production. Its capacity is limited to 5-inch diameter.

For close order precision it is necessary to set some machines by means of a template. Not only should the machine be tilted to give the proper radius but the center of the diamond wheel also must be accurately placed to avoid a protuberance on the glass. These adjustments are made in sequence until both coincide for proper curve. When using a new tool the radius should be watched closely during the period of generation of the curves of several hundred lenses, since it will wear and very likely a discrepancy will appear in the radius. For mass production it is not advisable to use one tool for more than one curve. The wear described will continue until the actual radius of the diamond tool matches the desired curve.

As diamond tools are used they often become glazed. To remedy this a pocket Carborundum stone is held against the face of the tool to relieve the metal back from the diamond grits, after which it will cut as rapidly as before.

[1] The Norton Company, Worcester, Mass., Super-Cut, Inc., Chicago, Ill., and others.
[2] Universal Shellac and Supply Co., 540 Irving Ave., Brooklyn 27, N. Y.
[3] Penn Optical and Instrument Co., Pasadena, California.

The most common grit size used is 120, for roughing out the curves. This size will permit grinding with no more than three grades of abrasive—No. 280 Aloxite for roughing and No. 30 Garnet Fines with No. 14 for finishing. The Aloxite will relieve the score marks of the diamond tool. These are not only in the form of a scratch but also leave an incipient fracture running a short distance into the glass. The Aloxite will also true the curve. Unless the

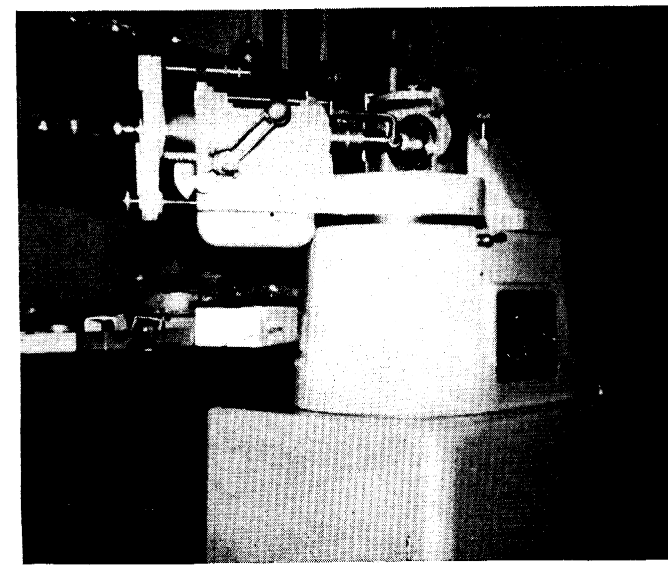


FIGURE 3
Lens generating machine

generator is allowed fully to clear itself from cutting the surface it will not actually be spherical. In any event, it seldom is truly spherical.

Where practicable, a finer diamond grit such as No. 400 may be employed for finishing. This grit size will permit fine grinding with only one or two grades of abrasives to prepare the lenses for polishing. Due to departures from spheres it is not always a practical shop practice, since the "coarse" roughing with No. 280 is rapid and effective and since the time of setting up must also be accounted for.

Diamond tools are customarily used in a diameter approximately 25 percent greater than the diameter of the lens to be cut. This allows some latitude in centering the edge over the lens center, prohibits a tendency to leave a rim at the edge of the glass, and permits the coolant to flow beneath the cutting tool.

Thickness of the glass is controlled by means of a stop on the machine. This is adjusted for each thickness desired. On some machines a micrometer stop is built in and the thickness of each finished lens will vary on the order of .001 to .002 inch. Allowance must be made for finishing with abrasive grits.

If attention is paid to the accuracy of the chuck that holds the lens in the machine, the edge thickness will vary but a small amount. This will considerably ease centering and edging operations.

Rough Grinding After Milling

After diamond milling, the lens blanks may have too short radii or protuberances at the center that will make blocking them unsatisfactory. Due to phenomena of the milling angle they may also have an aspheric surface—in fact, we should say they are likely to have a surface that is not a figure of

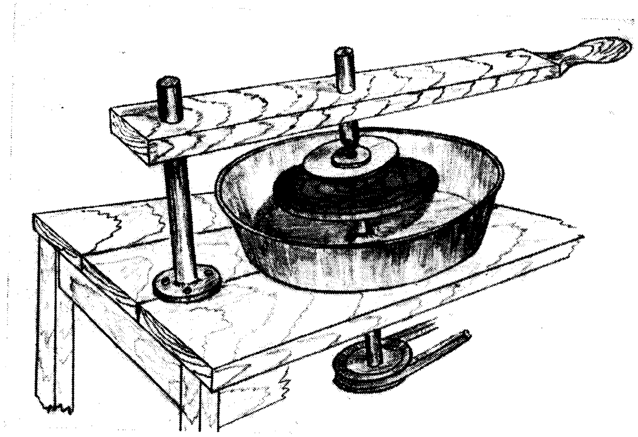


Figure 4

revolution. Naturally they will also have the characteristic marks of the diamond cutting tool.

If the lenses are to be blocked singly these faults will be taken care of after they have been blocked and placed for work on the grinding spindle. However, if they are to be blocked in multiples we have found it advisable to give each blank a rough grind with medium grits. This will lengthen the time of production by the length of time required to put the lenses through this process. It will, however, shorten the production time by an equivalent amount, perhaps more, by forefending against faulty blocking, also by shortening the rough grinding time in the block.

There is another important purpose for the preliminary rough grinding: it permits the lens to have slightly longer radius than specified if the surface is convex, and a slightly shorter one than specified if it is concave. The purpose of this is to cause each blank to seat in the forming tool of the block without rocking and will be described later.

For this preliminary grinding the only machinery required will be a vertical spindle of approximately 150 rpm speed, a tool $6/5$ the diameter of the lens, and a manually controlled cross-stroke arm with a pin. Such a simple spindle is shown in Figure 4. The cross-stroke arm is not used except with long radii that are susceptible to the use of a spinner. The spinner will be described presently.

After setting the tool on the spindle we place medium grits and water in the drip pan, provide ourselves with a small paint brush for painting the grits on the tool, and start the spindle revolving. Pick up the blank in the fingers, insert it in the grinding tool and stroke it back and forth by hand

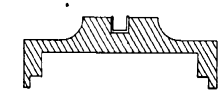


Figure 5

just as would be the motion if an automatic stroke arm were used, taking care that the stroke is about even from center to edge to hold the tool shape as long as possible. Rotate the lens in the fingers as the cross stroking is done. Paint on grits as required. Several minutes' time will suffice to rough the blank to spherical form and to relieve most of the marks of the diamond mill. A short trial will reveal the most satisfactory method of manipulating the lens blank but it will be somewhat as has been described.

With the manual method just described short radii may be ground. If unusually short, or if the lens is small such as for high powers in eyepieces, we may need to attach a handle to the lens to hold it.

The spinner method is illustrated in Figure 5. It is simply a cup-shaped metal holder with a hole for the driving pin. The holder is placed over the lens, the spindle is rotated and the cross stroke is managed by means of the arm on the spindle. The lens and cup will spin with the motion of the spindle but at a lesser rate due to the friction of grinding.

The spindle should be controlled in starting and stopping by a foot switch so that the hands will be left free for the remainder of the work. Trays with holes somewhat larger than the lenses should be provided to receive the lens blanks. These depressions in the tray will assist in holding the blanks apart and thereby in the prevention of chipping.

Templates

Accurate templates are a necessity in lens making, particularly for the stages of work up to polishing. After this final stage is reached, for the most precise work, proof plates, or test plates, are a must for duplication of radii, focal length and figure.

We will not dwell on the use of spherometers of various designs. These have their special uses. Existing literature (Twyman) on the subject will give needed information.

For lenses of short radius it is not difficult to turn up on the lathe matching convex and concave forms from sheet metal. The limiting radius is the swing of the lathe or the largest micrometer available for measurement. With care the diameters may be made accurately to 0.0005 inch, and thus the error of the radius is half of that amount. Templates so made should have a bevel on one edge so that the useful edge will be thin. Sheet metal of approximately .125-inch thickness will provide sufficient rigidity. For constant shop use the templates should be hardened and ground together. If not hardened they should at least be ground to relieve small burrs. By placing the pair on a flat surface and inverting them from top to bottom positions, as with mirror making, the radius will not be shortened or lengthened appreciably.

Long radius templates are a problem. Those who have made a study of it will have learned about Peaucillier's linkage (ATMA, 247), which in theory should provide any radius short of absolute flatness. They will, however, have found the theory impractical of application, due to magnification of errors caused by misfits of the linkage and the impossibility of establishing accurately the calculated position of the central pin. Other theories have been tried which likewise are cursed by factors of operation that reduce the accuracy required.

Once a special master template is formed and proved it is not difficult to match approximately this curve in quantities by means of planers, grinders, or even the lathe acting as a shaper, if the master is set up with a precision dial gage to show the run of the cutting tool and exhibit the errors in .0001 inch. These are reproduction problems. The main problem, however, is to make the first or master template accurately.

For small production runs, either in small plants or in the home hobby shop, the use of large special machines is denied by their lack. An alternative approximation must be used, one that may be refined to higher accuracy, and in the end proved to be as required. The alternative should be easily managed and the result usable even though it has faults. Let us turn to the simple radius bar.

To form such a bar we may use a rigid piece of wood, a sharp glass cutter, an accurate measuring tape, and a sharp centering pin. Examine the glass cutter for wheel wobble, and shim until the wheel runs true. Attach the cutter to one end of the bar. Measure the distance to the centering pin and affix the pin to the bar. With care, this may be done within a few thousandths of an inch. Place a piece of single strength window glass on a bench, place the radius bar in position and scribe the arc with it. Under the cut so made place a small nail and press the glass on each side of the cut. The glass will break smoothly along the line of the cut.

Thus far we have only an approximation. To refine the product still further we place the parts on a flat iron plate and grind them together with 280 aluminum oxide or any finer cutting powder, taking care to use short strokes and to invert positions.

The principle faults of such templates are transparency, which will make it more difficult to discern departures from curve, and the probability of breakage unless they are handled with great care. Certainly they are not adaptable to mass production lens making. However, they are an excellent starting point when only a few lenses of longer radii than permitted by our lathe are required.

We may refine the templates still further by making up proof plates, starting with surfaces milled or ground to fit the proper convex or concave curve of the template. In the section on making proof plates we will give methods and these need not be repeated here. After the proof plate is proved by measurement the templates may be corrected by proper grinding until they fit the proof plate in light-tight condition.

A further improvement of this simple form of radius bar will permit the edge of a grinder to form the convex and concave curves. For this we will require heavy channel iron or I-beam, to one end of which we attach a motor-driven grinder with suitable fixtures and in a position to allow the wheel to grind in the surface without running a groove into the grinding wheel. A coolant of water-soluble oil in water, supplied by a pumping system, is attached and directed at the point of work. The centering pin should be on ways capable of minor adjustments as well as major changes in radius from pin to edge of grinding wheel (actually from the pin to the metal, measured accurately after a trial cut is made). The grinding head should lift and fall with an eccentric to prevent the grooving. The head should be mounted with rollers for free movement about the arc.

If the template is to be convex it is mounted inside the wheel in the direction of the pin, if concave it is outside.

The metal template blank should be cut roughly to shape to minimize the amount of work to be applied by the grinding wheel.

After grinding the matching pair it will still be the order of effort to discover the accuracy of the work. Again we may inspect by matching to a proof plate. We may also run a trial lot of lenses and test with the proof plate to discover by interference how well the position of the pin has been measured. If the templates are out of truth we may either regrind them with the radius bar or, if the error is only nominal, we may grind them manually to truth in the manner mentioned. In shop use, especially in the grinding stages of making lenses, it is common for the working templates to wear out of truth. For this reason, where mass lots of lenses are to be made, it is wise to provide a master set of templates, which will provide a reference for the working set or sets. The remedy for errors that come from use is then to regrind them until they will fit the master set.

As will have been discerned, these methods involve, first, roughing, followed by sufficient refinement to enable precision production in small shops. They are not, perhaps, ideal. In fact, we do not know an ideal method of production of accurate templates that will automatically produce them to an accuracy of 1 part in 2000 or preferably 1 part in 4000.

In work, templates are also subjected to dropping and deformation by springing, and to denting as well as wear. These evils must be guarded against.

Glass templates for short radii may be ground and polished in the lathe and may be checked first by micrometers and second by interference methods against a proof plate. We may, of course, match our proof plate to the polished edge of the template so made.

For very long radii, say 300 inches or more, the radius bar becomes a cumbersome affair. It may be employed if the proofs of accuracy are adhered to. We may make up a spherical mirror by usual mirror-making methods and grind a glass template to fit it. We may even cut a strip from the glass tool with which the mirror was ground. We may approximate our curves by use of the dial spherometer, applying the mathematical formula for depth of sagitta of the curve. It is practical to do so, provided that in the event of precision production we additionally prove the results of these first approximations.

Making and Use of Proof Plates

Two terms are applied to the plates, either curved or plane, that are used to prove accuracy by interference methods. One is "proof plates," the other is "test plates," both meaning the same thing.

If we wish to prove convex surfaces we provide a concave proof plate but if it is a concave surface the proof plate is convex.

In high precision lens manufacture specifications for any lens will include some such tolerance as "plus or minus one fringe," or "plus or minus five fringes," depending upon the accuracy required. The accuracy applied to radius of curvature will often be stipulated as "one part in two thousand"—or larger if the lens is to be less precise. This means that if we have a radius of curvature of 35.818 inches, for example, we will have an allowance of approximately .017 inch in error of radius of curvature. This then would read plus or minus .008 inch. The example given is not the most precise specification, for often it will read plus or minus .003 inch, though seldom less than that amount.

If two equal but opposite curves exactly match by interference methods they will show straight fringes when viewed at the proper distance. The proper distance may vary from 24 inches to many feet, depending on the aperture of the lens and the proof plate.[4] If the lens departs from curve the amount may be ascertained by the fringe formation, and the direction of departure is also shown. If the proof plate is made carefully and corrected to a sphere as shown by the Foucault test, it is then certain that any error of curvature exhibited by the fringes will be known to be on the lens surface and not on the proof plate, since the Foucault test is more sensitive than the interference test for small errors of figure. Hence if we have a zone of any kind, a hole or a protuberance at the center, it may be seen.

[4] See ATMA, Selby, H. H., "Flats," formation of fringes, footnote pp. 122–3.

Whenever a sequence of high precision lenses are to be made we feel it highly advisable to make and use proof plates. Especially is their use indicated when focal lengths are to be matched. Matching focal lengths also involves the index of refraction of each glass and so the glass must be selected for actual index rather than for the general catalog index. This, however, is another subject and will not be delved into here.

The first question when making proof plates is to determine what material we will use for them. Pyrex is very good material, due to its lower coefficient of expansion than common glasses. Fused quartz is the nearest to an ideal material since it deforms but little from temperature effects. It is more expensive but if the number of lenses to be made warrants the slight extra cost (for small plates) it is practical to use it.

Having secured the material the first step is to edge the blanks and mill or grind the back surfaces for finishing—approximately flat if the radius of curvature is long, or convex if it is short. In the latter situation it is advisable to finish the viewing side convex, due to the edge effects of a strong negative lens, which confuse the periphery of the field. The radius need not be concentric with the business side of the proof plate but may be somewhat longer, the amount not being critical.

The next step is to mill the desired curve, or grind it if no lens generator is available, to match an accurate template. If it is yet uncertain that the template is true, then the procedure should be to match the templates and complete the grinding and polishing of both front and rear faces. The rear face needs only enough polish to be seen through easily. As soon as the concave curve is polished set it up under the Foucault test, find the exact center of curvature, and measure the distance from the plate to the knife-edge. The knife-edge and the pinhole must be exactly on the same axis and should move together. The measurement may be made with an accurate tape, or a rod which will be appropriately marked and later measured. The lens bench may be used, as explained by Selby in this volume.

After finding the radius of our proof plate, if the departure is severe we must go back to fine grinding. If the radius is short we invert with the tool on top and run with a small overhang. When it is thought that the curve is nearly correct we again give a short polish and test. If the radius is short, continue until it is at within at least .050 inch. If the radius is as long as 40 inches, an inch of departure may be polished away. The remainder of correction may be applied by proper polishing strokes. We continue to run and test until the plate is well polished (though it need not be a full polish), has the proper radius of curvature within a small allowable tolerance, and the figure is a true sphere as shown by the knife-edge test.

Glass tools are excellent for making proof plates in small quantities. We may use them in the same diameter as the proof plate and, by inversion of tool and work, control the radius of curvature.

If we must make a convex proof plate we may follow the same procedure as given, except that the convex plate will become the usable one. We test the convex curve for radius and figure, and work and test by interference until it is correct, doing all grinding on the convex plate until the radius is correct. We figure a concave plate accurately spherical, and match the convex plate to it within one fringe or less.

Now, having made our proof plates, we should retrace our steps to the templates and check the templates against them. If the templates now exhibit errors we may correct them by laying them sidewise on an iron plate and grinding with 280 aluminum oxide. If the templates exhibit a shorter radius than required we grind with the convex of the pair on "top" with long strokes, giving the effect of overhanging. This will grind most at the edge of the concave and at the center of the convex. If the error is the reverse we then reverse the procedure. In either event we continue correction until the template will give a light-tight fit to the proof plate.

The final step in finishing the proof plates is to mark them with a diamond writing pencil, giving the radius, the identification of the surface of the lens combination, and the lens combination they are made for. For example, if they were made for a 5-inch achromatic doublet we may mark them R_1 —55.98″ 5″ SP, the latter letters signifying "separated doublet." By doing this we will save some testing time when once they are laid aside after use, since we will certainly not be able in later days or months to remember which lenses they were made for.

In using proof plates we should provide a monochromatic light source. Usually it is handier in a portable form, since when a machine is used having a number of spindles the light source, to be effective, otherwise would need to be as long as the machine. Hence the portable form which may be taken from lens to lens more easily. If the lenses are large we will require some means of moving back from them the proper distance to view the fringes without their distortion due to improper viewing distance. A very good arrangement is described by Selby,[5] using a ¼-inch plate glass set at 45° with the light source above it. If, for example, the lens is 10 inches in diameter, then we will need to move back from the proof plate on the lens a distance of at least 28 feet. This distance need not be calculated by mathematics for it can be found with the first test by empirical methods. To do this we move back from the plate until the fringes cease showing more concave than the surface truly is. For example, let us assume that our first glance at the fringes shows us to have six fringes concave when we are close to the lens. We move back and the fringes begin decreasing in number until finally they appear straight or oppositely convex. Now we move forward toward the lens and plate and the fringes start bending inward and increasing in count until we have six fringes concave again. The distance at which they cease to be distorted due to this phenomenon of viewing distance is the correct one to use. If the surface is on the convex side, as we view them near the lens, we will

[5] ATMA, "Flats," page 124, Figure 5, left.

find that the fringes increase in number as we move away until a maximum number has been reached. This, then, is the error of the surface we are checking.

The same system may be used to discern which way the error exists. Move away from the plate and lens the proper distance, then walk slowly toward them again. If the fringes stay circular until we are very close to the pair, then suddenly bend in the opposite direction after we straighten up, we know that our error is on the side of convexity. If, however, the number of fringes increases, until when quite close we see many more of them, the error is toward concavity. All this may not be apparent or clear on first reading but is easily discerned when put to use.

If the lenses are small we may view them with the proof plate at arm's length and as near perpendicularly to the surface of the lens as possible. Pressure at the edge will cause the fringes to spread out if the error is toward convexity and close up if it is toward concavity. You may duck your head and, if they spread out, the error is toward convexity but if they close up it is toward concavity.

These terms "concavity" and "convexity" are synonymous with "radius too long" and "radius too short," respectively.

In the short section on polishing strokes will be found some information on correction of the errors that the proof plates will exhibit. Such things as high central knob, or a central hole, a turned down edge and high zone just inside center, or irregular zones in other parts of the radius, will all be discernible with the accurate proof plate.

Unless proof plates are used properly the result will be scratching and sleeking of the lens and of the proof plate. Eventually the proof plate would then become so abused as to be worthless, short of refinishing, while scratched lenses will not be acceptable.

The first step is to clean thoroughly both the lens and the plate. For small lenses it is not necessary to provide a separation but merely to set the proof plate gently on the surface, using both hands. One-handed geniuses seldom succeed long in avoiding an abrupt striking of the two together. For large lenses a small section of Scotch tape at three 120° points will provide sufficient parallelism to read the fringes and to keep the two lenses from contact.

Never should the two surfaces be wrung together. This applies likewise to flats or any surfaces of glass or quartz that are placed in position for interference reading. If the fringes do not at once appear prominently then one or the other or both surfaces are dirty and should be cleaned again, this time properly. A clean, soft cloth moistened with alcohol will usually clean the surface sufficiently. Ordinarily, lens tissue will be adequate for cleaning, and wiping lightly with dry and, of course, clean hands may follow. When the surfaces are clean the fringes will appear, merely from the weight of the proof plate.

It is well to provide a safe place for the proof plates when they are not actually on the lens but are being used frequently. A receptacle having separations to keep them from being fractured is excellent. Unusual care should be given them at all times.

Metal Tools

Not all metals are suitable for metal grinding tools. Some wear too rapidly, and some are too costly for general use. Cast iron is the material customarily used for curved and flat tools, principally because of its low cost and because it may be cast to the rough curve desired. It may be machined in the lathe (using the compound slide) and then may be scraped for accuracy much as wood is turned in a lathe. In such operations an accurate template is used for determining when the curve is sufficiently precise.

Tools of cold rolled steel wear much less rapidly than cast iron—about half as rapidly—and in use in unskilled hands the deformation from curve due to improper strokes is less. It is especially suitable for small lenses.

Brasses and bronzes of the most common alloys wear rapidly. Compared with cast iron a rough estimate is twice as quickly. Lead is too soft except for some special uses. Aluminum is not suitable for grinding tools, though it is very suitable for various lens-plant uses such as lap backings, spinners, blocking tools and cup supports for single lenses.

In spite of literature to the contrary, it is not always the rule to make metal grinding tools in mated pairs and to lap them in for correction of curves. This is, however, an excellent method if only a few lenses are to be made and if rapid production is not necessary. Since the paired-tools method is known to all we will not dwell upon it. We will comment on the alternative.

Having secured iron castings in a form approximating the required curves we may proceed directly to making our tools. The castings must be free from blow holes, at least on the grinding surface. We will assume the use of a lathe and an accurate template. We will not assume the use of a special lap lathe, or a lathe with a special toolpost grinder having an adjustable axis and abrasive cup wheel for grinding in a curve. We will also assume that no lens generator is available with which one could substitute an abrasive cup wheel for the diamond abrasive wheel. Diamonds will turn up the curve readily but will also charge the grinding surface with diamond chips which will scratch until doomsday.

Our first task is to true up the edge and back of the casting and attach the metal screw adapter if such is the plan. If not we bore the central hole for the driving pin of the grinding machine. We next recenter the casting with the curved face outward, making certain that the back and edge runs true. Take a rough cut to relieve the surface skin of the cast iron. Check with the accurate template. By using the longitudinal feed and the compound slide manually we proceed to take off the high spots. Put some prussian blue on the template and rub it across the diameter of the tool. The blue spots will tell where to cut next and the eye can judge how much. When near to curve insert a rest in the tool post and start scraping the high spots with a hand scraper. An old file ground with a slight curve will do admirably.

Check with the template and continue the scraping until there are at least four rings which touch from center to edge. Such a tool will grind in quickly on lens blanks using 280 aluminum oxide.

Cast iron, being brittle, will scrape easily. Steel will require more labor but is handled in the same manner.

Even with an accurate template we will probably depart a few fringes from the desired curve. A proof plate for precision lenses will tell us how much by giving a lens surface a quick grind, fining, and a quick polish. The number of fringes departure will tell us the state of the grinding tool because the short polish will not provide time for deformation from the curve of the tool.

After the grinding tool is correct as to curve it may be kept that way by proper strokes. In rapid production schedules this is the desire and not the result. Therefore, as often as the tool is deformed too greatly for use, it must be scraped again to curve. To relieve most of the charge from abrasive grains or powders which will dull the scraping tool we may spin it in the lathe with emery cloth held against the face. Perhaps if the departure is not great the cloth alone will suffice, by proper application, to correct the tool.

As will have been noted, this method is much akin to the paired-tools method. It cannot be assumed that, if the grinding tool is out of truth, merely grinding it against its mate will true it. Half of the wear occurs on each component, and if the two are not stroked properly both components will be out of truth. We would be back to the use of an accurate template and proof plate again to determine just what we have.

Those who are not accustomed to the use of metal tools may fear scratches but these do not often occur. We may use one grinding tool for several grades of abrasives provided we clean it thoroughly after each grade. For lenses of fairly long radius we may disregard the differences in radius due to the thickness of the grit; not, however, for lenses of short radius. With these it is better to provide a roughing tool and a fining tool. Due to the thickness of the grit the radius of the grinding tool will be lengthened and this tool will swing on the center of the lens, or the mating metal lap, after coarse grinding. This has the effect of lengthening the radius of the glass if one tool is used for both roughing and fining. For fairly long radii and with diamond milling, the coarsest grit, for example No. 280 aluminum oxide, is not of appreciable thickness.

It is advisable to groove the grinding tool with a series of grooves from center to edge while the tool is being formed in the lathe. This will insure an even spread of the grits. The number of grooves is not critical. The edges of the grooves should be given a light scraping to relieve any burrs. The edge of the tool should be given a chamfer.

The size of the grinding tool is a subject that deserves thought. See Figure 6. If the tool is to be used on top of the block or single lens it should be approximately $5/6$ of the diameter of the glass. If the glass is to be ground on top of the tool the diameter of the tool should be approximately $6/5$ of the diameter of the glass. The purpose of these diameters is to enable us to use proper strokes to maintain the accuracy of our grinding tool. With tools of equal diameter, as all mirror makers know, the one on top will have its radius constantly shortened by overhang, which occurs with each stroke no matter how short or how long. With equal diameters there is no possible method of avoiding this effect except to invert and revert.

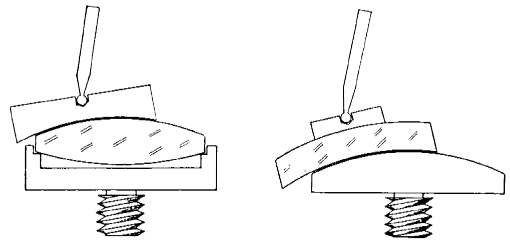


FIGURE 6
Tool on top, diameter $5/6$. Tool on bottom, diameter $6/5$.

The strokes to be used will be illustrated in the section on grinding and polishing and will not be repeated here.

Blocking Lenses in Multiple and Single Units

This section describes first a technic for blocking identical lenses in multiples, then one for blocking them singly.

In the first, or multiple-lens technic, the lenses, either convex or concave, are attached with blocking pitch in a pattern of concentric rings like those of Figure 7 to a blocking tool that is convex for convex lenses as in Figure 8,

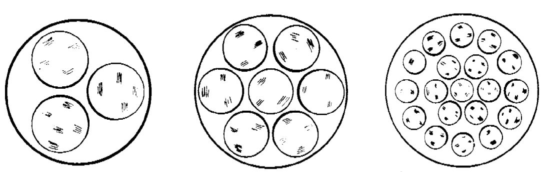


FIGURE 7

left, or concave for concave lenses as in Figure 8, right. Later they are ground and polished against tools and laps not shown in this section. These lenses are not, however, attached to their blocking tool in what may seem the most direct and simple manner, that is, by pitching them directly to it one by one. Advantages are gained by accomplishing the same end in an indirect though no

more time-consuming manner. So the lenses are first laid out in rings on the forming tool which has a radius of curvature equal to their own. This forming tool exists solely for bringing their surfaces mutually into exact coincidence with the sphere of which they are a geometrical part, and thus is an adjunct or a make-ready. Next the same lenses are picked up, all at one time, by the blocking tool to which they are caused to adhere by pitch and will remain adherent during grinding and polishing.

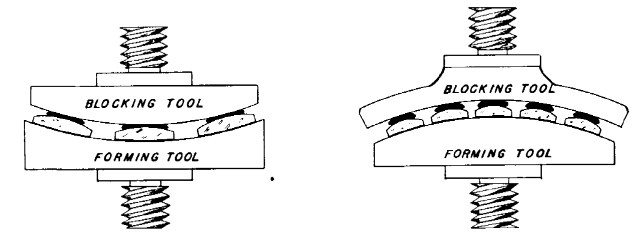


FIGURE 8

A brief preview of this blocking process, in which all except the barest elements are omitted for the sake of clarity, should make it easier to keep track of the more detailed repetition of the same process that will follow later. In Figure 8, left, is shown a convex blocking tool with rings of convex lenses attached to it with pitch. How they became thus attached is best explained by

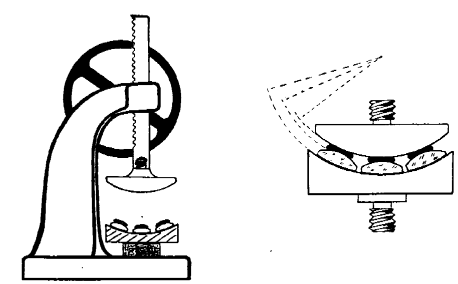


FIGURE 9

Figure 9, left. Here the same forming tool with the same lenses lying on its curved surface, each with a disk of pitch on top,but with none on the bottom, has been screwed to the base of a press. The blocking tool, attached to which the lenses will later be worked, the same one as in Figure 8, left, but as yet with no lenses attached, has been screwed to the top of this press and heated. It then has been lowered against the pitch on the lenses, has melted that pitch a little, the whole has been cooled, and the blocking tool has been raised again with all the lenses now adhering to it, held rigidly in the exact over-all sphere desired.

The radii of the forming and blocking tools themselves are not equal. As shown in Figure 9, right, the radius of the blocking tool is shorter than that of the forming tool by the thickness of the lenses plus that of the pitch. The forming tool has the exact radius of the lenses, though its curvature is opposite; also of the grinding tool and of the polishing lap not described in this section.

The forming tool is not the one for grinding since this would alter its radius, nor is it used for polishing. It exists solely as an adjunct for holding the lenses in geometrical coincidence with its spherical curvature.

The blocking and forming tools are made heavily of iron or aluminum.

If, instead of blocking convex lenses, we should wish to block concave lenses, all that has already been said would apply to Figure 8, right. The blocking tool would still be the one on top. It would be on top in the press, and will be again the one to be heated and pressed into the pitch and would be again the one to lift away with it the concave lenses that are stuck to it. In short, nothing has changed except the curvature of the lenses and tools.

Now let us start at the beginning of the multiple-lens blocking procedure and follow the successive steps through, hoping finally to gain a clearer and detailed picture of the tools we must provide, the materials to be used, and how they are manipulated. We shall assume that the lens blanks have already been milled to curve and rough ground with 280 aluminum oxide, as described in the previous section on rough grinding.

To stick the lenses on the tools a special pitch termed blocking pitch, available from most optical supply houses, is used. Blocking pitch may be had in a wide range of hardness to softness. Usually it is black and appears to be a mixture of asphalt pitch with a filler of earth or clay. It may be red, with a filler of red ochre. Flake shellac is often melted with it to harden it. When heated this pitch will flow readily but when cool it should be hard enough to hold the lenses rigidly under the temperature of the rooms in which the block is to be worked. If it is too soft the lenses will tilt out of the sphere with which they should coincide but if it is too hard they may snap off the tool, ruining the block so that the work must be done over again. Like all pitches, blocking pitch is innately contrary and at times will keep you at your wits' end as you try to eliminate the evil effects that flow from it. To predict all these effects is impossible, yet, in general, once the correct hardness has been found, a satisfactory percentage of the blocks will go through the manipulations without trouble. If, however, the room is subject to much temperature variation the blocking may prove troublesome, and a supply of blocking pitches having various hardnesses will be the only practical remedy.

The first operation in blocking lenses is to attach disks of pitch to each of them. For this we shall need a pot of some kind in which to melt the pitch, a hot plate to warm the lenses, and molds to make the pitch disks or "buttons." In France, also in Britain, these disks are called *mallets* but we call them buttons, a common term in lens plants of the U. S. A. One form of mold is shown in Figure 10, left. The one at the right is a special ring mold that will support large lenses at the 70 percent radius of equilibrium zone. These molds are made of iron. Chromium plating will enhance their appearance and prevent rust.

Now, placing the button molds in a receptacle of iced water to chill them, and heating the pitch and the lenses, we are ready to make buttons.

Lift one of the molds from the water, pour it full of melted pitch, place one of the heated lenses centrally on the pitch, to which it will adhere, and set the mold aside to allow the chilled iron to cool the hot pitch.

The depth of the mold will, of course, govern the thickness of the pitch button. The thickness of the buttons may be varied as required, though it is good practice not to use greater thickness of pitch than is actually needed to allow $3/16$ inch of pitch to remain after the blocking tool has partially melted the button. The glass should not be pressed on the hot pitch sufficiently to reach the cold iron mold.

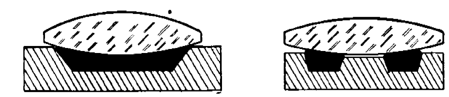


FIGURE 10

Our next step is to form the lenses in blocks, as previously outlined and now to be dealt with in greater detail. As already stated, the forming tool has the exact radius required for the lenses, also for the block, and is the same in radius as the grinding tool will be. It should be a trifle larger in diameter than the outside of the block to be made. The blocking tool has a radius shorter than that of the block by the thickness of the glass plus the thickness of the pitch buttons (Figure 9, right). Thus these buttons will all have equal thickness after the block is made.

The lenses are arranged on the forming tool in patterns like those shown in Figure 7 and will be held in the chosen pattern tightly enough to avoid lateral slipping during the blocking operation if they are merely moistened as they are applied to it. This statement is based on the assumption that the radius of the lenses is not greatly shorter than specified. If they are they will swing at the center and lateral movement will be encountered. The remedy for this condition is to rough grind the blanks with a trifle longer radius than required. They will then fit at the edges rather than the center.

Now the forming tool, with lenses and their pitch buttons, is screwed into the base of the press (we use a three-ton arbor press merely because it is adaptable to this work), made possible because all tools have uniform threads and thus are interchangeable. The blocking tool is also screwed into the spindle of the same press, as shown in Figure 9, left, and is heated by a Bunsen burner until it will melt the pitch. Next, the hand wheel of the press is rotated to lower the hot blocking tool onto the pitch buttons, applying only enough pressure to melt the buttons to a shallow depth. As their surface melts, the excess pitch runs down between the lenses onto the forming tool.

Now we play a stream of cold water on the blocking tool until it is quite cooled and the pitch has set. Unless this is done, and if the block is lifted away with the lenses before all pitch has entirely set, the lenses will sag and tilt as the blocking tool is lifted. Usually this occurs at the center and the result is that the central lenses have sagged out of truth. If this occurs, the block will have to be torn apart and reassembled from the beginning.

The same process is carried through if the lenses are concave, except that the forming tool is convex and the blocking tool concave.

The final step for preparation of the block for fine grinding is to relieve the pitch away from the surface that has resulted from the melted pitch flowing onto the forming tool between the lenses. After this the block is sent to the

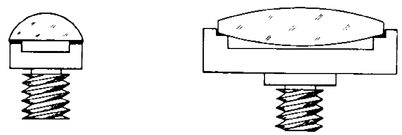


Figure 11

grinding room, and from thence to the polishing room. As has been explained, the forming tools are not used for grinding or polishing operations.

After the block of lenses is polished it is necessary to separate them from the blocking tool, and the pitch buttons from the lenses. One very satisfactory way to do this is to place the block in the cold compartment of an electric freezer. Upon being chilled the pitch usually loosens its hold on the glass, also on the iron block. Any lenses that retain pitch are put into the degreaser or into a solvent such as Triad, used in liquid form. For those who work lenses as a hobby the home electric refrigerator will serve for breaking up the block, provided the feminine side of the family will permit a mere man to get by with this.

The second technic described in this section, alluded to in its opening sentence, is for blocking lenses singly. For single lenses of short radius we do not require the process just described. We may merely warm the tool (Figure 11, left) by which the lens is held on the grinding and polishing machine, place on it a bit of medium-hard pitch—not necessarily blocking pitch—warm the lens and place it in contact with the pitch. When cool it is ready for grinding and polishing. It should be centered on the holder.

For single lenses of long radius and wide aperture, especially those having thin section, we have found it a good practice to provide the special tool shown in Figure 11, right. This supports the lens at the edges. The lens is secured by soft pitch so that no bending will occur to produce astigmatism. Naturally, the lens will bend somewhat in its unsupported central part but if need be

this can be dealt with in polishing. It is important that we do not support thin lenses, such as precise astronomical objectives, in a manner that will produce astigmatism. Consequently no blocking or polishing pitch that would cover the whole area should be considered. Even soft pitch will hold a tension that will not be relieved as rapidly as the polisher acts and, as a result, when the lens is taken from the block and set up for test the ill results will usually be pronounced.

The Strokes of Grinding and Polishing

To effect precision of radius and figure it is necessary to know how to control the grinding and polishing procedures to produce any specified accuracy. The physical laws that govern here apply to all optical surfaces whether curved

Figure 12

or plane. It is seldom that we will not be obliged to treat a surface with correcting strokes.

The position and length of the stroke of both grinding and polishing are the governing factors, assuming, of course, that the grinding tools are in truth. We must know how: (1) to bring down a high center (radius too short if the surface is convex, too long if concave); (2) to bring up a low center (radius too long if convex; too short if concave); and (3) to hold a radius once it is correct. In addition we must learn what causes zones and turned edge, and how to free the surfaces from them.

We will assume that a machine similar in principle to the one pictured in Figure 12 is to be used. All such machines provide adjustments for position, length of stroke, for variation of speeds of spindle and cross stroke, and for weighting.

In order to obtain as clear a picture as possible of the positions to be used, let us start by paying attention to the position of the center of the lap (or grinding tool—the methods are the same but the grinding tool effects a change more slowly at the beginning of the stroke and the end of it, as related to the center of the work). For the first example Figure 13, left, illustrates a lens with radius too long as proved by use of an accurate template or of a proof plate. Note that the stroke begins left of center of the lens and ends inside the left edge. The stroke illustrated is approximately one quarter diameter. The distance inside the left edge at which the stroke ends is such that the lap will not tilt and badly turn off the edge. Otherwise the more overhang used will result in a more rapid correction of the curve. If the stroke is not begun near enough to the center of the work a protuberance will result. The remedy in either case is to adjust the stroke until the figure runs true, and at a point that will bring the curve to truth as rapidly as possible.

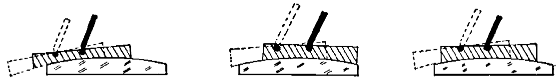


FIGURE 13

Figure 13, center, illustrates the position of a stroke to take down a high center, with the distance to the left approximately two thirds of the whole stroke length. This stroke, with the added effect of the natural sinking of the lap center, will lengthen the radius. If the lap is allowed to run too long the effect of sinking will cause a central hole. This can be avoided by re-pressing the lap to keep the facets and subfacets free from the sinking effect. Should the stroke not be adjusted correctly the edge will probably show the appearance of a turn, caused by leveling off the center of the lens before the edge is touched. To forefend against this the stroke may be adjusted a trifle more to the left (Figure 13, right) with its distance the same. One third stroke is not too great for this correction. If it begins evenly to right as related to the end of the stroke at the left, the lap will be given a peculiar motion at center that will result in a zone.

After the curve is corrected, or if perchance it is correct when first examined, we halve the stroke and position between the two extremes. We begin a trifle to the right of the center and use a length of stroke approximately one quarter diameter. We will need to watch closely the results of the positioning and to adjust as required. Experience soon tells one how to adjust the strokes for any desired effect and to avoid many of the ills. These positions may be calculated mathematically but since some generous scientists list lens making in the realms of the arts we will still be obliged to work out our own technic to fit our own peculiar conditions. Many factors enter into the picture, such as, for example, temperature and pitch hardness. The one affects the other. The

polishing agent introduces a third factor. A lap that will work nicely at one room temperature will seemingly disobey the physical laws at another. An illustration of this is the fact that if a lap is bringing a short radius to truth at one temperature it will probably refuse to do so if the room cools and the lap hardens. We must run and test and adjust to obtain the curve and figure needed.

The lap can be mutilated to assist in correcting a gross departure, either by scratching the center to shorten the radius of a convex surface or the edge to lengthen the radius. This is not often necessary unless the work has been careless up to the polishing stage.

We have given in the section on "Rough Grinding After Milling" the specifications of diameters for work on the bottom and work on top, *i.e.*, the lap on top $5/6$ of diameter, lap on bottom $6/5$ of diameter. Under normal conditions no difficulty should be encountered if these diameters are used to an approximate degree. At times a variation of the sizes will shorten the work period. The variations must be worked out for the conditions encountered.

The speeds of the spindle and cross stroke will vary with the diameter of the work and the precision of the lenses. For a small block of less than 6-inch diameter we may use from 75 to 150 rpm on the spindle. The cross-stroke speed may run from 40 to 80 per minute, counting one movement to and fro as one stroke. These speeds may seem excessive for highly precise work but there are the other factors of weighting and the type of polishing agent, as well as the pitch hardness. The best method is to run the speeds as rapidly as the work will allow without deformation from heat, regardless of our conviction in the matter. Particularly is this true until the time when a clear grainless polish is secured, after which we may reduce the speeds for best figuring effects.

Weighting is important. For preliminary polishing we add weights on the driving pin to effect the quickest polish without encountering severe distortion of figure. Otherwise the period of figuring will be increased. When the figuring period begins we may reduce our weights and change the polishing agent to effect a slower, and therefore a cooler, polishing action. If the lap backing is of iron of no unusual thickness it will probably prove sufficient weight in itself for figuring. If of aluminum we may add approximately 2 pounds per square inch of area. There is no hard and fast rule about it. It must be worked out for each set of conditions. A stock of different weights will settle the immediate question that arises.

For irregularities of surface we must pay attention to the lap contour to ascertain that it is polishing evenly in the position at which it has been set. Large laps are customarily given a system of cross grooves, and often subfacets, as mentioned in the section on forming the lap. Small laps require only the subfacets.

In polishing blocks of lenses we should note at the beginning of the period whether or not the whole block is polishing evenly. If the edge is polishing first the stroke position should be adjusted. Likewise it may polish first at the center and again we adjust the stroke. If the center of each lens is grey while the edge is polishing, we have encountered a temperature effect of the pitch. Unless the effect is gross we may continue polishing for a short time to find whether the condition persists. If it does persist the remedy is to warm-press the block in the tool in the blocking room and fine grind it again. Sometimes the lenses will be found tilted so that one side polishes before the other side is touched. A similar cure is indicated. If the center of each lens polishes first the effect of the blocking pitch is the reverse of the first example. If not gross the polishing may continue but if decidedly gross the block should be returned for correction and regrinding.

The temperature effects mentioned also will be an indication to the lay optician that lenses blocked in multiples may not be brought to the precision required for some types of lenses, such as astronomical achromats and fine camera objectives. Certain stresses generate strains that will be released when the lenses are unblocked and these will distort the figure. It is not a matter of consequence for terrestrial instruments, while it is very much a matter for concern in the higher types of lenses. We have given a remedy in the blocking section.

We have mentioned that the same technics of positioning apply to grinding, while it may appear that we have stressed their effects in polishing. The reason for this is that during polishing the effects are more noticeable if a proof plate is used. Metal tools wear slowly but if the positioning is wrong they will go out of truth all too quickly, simply because they will wear according to the physical laws given. We may temporarily overhang a metal tool to shorten a radius—one that has been ground with an untrue tool in a previous grade or if the tool was not true to begin with and provided the departure is not gross. This, however, will soon change the curve of the tool. These drastic remedies are not always the best cure for our ills. It may be better to correct the tool at once—in fact, it is likely to be so.

Forming the Lap

Lap backing tools must be provided for the approximate specific curve or plane to be polished. Usually these are of metal, aluminum or iron. For plane surfaces or curves of long radius the metal backings should be ribbed for rigidity, especially when the object is to be highly precise. Often it is advisable to provide a screw adapter to accomodate the lap to the polishing spindle. Such an adapter is shown in Figure 14. Certainly the lap must have a socket of some kind to fit the driving pin. One way of accomplishing both results is shown. The central tapered bushing will take the wear and may be driven out and replaced by new ones as often as required. When the screw adapter is not needed the bushing may be inserted directly in the lap backing. This will lower the pin closer to the work.

Deciding when to use the screw adapter will require the use of judgment. For small blocks of short radius the pin will be so high above the work that ill effects from a tilting action will be encountered.

If plane surfaces are to be polished an optical flat of reasonable accuracy

may be used to flatten warm and soft pitch. For curved surfaces some plants provide a curved lap forming tool of equal but opposite curve, over which the lap is formed. Single lenses obviously are no problem since the lens surface itself becomes the forming tool.

In many plants the curved block itself customarily is used for forming the lap. The technic is simple. Provide a pot of warm pitch of about the consistancy of molasses, and a pot of hot water. Set the block on the spindle. Handles to fit the screw adapter provide an easier means of manipulating the lap. Dip the face of the cold lap backing into the pitch and withdraw it. A thick film of pitch adheres. Let it cool slightly, and dip again. Continue until the thickness of pitch is approximately ¼ inch. Paint the block with a polishing agent to forefend against the pitch sticking to it. While the pitch is still warm set it on the block and press lightly. Lift quickly and turn, press again.

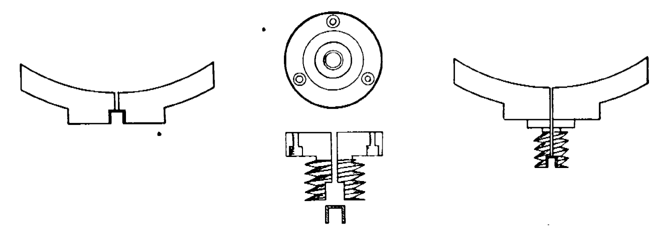


Figure 14

Continue until the pitch is too cold to flow further or until the lap is roughly formed. While the pitch naturally flows down over the edge of the lenses the turning of the lap and re-pressing takes out most of the ridges. Reheat the lap in hot water and while soft start the spindle and hold the lap on it. The lap will quickly spin to a smooth surface. As experience is gained this task is quickly done so that the temporary heating of the block, which would deform it, is not likely to become a problem.

As soon as the lap is spun smooth cool it under a cool water tap. Using the screw adapter, set it on another spindle or on a cup holder if no screw adapter is used, and start it spinning. Use a sharp single-edged razor blade or a sharp knife to cut circular grooves in the lap, from center to edge. Wash off the chips and it is ready for the start of polishing.

If subfacets are to be added stretch a clean piece of net or onion sack over the block and moisten it. Warm the pitch and set the lap on the onion sack, pressing and lifting until the facets please you. For small lenses it is not necessary to provide large circular channels but only the subfacets. For large lenses the lap will behave better if it has the deeper channels, which permit the central part of the pitch lap to spread as the pitch sinks. Crossed grooves are often used instead of circular channels. Which style is the better may be a subject of debate.

After the lap has been in use for a time, depending on its softness, it will need re-forming. Here again the hot water pot is used to soften it and re-form it as required. If the channels have filled they should be recut. Faulty stroking may deform the lap to such an extent that it will need re-pressing. In any event the second forming is easier to do.

Abrasives—Garnet Fines, Barnesite, Cerium Oxide, Rouge

The abrasives designated in the lists that follow this section are, in each kind, graded by numbers from coarse to fine. It is not pretended that this is a complete list of abrasive manufacturers; those included are for illustrative purposes. Except one example, we know of no abrasives that are adequately graded as to grit sizes for optical uses. They seem to be manufactured as general purpose abrasives. To be sure, we "get by" with them, for the most part but not always.

For illustration, if we select No. 280 aluminum oxide, grind a surface with this abrasive and then examine it we shall find many large and deep pits between plateaus of finer pits. If then we place a sample of the abrasive under a low power microscope we shall see these same large grains, some smaller ones, and some smaller still, down to visible powder sizes. Until the larger grits are broken down the sizes beneath them do not work but merely add poundage.

True enough, some of the manufacturers themselves warn that in their own brands the grain sizes are not graded as well as the powder sizes. However, we have found little difference in the grading of any of them except in the one example alluded to. Elsewhere in this volume is a chapter on the washing of such grits to adapt them to optical work. It would be well to study this closely.

When selecting abrasives for lens grinding the points that must be considered are: (1) fastest cutting grains, (2) less rapid cutting but smaller pit depths, (3) medium cutting small powders, (4) finest finishing powders.

In the first of these groups we would place Carborundum, regardless of its grain or powder size. The pits from this abrasive are very deep. Shallower pits are usually encountered with aluminum oxide. This abrasive, then, we place in the second group. Our experience indicates that, except in the largest roughing sizes, it is preferable not to use silicon carbide for optical work.

In the third group we place natural corundum or emeries. These cut fairly rapidly and, in powder sizes, will provide a fairly uniform surface that will polish readily. Due to the prevalence of scratches with the very smallest sizes we ceased using them and limited the use to No. 1500. Crown glass ground with this abrasive and polished at the usual speeds for precise surfaces will polish clear of pits in about six hours.

In the fourth group we place Garnet Fines, the only abrasives we know of at present (1953) that are numbered to measured size (by grain size in microns). Garnet Fines are manufactured from natural garnet, are well graded, give a uniform grind in all sizes, and an exceptional finish in the smaller micron designations. In fact, with No. 8 (8 microns, though this is not the smallest size) the grind, if properly done, will polish out on crown glass in about two hours.

We must, however, be fair. All the faults of grinding cannot be placed at the door of the abrasives. The optician must know how to get the most from the material he is using, and how to avoid other possible sources of damage to the surfaces. We list these sources in about the following order of importance:

(a) Scratches from unbeveled edges of the glass. The digs from this source are deep, very annoying, and needless. The remedy is obvious.

(b) Contamination with coarser grains, through carelessness.

(c) Failure to be cleanly in washing up between grades. This means the work, the tools, and the working area. The fault is laziness, the remedy obvious.

(d) Rough handling of metal tools in which they are knocked about the edges and the metal is "upset," causing a high protuberance which will surely dig the glass.

Most mirror makers are familiar with a sequence of grits that will, it is true, adequately handle the grinding operations of glass, such as No. 80, 120, 280 grains, 400 and 600 powders, followed by emeries, to which finer finishing powders were added in the decade roughly of the 40s. For grinding operations after diamond milling, with 120 diamond grits, we may select a sequence as follows: (1) 280 aluminum oxide to relieve the faults of milling and the scores of the diamond grits, (2) No. 30 Garnet Fines for the start of "fining." (3) No. 14 for medium finishing, (4) No. 8, No. 6 or No. 4 for final finishing. None of these grades will require tedious operations if the curve of the milled blank is close to truth. Normally, 20 minutes' grinding with each of the grades named will suffice for the finest surface of hard glasses such as Pyrex. Of course, there may be causes, such as the correction of curves, deep digs, or a soft, brittle glass such as the dense flints, that will increase these grinding periods.

Barnesite is a mixture of cerium oxide, rare earths, and possibly other elements, manufactured by Lindsay Light and Chemical Co., Chicago, Ill. Since its inception during the years of World War II it has become a standard product for rapid and scratchless polishing. It is known and used all over the world. As mentioned elsewhere in this chapter, we use it for all polishing operations except the most precise figuring. However, we have been unable to slow down its action sufficiently to obtain surfaces accurate to $\frac{1}{20}$ wavelength. For this we use a soft, slow-cutting rouge. We also know of good opticians who have stated that they use it even for those surfaces. They, being men of skill and honor, must therefore know something about handling the operations that we do not know.

Cerium oxide, termed by the French *rose d'or,* is an excellent polishing agent provided it is properly graded. It has a tendency to harden the lap surface (as also to a lesser degree does Barnesite) and therefore the lap should start a trifle softer than would otherwise be the case. It does not polish, in our hands, as rapidly as Barnesite. An advantage is that its color is not readily seen if in wrong places.

We have mentioned the use of a soft, slow-cutting rouge for figuring surfaces. Many rouges are on the market. Many of them sleek and scratch. In most cases the price of the rouge is low and we might well wish that the quality could be improved and the costs thereof be included in the price. In a fine, soft rouge there should be no conglomerations. Examined under a low power microscope each particle should be a separate crystal and not an over-burned aggregate that will not break down during polishing until after it has done its damage. A fine, soft rouge made and sold (not less than 5 pounds) by the Bausch & Lomb Optical Company is their wet red polishing compound.

Silicon Carbide

Carborundum: The Carborundum Co., Niagara Falls, N. Y. Grain sizes: 4, 6, 8, 10, 12, 14, 16, 20, 24, 30, 36, 40, 50, 60, 70, 80, 90, 100, 120, 150, 180, 220, 240. Powders: 280, 320, 400, 500, 600, 1000. (Also F, FF, FFF series, less well graded.)

Crystolon: The Norton Co., Worcester, Mass. Grain sizes 8 through 600.

Aluminum Oxide (synthetic corundum)

Aloxite: The Carborundum Co., Niagara Falls, N. Y. Grain sizes 4, 6, 8, 10, 12, 14, 16, 20, 24, 30, 36, 46 (40), 54 (50), 60, 70, 80, 90, 100, 120, 150, 180, 220, 240. Powders: 280, 320, 400, 500, 600. (Also F, FF, FFF series.)

Alundum: The Norton Co., Worcester, Mass. Grain sizes: 20, 24, 30, 36, 46, 54, 60, 70, 80, 90, 100, 120, 150, 180, 220, 240. Flours: 280, 320, 400, 500, 600. (Also unclassified flours F, 2F, 3F, 4F, XF.)

Natural Corundum

Bausch & Lomb Optical Co., Rochester, N. Y. Catalog numbers are listed thus, for example: 21–80–0060, which apparently has the significance of the final number. Both roughing and fining grades carry the same prefix of numbers, hence we list only the final numbers. Roughing grades: 0060, 0080, 0090, 0100, 0120, 0180, 0220. Fining grades: 0500, 0600, 0750, 1000, 1150, 1200, 1600, 2100, 2600.

American Optical Co., Southbridge, Mass.: M100, coarse, for roughing; M301, extra coarse for roughing; M302, medium, for smoothing; M302½, fine, for polishing; M303, extra fine, for polishing; M303½, superfine, for finishing; M304, ultra fine, for polishing.

Natural Garnet

Universal Shellac and Supply Co., 540 Irving Ave., Brooklyn 27, N. Y., distributor. Garnet Fines: Nos. 30, 28, 25, 20, 16, 14, 12, 10, 8, 6, 4. These numbers designate the actual size of grains of each powder in microns. This

material is softer than either natural or synthetic corundum and produces very shallow pits.

Surface Inspection During Polishing and Afterward

As polishing proceeds we will need an efficient means of determining when it has relieved the pits and sleeks. A 100-watt bulb with a 10 × magnifier used with good eyes should tell all that needs telling while the lenses are still in the block.

It is difficult to remove all the polishing agent and this may appear to be small pits. Wipe the surface with a clean finger. If the "pits" move they are not pits. If they do not move they are.

For use after lenses are fully polished there is a still better means of inspection. Place a fluorescent light bulb at a point just above the level of the

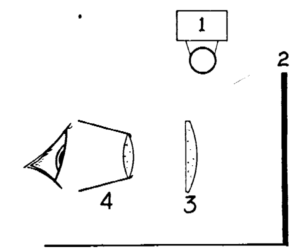


Figure 15

Inspection of lenses. 1. Fluorescent bulb and fixture. 2. Black paper screen. 3. Lens being tested. 4. 10× magnifier.

eye. In the background place a piece of rough black paper. Clean the lens with ether, or a solution of ether and ammonia, or a solution of ether, liquid soap and water, using a piece of lintless cloth. Hold the lens below the fluorescent bulb and look through it with a magnifier toward the black paper. Figure 15 shows the general arrangement. Here again, surface contamination may appear as pitting but the method already described applies. If pits or sleeks or scratches exist on the work a decent pair of eyes will find them. With the arrangement shown it is easier to find them than when the lenses are in the block.

Experience teaches us much about inspection. If we were at all suspicious that pits remain when the lenses are in the block, it is wise to polish until there is no doubt of their being polished out, since, once they are out of the block, if they are faulty, nothing remains to be done except to reblock them, regrind and repolish.

During this inspection bubbles, seeds, feathers, stones and striae of a coarse sort will be visible. Seeds in small quantities are not normally a reason for rejection. Small bubbles are prevalent in some glasses and we must accept the glass or do without it. Very small stones will not harm the image. Small and fine striae visible under an autocollimation test may be tolerated in lenses, except in high precision instruments. All depends on the use to which the lenses are to be put. In a coronagraph objective lens the glass must be perfect, and must be perfectly polished.

Centering and Edging

In commercial lens making operations centering and edging are customarily carried out by special machines having a turret, horizontal spindles, and a diamond abrasive wheel. These machines are fairly rapid in operation. Figure 16 is an example of such a machine. The cup chuck at its left, having a diameter smaller than that of the lens to be edged, is warmed with a Bunsen burner, centering pitch is applied to the rim, the lens is warmed and stuck to the pitch. It is then centered by means of a small wooden or plastic rod at the edge of the lens. It will be necessary to play the flame of the Bunsen burner on the chuck to soften the pitch enough so that the lens will move to centered position. This spindle has a foot clutch by which it may be engaged or disengaged as required to complete the centering procedure. A light to the rear

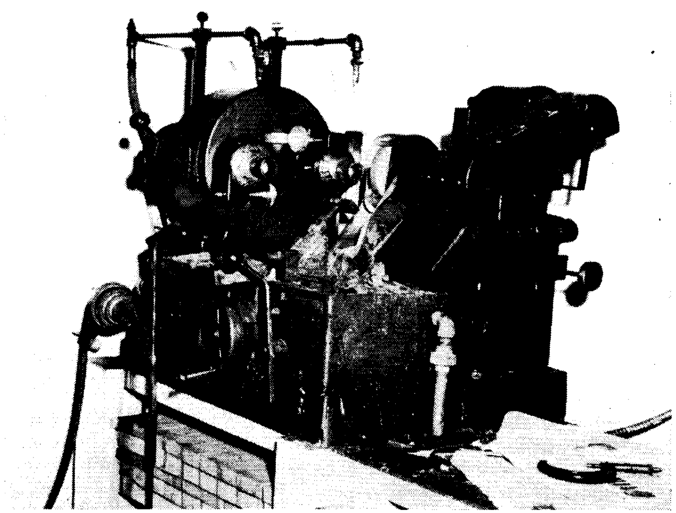


Figure 16
Centering and edging machine

of the operator permits examination of the eccentricity of the images from front and rear surfaces of the lens. As soon as the lens images of the light cease to rotate eccentrically, the chuck is cooled by a small stream of water. The left spindle is then swung, by means of the turret, to the right, or edging position. An automatic feed is a feature of the machine, and there are stops that end the advance of the diamond wheel when the correct diameter is reached. To prevent "firing," the lens is cooled by a stream of water as the edging proceeds.

Beveling the front edge of the lens is then accomplished with a metal lap having a much shorter curve than the lens, to which is applied a medium grit, such as No. 400 aluminum oxide, and water. The spindle is allowed to rotate for a few seconds to finish the edge of the lens. Removal from the spindle is accomplished by a sharp tap on the chuck with a small hammer. Next, the other side of the lens is similarly beveled by manual rotation of the beveling lap.

While the edging is proceeding on the cutting side another lens is being placed in position on the left spindle. The time of the operator is therefore very well occupied with these tasks.

Non-precise optics of terrestial types usually are given an allowance of eccentricity or "wedge." For very precise optics the centering should be carried out to the fullest extreme possible. This is especially true with high quality astronomical objectives and fine camera objectives. A small amount of wedge will have an ill effect on the definition.

The final diameter of a precise objective lens must, of course, be circular and not "egg-shaped" and it should be exactly the same as that of any mating component, otherwise cementing will produce a wedge from inability to center one element on the other.

For lenses larger than 4 inches aperture it is necessary to abandon the horizontal spindle for a vertical one, particularly if the lenses have appreciable weight, since it will be found very tedious to endeavor to keep a large lens in position of truth while the cooling of the chuck is carried on. Anyone having access to a lathe can devise a way to make at least a simple spindle for use in a vertical position with proper accessories for these special jobs.

For heavy lenses it is well to guard against scratches or marks from the metal chuck as well as from the rod by which the lens is pushed into position. A ring of paper beneath the lens will obviate the scratch and mark risk.

A substitute centering pitch may be made from sealing wax with a small admixture of rosin or hard pitch. The centering pitch should become viscous enough at a relatively low temperature for the lens to be moved into position but still rigid enough to hold while being cooled. If it is too soft for handling it may be hardened by melting in to it a quantity of flake shellac.

Diamond milling or grinding procedures should be carried out to provide the least wedge possible, and not over .003 inch of wedge should remain at the start of polishing. In some cases this will be far too much and the diameter of the centered and edged lens will be below the necessary aperture. Excessive wedge will slow down centering operations unduly. With diamond milling this is easily remedied by ascertaining that the base of the cup that holds the lens blank to be milled is exactly perpendicular to the axis of the milling spindle when set at zero curvature. With care, then, the remaining wedge will be of the order of .0005 to .001 inch.

Without such a machine, and where the blank is to be ground from beginning to end, it is necessary to provide a stop on a micrometer and special pointed anvils to measure the depth of glass at the same distance from the periphery each time. Unless the lens blank is truly circular the measuring cannot be accurate. An alternative is to use a plate with three ball supports at 120°, two vertical stops to position the lens and a dial gage to read the thickness as the lens blank is rotated. The thick and thin dimensions may be determined, and the discrepancy from parallelism measured thus. It is not difficult to grind on the side needing it most until the blank is practically relieved of wedge. Such a course of action is especially suitable for any lens of 4 inches or more aperture as a component of astronomical objectives.

Cementing of Lenses

We may divide lenses to be cemented into two classes: (1) Those that are to be subjected to extremes of temperature change; for example, from the heat of a desert to the cold of high altitudes in a short period of time. (2) Those that are to be subjected only to such changes as are encountered in normal usage, such, for example, as astronomical objectives or ordinary camera use.

For the extremes of temperature plastic lens cements of the thermosetting types, such as Allmyr CR-39, are a necessity. These prevent splitting apart of cemented systems due to the extreme cold. For the second class of lenses Canada balsam is favored.

We will examine first the subject of balsam cementing methods. Most existing literature on the use of balsam that we have read, recites that balsam is available in soft, medium and hard states, depending on how much of the natural turpentine has been driven from it by heating. In most cases the instructions continue with methods for using soft or medium balsam but not for the use of hard. The instructions given are somewhat in the following form: Lenses to be cemented are cleaned thoroughly free of dust, lint, greases or other contamination. They are then heated over a hot plate on which an asbestos pad and clean paper have been placed. A few drops of soft or medium balsam are placed in the center of the concave surface and the convex surface is lowered carefully onto the balsam. It is then rotated and stroked until the film of balsam is free of all bubbles and the excess balsam is pressed over the edges. A common bottle cork usually affords an excellent tool for this purpose.

When the bubbles and excess of balsam have been relieved, the combination of lenses is placed in a fixture to hold them in centered position. For this a three-jaw chuck of some simple form is efficient. The assembly is then placed in an oven. The balsam is hardened by baking approximately 50 hours at low temperature. For medium hardness bake at least eight hours.

The thickness of the film of cement should be of the order of .0001 to .003 inch, depending on how well the two surfaces are matched in curves, and how carefully the cementing operations have been carried out. In some cases the fitting of the curves may have been so slovenly as to prohibit satisfactory cementing.

Low heat is necessary if discoloration of the balsam is to be avoided. The temperature of approximately 250°F is satisfactory for this purpose.

Following hardening by baking, the combination is slowly cooled in the oven. The excess of balsam is cleaned from the combination with a soft cloth dampened with Xylol. They must not, of course, be subjected to more of any solvent than is fully necessary.

Soft balsam is the state most easily used if it must be filtered to relieve it of cloudy contaminations or lint and dust. For an apparatus that performs

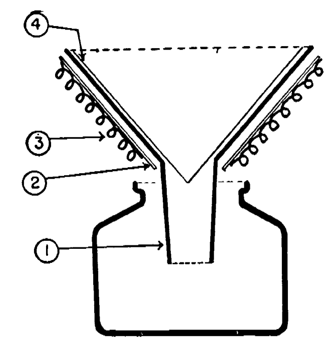


Figure 17

Filtering apparatus for Canada balsam. 1. Glass funnel. 2. Asbestos paper. 3. Nichrome coils for heating. 4. Filter paper.

satisfactorily see Figure 17. A glass funnel is lined on the outside with asbestos paper and over it coils of Nichrome wire are wound, having sufficient resistance to heat the balsam, at the voltage used, to a more liquid state, but not to overheat and discolor it. A large piece of filter paper is placed inside the funnel and filled with soft balsam. The filtered balsam is allowed to flow into a clean receptacle. This kind of treatment will result in a high degree of transparency.

The use of hard balsam has some advantages. It may be secured in stick form, or medium balsam may be hardened by heat treatment to make it. It may be heated over water, or over low heat, until it will fracture when a small drop is placed on the fingernail, cooled and pressed. This is a simple but effective test.

In the lens plant the lenses are heated, the end of a stick of balsam is melted a trifle over a Bunsen burner and several drops placed on the concave surface of the lens combination or it may be allowed to melt due to the heat of the glass. From this point on the cementing is carried out as has already been described except that, as soon as the lenses are cemented, the combination is allowed to cool slowly in a fixture and the task is finished except for final cleaning.

A 250-watt bulb is handy for heating the lenses or even for baking soft or medium balsam to hardness. In the non-stick form hard balsam is melted slowly to the softening point each time it is to be used, and is dealt with in the same manner as medium balsam. It scarcely seems necessary to say that all balsam must be protected from contamination whenever in use or not in use.

Plastic lens cements are colorless, of proper index of refraction for most uses, and are as easily applied as balsam. When set by heat they adhere most tenaciously to the glass surfaces.

They have some disadvantages, the principal one being that it is somewhat difficult to separate the lenses if for any reason they must be separated. From a production standpoint this is a drawback. Another drawback is that they shrink while setting, and the cement, if a surplus does not exist at the edges, sometimes shrinks in from the edges and forms what is termed "cement starts." The tiny formations due to this shrinkage may be seen around the entire edge or only at particular points as a lacy, fern-like discrepancy of cement which causes rejection of the cementing effort.

Plastic cements may be obtained (as far as we know) only in quantity, in monomer form or in jel form. The latter is the form that is obtained by treatment with a catalyst such as Lucidol benzoyl peroxide. The jel form is used in a consistency equivalent to the medium balsam or melted hard balsam. In the jel form it must be shipped packed in dry ice, and must be stored in a freezer to forbid as much as possible the thermosetting effects of room temperature. It is customarily shipped by air express on certain days so that its arrival will be expected on known days and it will be received by the consignee in condition for use. At normal refrigerator temperatures it will set too hard for use within four to eight weeks. It cannot be resoftened.

We have mentioned Allmyr CR-39,[6] a liquid monomer, and a catalyst, Lucidol benzoyl peroxide.[7] Let us see how we form the jel. Benzoyl peroxide is a granular material. To the clear liquid monomer we add 5 percent by weight of this catalyst. Other catalysts may be used but this is the recommended one for this monomer. Preferably these two ingredients should be combined in a covered mixing tank and heated carefully at 120°F (50°C), agitated meanwhile by a mechanical agitator. However, with some application of industry this may be accomplished manually by means of a glass stirring rod. We have usually placed the mixing tank in water and maintained the temperature at the level stated. The catalyst dissolves within about one hour, depending on the rate of stirring. After the granules are completely dissolved the mixture is cooled. The stirring is continued while cooling. If on cooling

[6] Columbia Chemical Division, Pittsburgh Plate Glass Co., Grant Building, Pittsburgh, Pa.

[7] Lucidol Division, Novadel-Agene Corporation, Buffalo, N. Y.

we find that the catalyst has not been completely dissolved the solution will appear cloudy and translucent. This will not do harm if it is only barely perceptible, but if it is very cloudy this is evidence that the dissolution of the granules has been scamped and the solution must be reheated for a (shorter) period. During this process it should be observed critically. On reheating, the solution will steadily thicken until it forms a jel of the proper viscosity. If it is not watched it may harden beyond the point of usefulness and would then be fit only to throw away. When it has reached the consistency desired it should be cooled over cold water and stored in a cold place.

Cementing of the lenses is done as has been described for balsam. The operator should make certain that they are properly alined in their centering fixtures. They must be wiped clean of surplus cement and should then be ready for baking. They should be warmed slowly to 80° to 85°C and this temperature maintained. The hardening of the cement will be accomplished at that temperature within about eight hours of this baking.

The above is a rough general outline of the materials and procedure used in cementing. Further information may be obtained from each of the producers of the available cements. In writing, we have used the one example described solely because our experience with it has been the most extensive.

Decementing is accomplished by soaking the lenses in acetone for 12 hours or more, after which they are shocked apart by dipping them in hot glycerin, lubricating oil or castor oil. The temperature for the hot glycerin should be approximately 390–420°F.

For large lenses this decementation by shock leaves much to be desired, especially when the glass is, perhaps, not perfectly annealed and the danger of fracturing it is greater. However, in production it is inevitable that certain percentages of the lenses will require separation for various reasons, such as (a) faulty preliminary inspection for surface defects, (b) accidental chipping of one element, (c) decentering, (d) cement starts. Others will be encountered only too soon. Hence, it seems best to keep in progress a thorough analysis of these difficulties and to obviate them as rapidly as possible.

Degreasers—Cleaning

One of the developments of recent years that has been adapted for use in modern lens-making plants is the use of hot vapors of such solvents as "Triad"[8] for quickly removing blocking and ordinary polishing pitches, greases and waxes from the surfaces. As lenses and prisms are removed from their respective blocks various amounts of pitch or such greases and waxes as paraffine, Saracene, Stickum, and others will need to be removed. These will adhere so strongly that their removal by less effective solvents involves a considerable waiting period.

In practice a special tank is constructed somewhat like the schematic drawing in Figure 18. The two sumps are filled with Triad to approximately

[8] The Detrex Corporation, P.O. Box 501, Detroit, Michigan, makers and suppliers of degreasing tanks and solvents Triad, Perm-a-clor, and Perchlorethylene.

the heights shown. Under sump 1 there is an electric heater that melts the liquid solvent to a temperature above the vapor point. This vapor rises in the tank until it is cooled by the water jacket through which cool water is circulated. It condenses along the sides and returns to the sumps. These degreasers are available in capacities to fill the needs of any plant.

The work to be cleaned is stacked in wire baskets that will fit into the vapor region of the top part of the tank, and is lowered by wires into the hot vapor

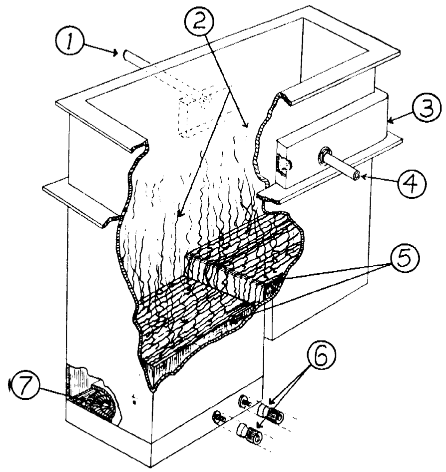


FIGURE 18

Schematic sketch of a degreaser of a type made in many sizes and for various uses. 1. Water outlet. 2. Vapor area. 3. Water jacket. 4. Water inlet. 5. Solution level. 6. Electrical connection. 7. Heating element.

where all pitches, greases, and waxes are dissolved off the glass in a few seconds. The temperature of the vapor is approximately 180°F and is much too hot to allow skin to remain on fingers immersed in it for more than a quick plunge and withdrawal. Since the heat affects all parts of the lenses at one time, it is seldom a cause of fractures in lenses of 3-inch aperture and under.

The advantages of these degreasers are the speed with which the lenses are cleaned and the complete removal of all forms of the materials mentioned that are soluble.

The principle disadvantages we have encountered are dual. One is that, if the surfaces have been coated with shellac, the heat polymerizes it and causes difficulty at times in removing it with alcohol. The degreasers we have used do not remove shellac. The second disadvantage, not, however, often encountered, has been an etching effect on certain types of glass, particularly in incipient fractures left from diamond milling and which are invisible after

adequate polishing until the etching takes place. Under ordinary inspection methods, the defects so caused appear to be scratches, but under a microscope the effects of etching appear to be lines of pits closely spaced.

These solvents are rather effective for certain operations in the cold liquid state, and where only a small number of lenses or other surfaces are to be cleaned. It may not be practical to keep the heated tank ready for use in these cases since, of course, some of the vapor is lost into the atmosphere. Even the liquid has decided advantages over such solvents as alcohol, kerosene or turpentine. These solvents are widely used in dry-cleaning establishments and this may suggest a local source of the material.

Other solvents and detergents that may be used with satisfaction for various needs are: For lacquers; acetone, lacquer thinners. For shellac and various cleaning operations; ethyl and methyl alcohols. For various surface contaminations; mild soaps, ether solutions, Dreft, Aerosol, Soilax, and other synthetic detergents which are completely soluble in water.

A Spherometer for Measuring Radii of Curvature of Small Strongly Curved Surfaces

By Irvine C. Gardner

Lens surfaces one half inch or less in diameter and with radii of curvature of 3 inches or less are difficult to measure on an optical bench or by means of a tripod or ring type spherometer. The spherometer to be presented in this chapter was originally described by Arnulf [1] and is particularly adapted for the measurement of the radii of curvature of small strongly curved surfaces. Such surfaces are found in microscope objectives and short-focus photographic objectives and projection lenses used on substandard motion picture equipment. The amateur who wishes to construct lenses of this character will find a spherometer of the type to be described almost a necessity. It is most easily constructed if one has a complete biological microscope which can be permanently converted into a spherometer. In this discussion it will be assumed that one has such a microscope available but the ingenious amateur, after understanding the requirements of the instrument from this description, will doubtless be able to improvise and avoid this requirement if necessary.

The eyepiece of a biological microscope is usually of the Huygens type. To check this remove the eyepiece from the microscope tube and, without modifying it in any way, try to use it as a magnifying glass to examine a postage stamp, an ink dot on a piece of paper, or any other suitable test object. It is probable that you cannot obtain a sharp image through the eyepiece because the proper position for the object is within the eyepiece between the two lenses. If this proves to be the case the microscope has a Huygenian or some other negative eyepiece and it is not suitable for use. It will be necessary to buy or make a positive eyepiece. The simplest positive eyepiece is the Ramsden. Two plano-convex lenses having the same focal length (20 to 25 mm) are mounted in the opposite ends of a short tube with the curved surfaces facing each other. The spacing of the lenses should be adjusted until the system can be used as a magnifier to give a sharp image when the object is approximately 4 mm from the plane surface of the lens farthest from the eye. For satisfactory operation the lenses must be permanently mounted to maintain this separation and the tube forming the mount for the lenses must be turned to the proper size to properly fit in the eye end of the microscope. It must be possible to adjust the eyepiece up or down for focusing and the friction must be sufficient to cause it to remain at any adjusted position.

For measurements of radii of curvature low power (long focal length) objectives are most often required. It is convenient to have objectives of 16, 32, and 48 mm focal length. Objectives of this type can be purchased from the Gaertner Scientific Corporation, 1201 Wrightwood Avenue, Chicago, Illinois. If the dealers in war surplus materials have available telescope objectives of

[1] Albert Arnulf: La Mesure des Rayons de Courbure des Surfaces Sphériques employées en Optique. (1930) Institute d'Optique, 3 and 5, Boulevard Pasteur, Paris.

50 to 60 mm focal length and of 90 to 100 mm focal length, two of the first objectives mounted close togther with the flatter flint faces turned toward the object will provide a useful objective of approximately 32 mm focal length and two of the longer focal length will combine to produce an objective of approximately 50 mm focal length.

Figure 1, left, illustrates the change that must be made in the microscope tube. Two sets of cross-wires, shown at A and B, are mounted in the tube. The cross-wires at A must be positioned within the focusing range of the eyepiece in order that the eyepiece can be adjusted to permit them to appear

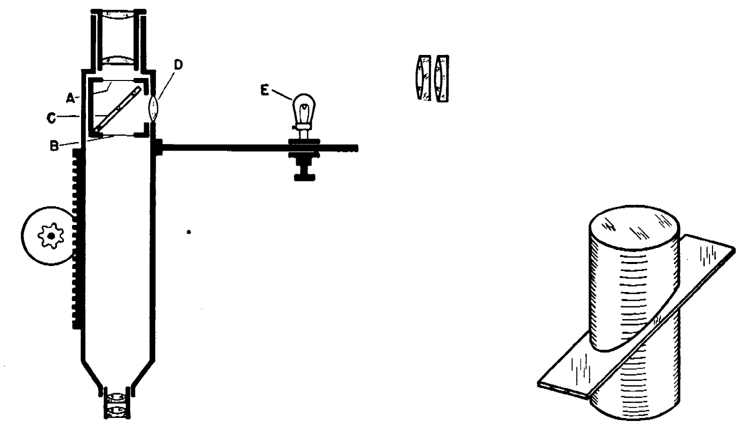


Figure 1

Left: Microscope tube with Ramsden eyepiece and required parts for use as a spherometer. Right: An easy method for edging an elliptical mirror.

perfectly sharp. Below the cross-wires there is the diagonal mirror C which makes an angle of 45° with the axis of the microscope. An ellipse cut from a piece of microscope cover glass and unsilvered is a satisfactory mirror. Figure 1, right, illustrates a jig for producing an elliptical mirror. A metal circular cylinder of the proper diameter is cut in two at an angle of 45°. By means of sealing wax or a mixture of beeswax and rosin the cover glass and the two parts of the rod are assembled as shown in the same illustration. The projecting parts of the cover glass are chipped and ground off flush with the cylindrical surface. The grinding can be done with emery and water by hand on a plane lap or in a lathe. The lower set of cross-wires is mounted as close to the upper set as the diagonal mirror will permit. The cross-wires of each set intersect at 90° and the lower pair should be rotated 45° with respect to the upper. In other words, if the upper cross-wires are assumed to extend north, south, east and west from the center, the lower ones will extend northeast, southeast, southwest, and northwest. With a little ingenuity the two sets of cross-wires and the diagonal mirror can be assembled as a unit before sliding it into the microscope tube. An opening in the side of the unit must be provided for the admission of light to the diagonal mirror.

After the unit composed of the cross-wires and mirror has been constructed and its position determined with respect to the eyepiece, an opening in the side of the microscope tube must be cut as shown in Figure 1, left. This opening is covered by a window, *D*, which is cut from a lens of approximately 1¼-inch focal length. A support must be provided to carry a small flash lamp bulb, *E*. The light from the lamp passes through the opening in the side of the microscope tube and is reflected downward toward the microscope objective. When the lamp is correctly adjusted an image of the filament will be found centered in the microscope objective. This can be checked by stretching a layer of tissue paper over the objective to serve as a screen and looking into the objective from below. It is advisable to have the lamp adjustable to permit it to be moved toward or from the microscope body until this adjustment is attained. Means for this adjustment can be easily provided by mounting a rod at right angles to the microscope axis. The lamp is carried on a slider which can be clamped at any distance. This arrangement is suggested in Figure 1. A machine screw is a simple and adequate means of clamping the slider as the adjustment does not have to be changed often. A flash lamp bulb operated by two dry cells or by a door-bell transformer will give all the light that is required.

Although the spherometer is not completed at this stage an interesting test can be made which will show whether or not the optical system is satisfactory. A lens surface with a radius of curvature of 25 to 50 mm is a suitable test object. The curved surface of a plano-convex lens with a focal length of 50 to 100 mm will be about right. First, focus the eyepiece carefully on the upper cross-wires. Then place the lens on the microscope stage with the curved surface upward and center it approximately with respect to the axis of the microscope. Rack the microscope upward to its limiting position and turn the flash lamp bulb on. Now, while looking into the eyepiece, slowly rack the microscope downward. At first a bright field should appear and then a reflected image of the lower system of cross-wires should come into view and become sharper as the movement is continued. Finally both sets of cross-wires should appear equally sharp and apparently in the same plane. In general the intersections of the two sets of cross-wires will not be superposed. By moving the test lens laterally on the stage the image of the lower cross-wires can be centered with respect to the upper cross-wires which are viewed directly through the eyepiece.

There are two positions for which this reflected image can be obtained, sharp and in the same plane with the upper cross-wires. If the objective of the microscope is very close to the test surface you probably have the lower position and it should be possible to find the second position by racking the microscope upward a distance approximately equal to the radius of curvature to be measured. On the other hand if the distance of the objectives from test surface is somewhat greater than the radius of curvature of the test surface the second reflected image will probably be found by racking downward. The range of

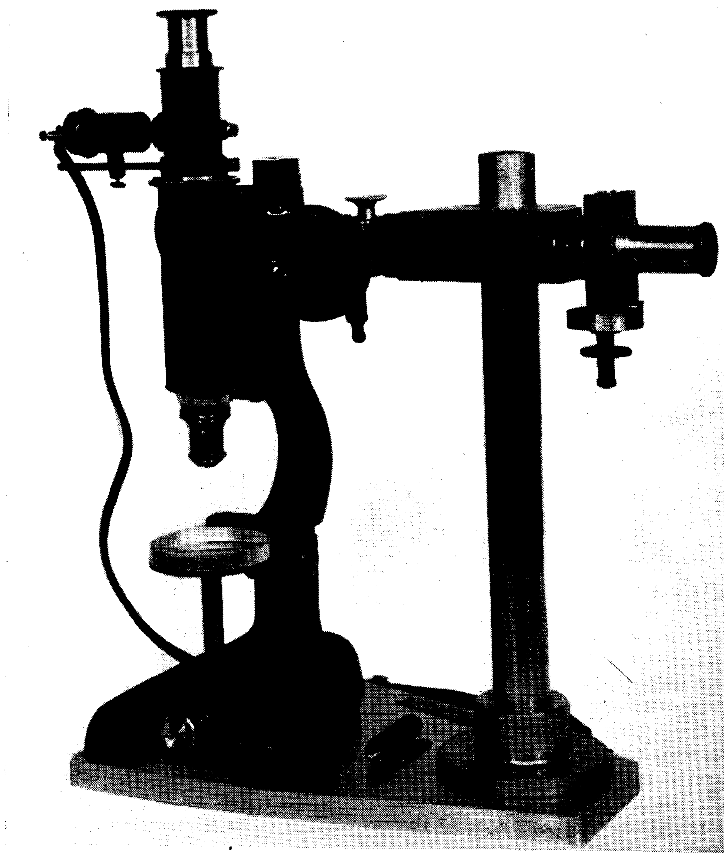
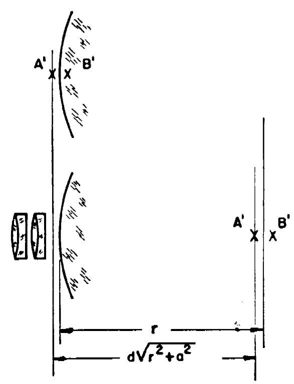


FIGURE 2

Optical spherometer as constructed for use at the National Bureau of Standards. The vertical movement of the microscope is read on a vertical scale ruled with diamond on stainless steel. The least reading of the micrometer drum on the microscope for reading this scale is 0.01 mm. Microns can be read by estimating tenths. This instrument was designed by Mr. F. A. Case of the National Bureau of Standards Staff.

adjustment provided by the rack and pinion movement must be somewhat greater than the radius of curvature to be measured and the two positions which have been mentioned must both lie within this range of movement. It may happen that the reflected image for one position is obtained when the microscope is near the middle of its vertical movement and there is not sufficient range of motion to reach the second position. In this case it will be necessary to remove the microscope stage and provide a support which will raise or lower the test surface as required. It is convenient to provide a small circular table carried by a vertical rod which slides up or down to adjust to any height. Such a table will have to be adjusted at different heights for



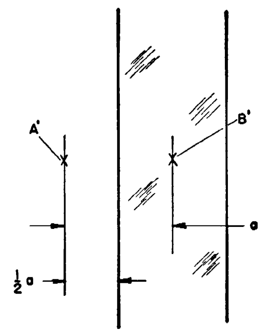


FIGURE 3

Diagrammatic sketch of optical system of spherometer

FIGURE 4

The two positions for which the two sets of cross-wires viewed through the microscope, appear to be in the same plane.

convex and concave surfaces. When the adjustments have been made to bring both settings within the range of the rack and pinion movement pass back and forth from one setting to the other and adjust the test surface laterally on its support until the intersections of the two sets of cross-wires remain superposed for both settings.

The distance through which the microscope tube is moved to proceed from one reflected image to the other is approximately equal to the radius of curvature. Consequently a means must be provided to measure the movement of the microscope. A 6-inch mechanics scale such as is sold to be clamped into try-squares, centering gages, levels, etc., provides an inexpensive scale for the purpose. This can be mounted vertically on the microscope barrel and a pointer or vernier fastened to the fixed part of the rack and pinion movement. These scales can be ordered graduated in millimeters although the ones carried

in stock in this country are usually graduated in inches. With a simple indicator it is possible to read the radius of curvature to tenths of a millimeter and with an accurate vernier the readings can be made to two or three hundredths of a millimeter. It is more elegant and precise to have a carefully engraved and calibrated scale read by means of a micrometer microscope. This arrangement is shown in Figure 2, which is a photograph of the spherometer of this type as used at the National Bureau of Standards. With this arrangement successive readings should differ only a few microns. This instrument was designed and its construction supervised by Mr. F. A. Case of the National Bureau of Standards Staff.

The theory of operation will now be explained and the exact formula for the radius of curvature derived. Figure 3 shows the optical system of the microscope with the two sets of cross-wires at A and B. The images of these cross-wires at A' and B' are shown as they would be formed by the microscope objective if light were traveling from left to right. In other words A' is conjugate to A, and B' is conjugate to B with respect to the objective. The distance from A' to B' is designated a. In use light does travel from B through the objective and forms an image at B'. If now a reflecting surface is brought into position so that, by reflection in this surface, an image of B' is formed at A', then this light will proceed after reflection back through the objective and form an image in the plane of A, since A and A' are conjugate. It is evident from our experiment that there will be two such positions for a given spherical surface. The equation relating to these two positions will now be derived. The equation connecting object and image distances for a spherical reflecting surface is

$$-\frac{1}{s'} = \frac{1}{s} - \frac{2}{r}, \tag{1}$$

where s is the distance from the surface to the object, s' is the distance from the vertex of the surface to the image, and r is the radius of curvature. All distances are measured from the vertex of the surface and are positive if they extend to the right. In the upper half of Figure 4 s and r are positive and s' is negative because it lies to the left of the vertex. In the lower half s, s', and r are all positive because all distances are measured to the right of the vertex. Since the distance from A' to B' is a, one has the equation

$$-s' + s = a. \tag{2}$$

Combining this with equation 1 the quadratic equation

$$s'^2 + (a - r)s' = \frac{ar}{2} \tag{3}$$

is obtained. This has the two roots

$$s' = -\tfrac{1}{2}(a - r) + \tfrac{1}{2}\sqrt{a^2 + r^2} \tag{4}$$

and

$$s' = -\tfrac{1}{2}(a - r) - \tfrac{1}{2}\sqrt{a^2 + r^2} \tag{5}$$

corresponding to the two settings for which the reflected image of the cross-wires was obtained. Since A' has a fixed position with respect to the microscope tube the total displacement, d, required to pass from one reflected image to the other (see Figure 4) is equal to the difference of the two values of s' given by equations 4 and 5. Therefore

$$d = \sqrt{a^2 + r^2}. \tag{6}$$

Squaring both sides and solving for r, one obtains the equation

$$r = \sqrt{d^2 - a^2}. \tag{7}$$

To determine r by this equation it is necessary to determine the value of a. To do this place an optical plane on the microscope table and adjust the microscope until the reflected image of the lower cross-wires is seen in the plane of the upper cross-wires as in the previous settings. This condition is illustrated in Figure 5. It is evident that A' and B' will lie on opposite sides of the plane

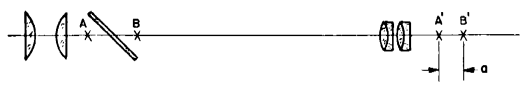


FIGURE 5

Method of determining the value of a by use of a plane reflecting surface.

surface and equidistant in conformity with the relation between object and image with respect to reflection in a plane mirror. If an optical plane is not available the surface of a piece of plate glass selected to give a clear reflected image will introduce no important error. After the reading corresponding to the reflected image is obtained the microscope is focused on the reflecting surface. This may be facilitated by dusting a powder such as fine dry rouge upon the surface to provide an object upon which to focus. When the powder and the upper cross-wires appear in focus simultaneously a reading on the scale is again made. It is evident that the difference between these two readings, multiplied by 2, will give the value of a. All information is now available for measuring a radius of curvature precisely. The surface to be measured is placed on a suitable stage and the two settings made which give the reflected image in the plane of the upper cross-wires. The difference of these two readings is d. Substituting d and a in equation 7 gives r.

There remain some general considerations of interest in connection with this method of measuring radius of curvature. If the cross-wires A and B are brought as close together as possible the length a, when a microscope objective of short focus is used, may be so small that it is sufficiently accurate to write r equal to d. The question then arises, why not always use an objective of short focal length in order that a may be neglected? The reason why this cannot be done is apparent on reference to Figure 4. It is seen that the distance from the front surface of the objective to B' must be somewhat greater than the radius of curvature of the surface to be measured in order that mechanical interference may not prevent the setting in which B' is beyond the center of curvature as shown in the lower half of the figure. This condition only arises when measuring a convex surface. When measuring a concave surface the center of curvature is accessible even if B' is very close to the objective. A second limitation arises because the travel provided by the slow motion of the microscope stand must be approximately equal to the radius of curvature to be measured. On a standard microscope stand a movement of approximately 75 mm is provided and consequently this is the longest radius of curvature that can be measured with the instrument as described. If one has an optical bench with horizontal ways it is evident that a microscope with double cross-wires as described can be mounted horizontally on the bench and used to measure concave surfaces of any radius falling within the length of the optical bench, the value of d being read on the scale of the bench. This method could also be extended to the measurement of convex surfaces on the optical bench provided that a microscope objective is provided of such focal length that the distance from the objective to B' is greater than the radius to be measured. But in this instance a new complication, not insurmountable but difficult, arises. If the distance from the objective to B' is increased without increasing the diameter of the microscope objective, there will be so much depth of focus that the settings cannot be determined with precision. If, for example, the distance from the objective to B' is to be increased to 250 mm (10 inches) the diameter of the microscope objective should be of the order of 50 or 60 mm (2 to 2½ inches) if sharp settings are to be made. The experienced microscopist will recognize that an objective of large *numerical aperture* is required if precise settings are to be obtained. Consequently when measuring either a convex or a concave surface it is well to use a microscope objective of the shortest focal length available which is suitable for the particular surface. In general the objectives of the shorter focal lengths have the larger numerical apertures and consequently will give the most precise settings. Also for the shorter focal lengths a becomes less and there is a greater probability that its value will not need to be taken into account in the formula.

Objectives of long focal length and of large numerical aperture (large diameter) are not commercially available and are difficult to improvise. Consequently if it is necessary to measure a convex surface of large radius of curvature precisely it is advisable to make a matching concave surface. Its radius of curvature can be measured on an optical bench by the method referred to in this chapter or by any of the other well known methods. The concave and the convex surfaces are then placed together and the difference between the radii of the two surfaces determined by counting the Newton's rings.

The Design of Telescope Objectives by the G-sum Method

By Alan E. Gee

Ellison and Haviland have, in ATM and ATMA, proposed methods for the design of achromatic objective glasses. These methods are very simple, and produce objectives that are properly corrected for color, and in some applications are completely satisfactory. However, their degree of correction for spherical aberration and coma depend entirely upon the particular glasses chosen. The designer has no control over these aberrations, and no means of determining whether they are good or bad for any two particular glasses. The purpose of this chapter is to carry the algebraic design further so that it will also include full correction for spherical aberration in all cases, and full correction for coma in particular cases.

We shall investigate the cemented type of objective, and the Fraunhofer

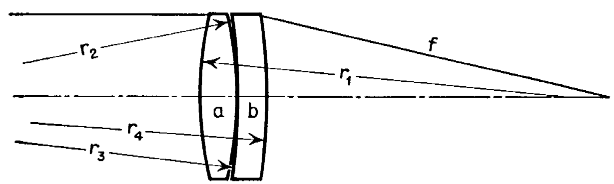


Figure 1

type in detail, with a brief discussion of four other types: objective having equiconvex crown element, objective with one surface of the flint element plano, an air-spaced type, and a Barlow lens.

Because we shall be correcting for additional aberrations, these methods will be somewhat more complicated and difficult than those of Ellison and Haviland. (Our worst mathematical chore will be the simultaneous solution of a linear and a quadratic equation.) Nor will we be designing as completely as ray tracing would afford. In fact, we shall carry our design just to the point where the experienced designer would ray trace to determine exactly what aberrations remain, and try to correct them by differential corrections. Our methods will be approximate (as are all algebraic lens design methods), so that the completed lens will have small residual aberrations. However, in the typical $f/15$ telescope of moderate aperture these will be very small, and the only one of importance, residual spherical aberration, can be completely corrected by figuring the last surface of the lens, as would probably be done in any case.

First thing we must decide upon is a simple sign convention so that positive and negative signs in our solutions will have a meaning. We will always assume that light is entering our objective from the left hand side (meaning simply that the object is on the left). Our convention will be, then, that ***surfaces*** having their centers of curvature to their right will have positive

curvature and radius. Those having their centers of curvature to their left will be negative. A magnifying lens will have positive curvature and focal length, a minifying *lens* negative. For example, in Figure 1 r_1 is positive, r_2, r_3, and r_4 are negative; element a is positive, element b is negative.

For designation of the various parts of our lens we will use the following notation:

subscript a refers to the crown element.

subscript b refers to the flint element.

subscripts 1, 2, 3, or 4 refer to the surfaces of the lens, numbered from left to right.

n = index of refraction for D light.

V = V-number, or constringence.

P = power of a lens element.

f = focal length; if without subscript this means of the complete objective.

C = curvature.

r = radius of curvature.

Δn = dispersion $(n_F - n_C)$.

First we will list and number all the equations with which we shall be working. Not all the equations will be used for any particular lens type, but all will appear in this discussion before we are finished.

Achromatism:

$$C_a = \frac{1}{(V_a - V_b)f(\Delta n_a)} \quad (1)$$

$$C_b = \frac{1}{(V_b - V_a)f(\Delta n_b)} \quad (2)$$

Spherical Aberration:

$$P_a = \frac{1}{f_a} = C_a(n_a - 1) \quad (3)$$

Now take a deep breath:

$$[G_1C_a^3 + G_2C_a^2C_2 - G_3C_a^2P_a + G_4C_aC_2^2 - G_5C_aP_aC_2 + G_6C_aP_a^2]_a$$
$$+[G_1C_b^3 - G_2C_b^2C_3 + G_3C_b^2P_a + G_4C_bC_3^2 - G_5C_bP_aC_3 + G_6C_bP_a^2]_b = 0 \quad (4)$$

(This looks like a humdinger, but it really isn't too bad. We know everything in it except C_2 and C_3. The G-terms refer to index functions given in Table 1 on the following page.)

Coma:

$$[\tfrac{1}{4}G_5C_aC_2 - G_7C_aP_a + G_8C_a^2]_a + [\tfrac{1}{4}G_5C_bC_3 - G_7C_bP_a - G_8C_b^2]_b = 0 \quad (5)$$

Curvature:

$$r = \frac{1}{C} \quad (6)$$

$$C_a = C_1 - C_2 \quad (7)$$

$$C_b = C_3 - C_4 \quad (8)$$

Sagitta:

$$x = \frac{y^2}{2r} \quad (9)$$

Table 1—*FUNCTIONS of N**

N	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8
1.43	.440	.830	1.137	.516	1.461	.946	.580	.307
4	.456	.854	1.170	.526	1.491	.966	.593	.317
5	.473	.878	1.204	.535	1.521	.985	.605	.326
6	.490	.902	1.237	.545	1.550	1.005	.618	.336
7	.508	.926	1.271	.555	1.579	1.025	.630	.345
8	.526	.950	1.306	.564	1.609	1.044	.642	.355
9	.544	.975	1.340	.574	1.638	1.064	.654	.365
1.50	.562	1.000	1.375	.583	1.667	1.083	.667	.375
1	.581	1.025	1.410	.593	1.696	1.103	.679	.385
2	.601	1.050	1.446	.602	1.724	1.122	.691	.395
3	.620	1.076	1.481	.611	1.753	1.141	.703	.405
4	.640	1.102	1.517	.621	1.781	1.161	.715	.416
5	.661	1.128	1.554	.630	1.810	1.180	.727	.426
6	.681	1.154	1.590	.639	1.838	1.199	.739	.437
7	.702	1.180	1.627	.647	1.866	1.218	.752	.447
8	.724	1.206	1.665	.657	1.894	1.237	.764	.458
9	.746	1.233	1.702	.666	1.922	1.256	.776	.469
1.60	.768	1.260	1.740	.675	1.950	1.275	.788	.480
1	.791	1.287	1.778	.684	1.978	1.294	.799	.491
2	.814	1.314	1.817	.693	2.005	1.313	.811	.502
3	.837	1.342	1.855	.702	2.033	1.332	.823	.513
4	.861	1.370	1.894	.710	2.060	1.350	.835	.525
5	.885	1.398	1.934	.719	2.088	1.369	.847	.536
6	.909	1.426	1.973	.728	2.115	1.388	.859	.548
7	.934	1.454	2.013	.736	2.142	1.406	.871	.559
8	.960	1.482	2.054	.745	2.170	1.425	.882	.571
9	.985	1.511	2.094	.753	2.197	1.443	.894	.583
1.70	1.012	1.540	2.135	.762	2.224	1.462	.906	.595
1	1.038	1.569	2.176	.770	2.250	1.480	.918	.607
2	1.065	1.598	2.218	.779	2.277	1.499	.929	.619
3	1.092	1.628	2.259	.787	2.304	1.517	.941	.631
4	1.120	1.658	2.301	.795	2.331	1.535	.953	.644
5	1.148	1.688	2.344	.804	2.357	1.554	.964	.650
6	1.177	1.718	2.386	.812	2.384	1.572	.976	.669

* From Conrady, "Applied Optics and Optical Design," by permission of Oxford University Press, New York.

To proceed with our design, we will select two typical glasses at random, and follow a step by step numerical example.

Crown	C—2	$n_a = 1.513$	$V_a = 60.5$	$\Delta n_a = 0.00847$
Flint	DF—3	$n_b = 1.621$	$V_b = 36.2$	$\Delta n_b = 0.01715$

For design purposes we will assume a desired focal length of 10 inches. Later this can be scaled to any desired value. A 10-inch slide rule will suffice for all calculations.

From equations (1) and (2), we solve for the curvatures of the two lens elements to achromatize.

$$C_a = \frac{1}{(60.5 - 36.2)10(0.00847)} = 0.486 \quad (10)$$

$$C_b = \frac{1}{(36.2 - 60.5)10(0.01715)} = -0.240 \quad (11)$$

Equation (3) gives us P_a:

$$P_a = 0.486(1.513 - 1) = 0.249 \quad (12)$$

From equation (4) we obtain a relationship between C_2 and C_3. To evaluate the G-terms, we go to Table 1, using as argument the index of the crown glass to get the G-values for the a bracket, and the index of the flint for the b bracket.

$$[0.581 \times (0.486)^3 + 1.025 \times (0.486)^2 C_2 - 1.410 \times (0.486)^2 \times 0.249 + 0.593 \times 0.486 C_2^2 - 1.696 \times 0.486 \times 0.249 C_2 + 1.103 \times 0.486 \times (0.249)^2] + [0.814 \times (-0.240)^3 - 1.314 \times (-0.240)^2 C_3 + 1.817 \times (-0.240)^2 \times 0.249 + 0.693 \times (-0.240) C_3^2 - 2.005 \times (-0.240) \times 0.249 C_3 + 1.313 \times (-0.240) \times (0.249)^2] = 0 \quad (13)$$

Collecting terms:

$$0.0123 + 0.0368 C_2 + 0.288 C_2^2 + 0.0441 C_3 - 0.166 C_3^2 = 0 \quad (14)$$

Note that we have carried only three significant figures. This is sufficiently accurate.

We can now complete the design of a cemented type objective quickly. For this type, $C_2 = C_3$ and we therefore substitute in (14) and collect terms:

$$0.122 C_2^2 + 0.0809 C_2 + 0.0123 = 0 \quad (15)$$

This is a quadratic equation of the type $ax^2 + bx + c = 0$, whose solutions are:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Thus:

$$C_2 = C_3 = \frac{-0.0809 \pm \sqrt{(0.0809)^2 - 4(0.122)(0.0123)}}{2 \times 0.122}$$

$$C_2 = C_3 = -0.426 \quad \text{or} \quad -0.235 \qquad (16)$$

Either of these values could be used, but it is better for the crown element to be as nearly equiconvex as possible. As we shall see later, the −0.235 value more nearly realizes this, so we discard the −0.426 value.

We now know C_a, C_b, C_2 and C_3 for our cemented lens. Equation (7) gives us C_1.

$$0.486 = C_1 - (-0.235) \qquad C_1 = 0.251 \qquad (17)$$

and equation (8) gives C_4

$$-0.240 = -0.235 - C_4 \qquad C_4 = 0.005 \qquad (18)$$

From equation (6) we get our radius

$$\left.\begin{aligned} r_1 &= \frac{1}{C_1} = \frac{1}{0.251} && +3.98 \text{ inches} \\ r_2 &= \frac{1}{C_2} = \frac{1}{-0.235} && -4.26 \text{ inches} \\ r_3 &= r_2 = && -4.26 \text{ inches} \\ r_4 &= \frac{1}{C_4} = \frac{1}{0.005} = && +200.0 \text{ inches} \end{aligned}\right\} \qquad (19)$$

This completes the design of a cemented type objective. We have assumed a focal length of 10 inches. For any other focal length we simply scale up (19). For example, if a 60-inch focal length objective is desired, we have only to multiply the values in (19) by 60/10, or 6, to obtain the proper radii. Our computed value for r_4 came out to be 200 inches. When this is scaled up to a longer focal length, say 60 inches, it becomes too long to measure by the Foucault test. In this case the surface could be made plano without ill effects. Entirely by chance our design gives us a cemented lens in which, in addition, the last surface is flat (a very easy type to make). This should not be expected, although r_4 will almost always be of much longer radius than any of the other three surfaces.

The cemented lens just designed is properly corrected for chromatic and spherical aberration but is only approximately corrected for coma (any correction for coma must be strictly accidental—we haven't designed for it).

Now we will proceed with the design of a Fraunhofer type objective that will, in addition, be properly corrected for coma. Equation (5) gives us an additional relationship between C_2 and C_3 (again getting the G-values from the table).

$$[\tfrac{1}{4} \times 1.696 \times 0.486\, C_2 - 0.679 \times 0.486 \times 0.249 + 0.385 \times (0.486)^2]$$
$$+ [\tfrac{1}{4} \times 2.004 \times (-0.240)C_3 - 0.811 \times (-0.240) \times 0.249 - 0.502 \times (-0.240)^2] = 0 \qquad (20)$$

Collecting terms:

$$-0.0283 - 0.205\, C_2 + 0.120\, C_3 = 0$$

or

$$C_3 = \frac{0.0283}{0.120} + \frac{0.205}{0.120} C_2 = 0.236 + 1.71\, C_2 \qquad (21)$$

We now have two relationships between C_2 and C_3. Substituting the value of C_3 from (21), for C_3 in (14), gives

$$0.0123 + 0.0368\, C_2 + 0.288\, C_2^2 + 0.0441(0.236 + 1.71\, C_2)$$
$$-0.166(0.236 + 1.71\, C_2)^2 = 0$$

which simplifies to

$$-0.197\, C_2^2 - 0.0218\, C_2 + 0.0134 = 0 \qquad (22)$$

Again we have a quadratic of the form $ax^2 + bx + c = 0$ with solutions

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Thus

$$C_2 = \frac{0.0218 \pm \sqrt{(-0.0218)^2 + 4 \times 0.197 \times 0.0134}}{-2 \times 0.197}$$

$$C_2 = -0.323 \quad \text{or} \quad +0.211 \qquad (23)$$

We discard the positive value because it would give us a very peculiar lens shape. Substituting the value −0.323 from (23) in (21) gives:

$$C_3 = 0.236 + 1.71 \times (-0.323) = -0.316 \qquad (24)$$

We now solve for the radii, using equations (6) – (8) exactly as with the cemented type.

$$0.486 = C_1 - (-0.323) \qquad C_1 = 0.163 \qquad (25)$$

$$-0.240 = -0.316 - C_4 \qquad C_4 = -0.076 \qquad (26)$$

$$\left.\begin{aligned} r_1 &= \frac{1}{C_1} = \frac{1}{0.163} = 6.13 \text{ inches} \\ r_2 &= \frac{1}{C_2} = \frac{1}{-0.323} = -3.10 \text{ inches} \\ r_3 &= \frac{1}{C_3} = \frac{1}{-0.316} = -3.17 \text{ inches} \end{aligned}\right\} \qquad (27)$$

$$r_4 = \frac{1}{C_4} = \frac{1}{-0.076} = -13.20 \text{ inches}$$

This completes the design of the Fraunhofer type. Again, we scale up from 10 inches to whatever focal length is desired.

The two lens types we have considered are probably the most important for amateur consideration; however, we can briefly discuss several others.

Equiconvex Crown Type: Equation (10) has given us the value of C_a. If the crown is to be equiconvex, $C_1 = -C_2$, or from equation (7)

$$C_a = -C_2 - C_2 = -2C_2$$

$$C_2 = -\frac{C_a}{2} \tag{28}$$

Thus, dividing the value of C_a from (10) by −2 gives us the value of C_2. Substituting this value of C_2 in (14) gives a quadratic in C_3 which we can solve as before. Knowing C_a, C_b, C_2 and C_3 we proceed as in the previous examples. The lens would be properly corrected for chromatic and spherical aberration but coma correction would be accidental.

Flint with Plano Surface: We would proceed practically as with the example above. If the flint has a plano surface, $C_4 = 0$. Thus $C_3 = C_b$ from equation (8). Substituting this value of C_3 in (14) gives a quadratic in C_2 which can be solved as before. Knowing C_2, C_3, C_a, and C_b, we find the radius as before. Again, coma correction would be accidental.

Airspacing: Neither of the two types just given is very practical unless, in addition, we can make the two inner surfaces of the lens equal. In some cases this is possible by suitably spacing the elements. Let us consider that we have determined the curvatures for any one of the lens types given (other than, of course, the cemented type, where the inner surfaces are already equal). If C_2 is slightly larger numerically than C_3, it is possible to readjust the curvatures, making $C_2 = C_3$, then separate the elements to compensate. The effective focal length of the lens is increased slightly, and the aberrations are slightly affected, but the effect is very small if the spacing is small. We will adopt a criterion presently.

Referring back to our Fraunhofer design, we note that C_2 is slightly larger numerically than C_3, so we can use it as an example. Our computed curvatures were

$$C_a = 0.486$$
$$C_1 = 0.163$$
$$C_2 = -0.323$$
$$C_3 = -0.316$$

Let us arbitrarily make $C_2 = C_3 = -0.316$. Our new C_a from equation (7) is

$$new\ C_a = C_1 - C_2 = 0.163 - (-0.316) = 0.479$$

From equation (3)

$$P_a = \frac{1}{f_a} = C_a(n_a - 1)$$

For our old C_a

$$\frac{1}{f_a} = .0486(1.513 - 1) \qquad f_a = 4.02 \text{ inches} \tag{29}$$

For our new C_a

$$\frac{1}{f_a} = 0.479(1.513 - 1) \qquad new\ f_a = 4.08 \text{ inches} \tag{30}$$

We must airspace our elements a distance

$$(new\ f_a - old\ f_a) = 4.08 - 4.02 = 0.06 \text{ inches} \tag{31}$$

Our adjusted lens then has these specifications:

$r_1 =$ 6.13 inches
$r_2 =$ −3.17 inches (only change)
$r_3 =$ −3.17 inches
$r_4 =$ −13.20 inches
spacer = 0.06 inch

We must adopt a criterion for this procedure. It will be quite arbitrary, but a safe limit must be placed somewhere. Our criterion: The airspace distance must not exceed 1 percent of the focal length of the objective. Our designed focal length was 10 inches, the airspace 0.06 inch. We are within the criterion.

Barlow Lens: A Barlow lens is a negative achromatic objective used to increase the magnifying power of telescopes by greatly increasing their effective focal length, without materially increasing their physical length (see Bell, "The Telescope"). They are far superior to short focal length eyepieces for obtaining high magnifying powers, so we will consider the design of one.

The cemented type design is proper for this purpose, with only two modifications. One is that f, the focal length of the Barlow (usually 4 to 8 inches) will be negative and must be entered as negative in all formulas where it appears. The second is that in place of P_a in formula (4), we must use the value $(P_a - 2/f)$, the f again being the focal length of the Barlow and a negative value. (Thus $-2/f$ will always be positive.) This value is exactly correct for a Barlow magnifying 2×, and very nearly correct for a wide range of magnifications. The value $(P_a - 2/f)$ may turn out to be either + or −. It must be entered in (4) in place of P_a with the proper sign.

The typical shape for a Barlow is concavo-convex with the convex side toward the object. The value of C_2 from (15) should be chosen with this in mind. The Barlow is better designed flint leading.

So far as we have not considered thicknesses, and will not in so far as the optical design is concerned. However, the lens must be thick enough for mechanical strength, so a few words on assignment of thickness are in order.

Let us use the Fraunhofer lens as an example, scaled up to a 4-inch objective of 60-inch focal length. Multiplying the radii from (27) by 60/10, or 6, gives

$$r_1 = 36.8 \text{ inches}$$
$$r_2 = -18.6 \text{ inches}$$
$$r_3 = -19.0 \text{ inches}$$
$$r_4 = -79.2 \text{ inches}$$

We decide arbitrarily that an edge thickness of 0.25 inch for the crown, and a center thickness of 0.35 inch for the flint is about right. The sagitta formula (9) gives the remaining information we need.

$$x = \frac{y^2}{2r}$$

where x is the sagitta and y the semi-diameter or radius of the objective.

$$x_1 = \frac{2^2}{2 \times 36.8} = 0.055 \text{ inch}$$

$$x_2 = \frac{4}{2 \times 18.6} = 0.110 \text{ inch}$$

$$x_3 = \frac{4}{2 \times 19.0} = 0.105 \text{ inch}$$

$$x_4 = \frac{4}{2 \times 79.2} = 0.025 \text{ inch}$$

Referring to the diagram of the lens (Figure 1) we see that we must add x_1 and x_2 to 0.25 to get the central thickness of the crown, and must add x_3 to 0.35 and subtract x_4 to get the edge thickness of the flint. Thus

Crown center thickness = 0.055 + 0.110 + 0.250 = 0.415 inch
Flint edge thickness = 0.105 + 0.350 − 0.025 = 0.430 inch

Both could be made from blanks 0.5 inch thick.

Again referring to the diagram of the lens, and noting that r_3 is greater than r_2 in the Fraunhofer lens, we must provide a spacer to keep the lens elements from touching together at the center. The thickness is just

$x_2 - x_3 = 0.110 - 0.105 = 0.005$ inch plus a few thousandths for safety. So we plan on three small shims 0.007 inch thick spaced 120° apart at the edge of the lens to space the elements when they are placed in their cell. Such spacers are needed only if r_3 is numerically greater than r_2.

How good are these designs? The three numerical examples given in Table 2, which were worked out from scratch as examples, were scaled up to 4 inches aperture, 60-inch focal length, and thicknesses added, then ray traced to see. All three lenses were much better than the Rayleigh limit (the generally accepted standard of perfection) in spherical aberration. This means that no local figuring of the last surfaces would be necessary. The Fraunhofer lens and the airspaced lens were better than the Rayleigh limit in coma. The cemented lens was slightly outside the limit in coma, but well within accepted tolerance for this aberration in object glasses. (This was accidental; we didn't design this lens to be coma-free.) The Fraunhofer lens had sensibly perfect color correction. Both of the other two were slightly undercorrected, but not sufficiently to be objectionable. Any one of the three lenses would make completely satisfactory objectives up to 6-inch aperture. The Fraunhofer lens could be pushed way beyond this and still be within the Rayleigh limit on all three aberrations. The accuracy of these methods, then, is all that could be desired for $f/15$ telescope objectives. It just takes a little more work than the simpler methods, in exchange for which you get the assurance that your design is right.

Table 2—*ABERRATIONS OF THE DESIGN EXAMPLES*

The following are based upon a 4-inch aperture, $f/15$ objective made from C-2 and DF-3

Lens A—Cemented	
r_1 = 23.9 inches	Longitudinal spherical aberration −0.0114 inch
r_2 = −25.6 inches	Longitudinal chromatic aberration −0.062 inch
t_a = 0.4 inch	
r_3 = −25.6 inches	OSC[1] −0.00086
r_4 = ∞	f 57.91 inches[2]
t_b = 0.25 inch	
Lens B—Fraunhofer	
r_1 = 36.8 inches	Longitudinal spherical aberration +0.0042 inch
r_2 = −18.6 inches	Longitudinal chromatic aberration +0.00039 inch
t_a = 0.415 inch	
r_3 = −19.0 inches	OSC +0.000012
r_4 = −79.2 inches	f 60.05 inches
t_b = 0.35 inch	
Lens C—Airspace	
r_1 = 36.8 inches	Longitudinal spherical aberration −.0096 inch
r_2 = −19.0 inches	Longitudinal chromatic aberration −0.037 inch
t_a = 0.4 inch	
r_3 = −19.0 inches	OSC +0.00019
r_4 = −79.2 inches	f 60.83 inches
t_b = 0.35 inch	
Airspace 0.36 inch	

1 OSC is a measure of coma.

2 This shortened focal length resulted from rounding off the design value of r_4 to ∞. The nominal 60-inch focal length can be restored by multiplying all radii of curvature by 60/57.91.

The Overhaul and Adjustment of Binoculars

By G. Dallas Hanna
California Academy of Sciences, San Francisco

Under this heading it is proposed to discuss constructional features of a few forms of binocular telescopes, the endeavor being to provide sufficient information so that some owners of these instruments may be able to care for them properly. I know of no published treatise on the subject which gives more than basic principles of the optical systems. There are some very general accounts [1] of testing instruments for binoculars but there have been no details of construction of these or methods of using them. It is true that several of the military branches issued mimeograph sheets during World War II and these contained some details of value to the personnel of the overhaul shops which were maintained in many theaters of operation. Such documents were not available to the public.[2] In general, how to take a binocular apart, repair it, put it together properly and adjust it, is information which has been passed along from one person to another orally. I am no exception. I received my instruction from a master teacher, Mr. Daniel Brower, then stationed at the U. S. Optical School at Mare Island, California, and who was detailed by Commander F. R. Kalde (U.S.N.R.), then in charge of the school, to assist the California Academy of Sciences in setting up an overhaul shop for naval optical instruments in World War II. As a result of this instruction we completely overhauled over 6,000 binoculars of many types and put them back in service. My deepest gratitude is extended to these two men.

It has often been said that if a person wants to learn how an optical instrument functions, learn its good points and its weak points, he should start overhauling. And it is the general belief of shop men that if the designers of binoculars would tear down a few of their instruments after they have been out in service, details of construction might as a result be altered greatly.

However, it is believed that a "good" binocular has not been made and it is doubtful whether one ever will be. This comes about through the impossibility of assembling two precisely similar optical systems and keeping them in some fixed relationship to each other, usually parallel. Nevertheless, there are millions of the instruments in use and people like them with all their faults.

My personal preference is a monocular; that is, one half of a prism binocular, 6×30. The reasons will be apparent in subsequent pages. It will suffice here to state that in 1920 a committee appointed by the National Research Council, after protracted tests, optical and psychological, found that the detail seen with a monocular was nearly the same as that with a binocular.[3] But the inherent desire to look with two eyes instead of one is deep-seated in the animal kingdom and cannot be discounted by one individual or one committee.

[1] Jacobs, "Fundamentals of Optical Engineering."
Brown, Earle B., "Optical Instruments."
Glazebrook, "Dictionary of Applied Physics," Vol. 5, "Telescopes, small."

[2] The following, however, published in 1945 as "Restricted," has since been removed from that category: War Department Technical Manual TM 9–1980 "Ordnance Maintainance Binoculars, Field Glasses, and B.C. Telescopes, All Types." This document contains a great store of information on methods used by the Army.

Types of Binoculars

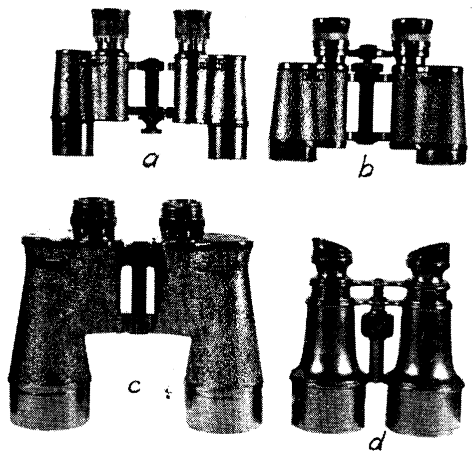
There are hundreds, perhaps thousands, of models of instruments in which the manufacturer has tried to tie two telescopes together so that both eyes can be used by the observer. It is obviously impossible to consider them all or even a very small fraction of them. There are many trick or freak models and special constructions for specific purposes. No history of the development of the various forms has been noticed in the literature although it would make a very interesting book. There are binoculars with prisms and without. Mechanical details vary with the ingenuity of the designers (Figure 1). Even the types and arrangements of erector prisms differ greatly in different models. For the present purpose it is necessary to narrow the field and there have been chosen for consideration four types which are widely distributed.

1. Modern binoculars: Under this heading are included such instruments as were made for military use during World War II. The number of these runs into the millions and eventually most of them will probably be in private hands.
2. Semi-modern instruments: The binoculars made for use in World War I have been distributed to the public to a very large extent. They represent a special construction and deserve consideration.
3. Binoculars with central focusing devices: This is the type of instrument which was generally manufactured for public sale, at least until somewhat recently. They have a device in common, a central knob, the turning of which moves the oculars inwardly or outwardly simultaneously.
4. Galilean type binoculars (field glasses): Under this category are included those instruments which do not contain any prisms or lenses especially to erect the images. This is accomplished by the suitable choice of positive objective lens and negative ocular lens. For many purposes they are superior to any assembly which contains erector prisms. Instruments with prisms have by custom come to be called "prism binoculars" or just "binoculars," while those without have become established in our language as "field glasses" and "opera glasses."

In the above classification no significance has been attached to magnification or "power." It is customary to express this quantity as the first figure

[3] Hyde, Cobb, Johnson and Weniger, *Journal of the Franklin Institute*, Phila., Vol. 189 (1920), pages 185–224, 331–369. From the summary: "In the foregoing it has been shown that in the hands of not very highly experienced observers the binocular performs slightly better than the monocular, and that the difference in performance can, for 6-power glasses, be expressed as an effective difference of about 4.5 percent; *i.e.*, a monocular of magnification 6.27 would show the same performance as a binocular of magnification 6.00."

in a compound expression such as 6×30, 8×30, 7×50, etc. The last figure signifies the effective millimeter diameter of the objective lens and therefore gives comparative indication of the light gathering power. Thus a 7×50 instrument will furnish more light and therefore a brighter image than an 8×30, in spite of the fact that the latter has the higher magnification. Binoculars with much higher magnification and much larger objectives than these have



All drawings by the author

FIGURE 1

Four common types of binoculars. a. *A 6 × 30 form used in large numbers in World War I. Collimation is affected by means of headless screws through the body casting, which permits sliding the prisms.* b. *The central focusing screw for both oculars seems to make it difficult to keep the instrument in precise adjustment.* c. *A modern 7 × 50 binocular used extensively in World War II. If properly assembled it is a very sturdy, waterproof and dust proof instrument.* d. *Galilean type of "field glass," with central focusing screw. Some are made with individually focusing oculars and these retain their adjustment for longer periods.*

been made and used. However, they become so massive that they are impractical to use except when attached to a fixed support. We have overhauled some 16×150, also 9×75, but they are comparatively rare.

One other factor enters into the utility of a binocular, though this is rarely mentioned in advertising literature. This is the effective diameter of the exit pupil of the instrument. The importance of this can be best understood if we consider the futility of the exit pupil being larger than the entrance pupil of the eye. If the maximum diameter of the average iris of the eye in

daylight is less than the diameter of the exit pupil it is obvious that the observer is not using all the light which is furnished by the instrument. In practice it has been learned that the combination 6×30 to 6×42 is about the maximum optimum magnification and diameter of objective for daylight use. In darkness the iris expands and it is then possible to utilize to full advantage a greater power such as 7×50 or even more. For this reason such instruments are sometimes called "night glasses." They are more effective at night than one of lower power and smaller objective, but not necessarily so for daytime use. The difference in magnification is usually unconsequential and for ordinary use is offset by extra size and weight.

One other factor which may at times be of importance to the observer is the angle of view taken in by the optical system. This is greater in prism type instruments than in the Galilean form.

The above data may be conveniently assembled in the form of a table (Table 1).

TABLE 1 *

Types	Power	Diameter of objective in millimeters	Field of view in degrees	Diameter of exit pupil
Prism binocular	6	15	8.3	2.5
" "	6	30	8.3	5.0
" "	8	40	8.75	5.0
" "	7	50	8.5	7.1
Galilean	4	50	4.0	—

* Adapted from "Fundamentals of Optical Engineering," by D. N. Jacobs, 1943. McGraw-Hill Book Co., Inc., by permission.

I. MODERN BINOCULARS

Late types of military binoculars have numerous features common to all models. They have excentric rings around the objectives for collimation purposes, individually focusing oculars, a tapered hinge pin, and most of the metal parts are alloys of aluminum or magnesium or both. Prisms are mounted on a separate frame and not attached to an internal shelf as in many older models.

With these general considerations we may pass at once to constructional details.

Body: Die castings are universally used for the bodies (or barrels, as shop men usually call them) in modern instruments. In manufacture they are clamped in an elaborate and extremely accurate fixture in order to perform the various machining operations which are required. Top and bottom are milled off parallel. Three lugs in the interior are milled off parallel to these surfaces and drilled and tapped with blind holes (usually 4 × 48) to support the prism frame. The lugs which form parts of the hinge are machined parallel to the surfaces mentioned. The objective end is bored to receive the objective cell and collimating ring and threaded for a retaining ring. The ocular end may be completed in one of two ways. In older models it is machined off to take a pressed sheet aluminum cap which is attached by three oval-head screws (4 × 48). Provision is made in the casting for threading that portion into which the ocular sleeve is later screwed. In the later models, the ocular sleeve and cap are one die casting which is attached to the top of the barrel by several screws. In this one a gasket, usually synthetic rubber, is placed between. Screws used should be 4 × 48 but some manufacturers have used flimsy 3 × 56 or even 2 × 64, both of which are prone to twist off in disassembly. It is obvious that, in order to keep the various

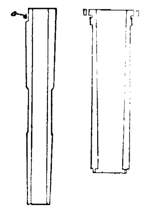


FIGURE 2

Hinge pin and sleeve. The taper of one modern 7 × 50 instrument is 0.50 inch per foot. The sleeve is anchored to one barrel with dowel pins at the top. The pin is anchored to the other barrel by means of a dowel pin at a.

optical elements in strict alinement in the body, the machining work on it must be beyond reproach. Tolerances have to be kept very low. Without elaborate fixtures it is impossible for the assembly man to check the work very closely.

Hinge: This is the heart of the binocular and, as made at present, 1953, it is an absurdity. Two of the projections from the body casting form the outer ears and the other two form the inner. Between the latter a brass sleeve is firmly anchored either by threading or rolling. This entire assembly is then reamed out with a taper reamer. In a few models a Brown and Sharp No. 4 reamer is used. In others special tapers are made, and thus no readily available reamer is accessible. The hinge is completed by inserting a taper pin of proper size so that both ends are nearly flush with the outer ears (Figure 2). A screw with a large head and spanner holes is inserted in the lower end and the pin is pulled down taut. A grease of some sort has of course been placed on the pin. This screw is usually a die casting, very weak, and often twists off. Repair men make them up by the hundreds for replacement. Naturally, they are threaded off-standard, ¼ × 36. The interpupilary scale is attached to the upper end of the hinge pin. Both it and the lower screw are usually anchored in place with 0 × 80 or 1 × 72 headless set-screws.

Everyone recognizes the superiority of tapers for near perfect rotational

movement. They are standard in certain instruments where strict alinement must be maintained, and in a binocular hinge the slightest misfit makes collimation impossible. That evidently was the thought behind the adoption of a taper pin and all would be well were it not that, in order to produce a hinge which will not flop around in handling, the pin must be pulled down into the taper tightly. This squeezes out the grease and it is not long before the tube or the pin or both are badly galled so that smooth operation is impossible. Most users of binoculars want the hinge motion to be very stiff so that, once adjusted to interpupilary distance, ordinary motions of the body will not dislodge it. It seems inconceivable that designers would go to the trouble to make a fine bearing and then put a brake on it. Yet that has been the situation in modern binoculars. There are many ways by which restraint can

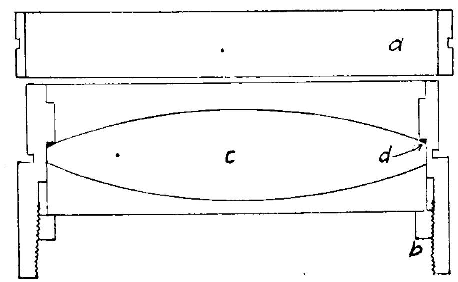


FIGURE 3

Objective cell with retaining ring and excentric collimating ring. a. *Excentric ring.* b. *Objective cell with retaining ring.* c. *Objective.* d. *Shoulder of cell is machined at this point at time of assembly to fit the focal length of the particular objective chosen.*

be put upon rotary motion without tightening a bearing. If the method used by the binocular designers were used in such a machine as an automobile the consequences would be tragic.

To be any good a taper fit must be a fit. An approximation is not sufficient. Evidently the tolerances allowed in binocular factories have been far too wide, since pins rarely fit their sockets. As a consequence, the better repair shops make up their own pins to a definite taper and re-ream the hole. In many cases, however, it is possible to salvage the old pin by lapping it into the hole with fine Carborundum grains (about 600) and oil. Undoubtedly some of the material becomes imbedded in the metal but after washing away all loose grains with a solvent a beautiful fit can be obtained by turning the pin in the socket, dry, a few times.

In some shops this operation became routine on more than 50 percent of all binoculars overhauled during World War II.

Objective Assembly: The objective fits in an aluminum cell (Figure 3) and is held there by a retaining ring usually threaded 36 per inch on 7×50s.

This ring has two notches in the outer edge for fitting a spanner wrench to tighten or loosen, but the metal is so thin that very often it gives way on a "frozen" or corroded instrument. Then there is no alternative but to cut the ring with a hand engraving tool, using extreme care not to injure the objective. The outer end of the cell has two (sometimes only one) notches. These serve for turning the cell in the body, as will be better understood when the time comes to collimate the instrument.

All good workmen seat the objective in the cell on a wax or waxlike material to aid in waterproofing the instrument. One of the best materials known for the purpose and which was widely used in military shops in war time is Prestite Fuel Tank Sealer, made by the Prestite Engineering Company, 3900 Chouteau Avenue, St. Louis, Missouri. This may be rolled out by hand into a "wire" about $1/16$ inch in diameter. To hasten the work we equipped a small hydraulic press with a cylinder to hold the Prestite and squeezed it out into a wire or ribbon. Assemblers would wind a yard of this on a tube for use at the work benches.

Around the objective cell there is fitted an excentric collimating ring. This has two notches (sometimes one) in the front end, and their purpose will be apparent later.

All the elements mentioned are made of aluminum alloy in the model being discussed but it would not be surprising if magnesium alloys should appear in the future. Since objective cell and collimating ring have to be rotated in collimation it is obvious that they must turn freely. These metals are very prone to gall. They make about the poorest bearings which can be imagined. On the other hand if they are too loose they will flop around and collimation will be extremely difficult. Another retainer ring is provided to screw into the body and hold objective cell and collimating ring rigidly in position. This is not tightened down, however, until final collimation has been completed.

An objective cap is provided to screw on the outside of the body. In many models this is made of a brittle die-casting material and usually breaks the first time the binocular is dropped on concrete or a steel deck. Many of these have been replaced by brass, turned out in the repair shops.

These parts complete the objective assembly, except that the objective cell and objective cell retaining ring are usually locked in place after collimation by two 0×80 headless set-screws as well as by the retaining ring.

Lubricants: The moving parts of such an instrument as a binocular must of necessity be well lubricated. This is especially true since most parts are made of aluminum alloys which gall badly. The hinge and the oculars must maintain a free but not "sloppy" movement throughout their life. Collimating rings and objective cells must have free movement until the instrument is finished during assembly. Many greases have been tried and there are several in current use. The one, however, which proved most satisfactory in rough marine usage during the war was "Lubriplate," manufactured by Fiske Brothers Refining Company, Lockwood and Neptune Streets, Newark, New Jersey. Grade 130A was used almost entirely in overhaul work in many shops for

hinge pins and for ocular spiral threads. This is a somewhat stiffer mixture than other grades and is reputed to have special protective properties against corrosion of aluminum by salt water. Grade 220 was used on objective assemblies, ocular body screw threads, and elsewhere. Good operators always put a trace of lubricant on such screws as those which hold top and bottom plates, interpupilary scales, and in fact all screws used in the assembly of the instrument. Manufacturers have not taken this precaution and as a result many of their screws have to be drilled out in overhaul work.

Some makers of binoculars have used a stiff resinous grease for hinge pins and ocular spiral threads, primarily to conceal the poor mechanical fits of these parts. Such practice invariably leads to trouble. One overhaul shop during the war experimented with making its own grease and sent some instruments out lubricated with a mixture of lanolin, beeswax and rosin. These binoculars promptly "froze" and many of the hinges were broken by the users in trying to adjust for interpupilary distance.

Waxes: In order to seal a binocular properly against entrance of moisture and dust it is necessary to wax the objective cap on. Other places requiring the same treatment are the junctions of the body caps to the bodies in those models which employ this construction and around the ocular assembly where it screws into the body casting. There are no doubt many formulas which are suitable for the purpose. Some compounds have gum rubber incorporated in them. But when this material became unavailable due to wartime scarcities it was found that a very satisfactory wax could be made by melting together equal parts of beeswax and rosin or pitch and adding lampblack until the proper density of blackness was obtained. A can of this is usually kept melted on a hot plate in a binocular overhaul shop and is applied with a stick. Naturally it is the last part of the assembly before putting the instrument in its case. When a sufficient bead has been put around the objective retainer rings, the caps are screwed on, the instrument is set on the hot plate long enough to melt the beads, caps are tightened solid and the surplus wax wiped off with a cloth while still melted. This produces a neat and thoroughly waterproof job. The objective may be soiled slightly in the process and require cleaning with a cotton swab moistened with acetone, carbon tetrachloride, or gasoline, followed by Aerosol.

The waxing of the body caps and their screw heads is done with the same stick and the beads or drops are smoothed out and melted in with a small soldering iron.

These notes on waxing and lubricating are applicable to all makes and models of binoculars. These are two of the most important steps in assembly and should never be slighted or neglected.

Ocular Assembly: The mechanical construction of modern oculars varies somewhat with make and model but they have basic features in common. One which has been widely used is here described.

The central tube in which the lenses fit is made of light alloy with a sextuple thread cut on the outside. The eyelens doublet is fitted in the small end with the flat (flint) surface out. A ring of Prestite (or lacking this a bead of black wax) is first put on the small shoulder which supports the lens. A blank spacer sleeve is next placed in the tube; this is shaped somewhat conical at the small end. The field lens (or collective lens as it if often called) drops in on top of the spacer sleeve and the retainer ring is screwed down tight with a spanner wrench. This one retainer ring locks both lenses in place and is an improvement over older models which either used two or, what is very bad practice, had both lenses bezeled into the tube. In many military binoculars an adapter was screwed upon the inner end of the ocular tube, either inside or outside thread. This held a "mil-scale," or reticle, which was in the focal plane of the eyepiece, and gave the operator a method of estimating the distance of an object, one dimension of which he knew with reasonable accuracy. This device is not usually employed in marine operations and it is definitely distasteful to the general public. From the construction it is obvious that the ocular is of the Ramsden type.

In many models of 7×50 binoculars this lens tube assembly screwed into a sleeve which was an integral part of the body cover die casting. The sleeve was milled internally with a sextuple thread. This casting is also threaded at the top for a short distance, either inside or outside, depending upon the model, with a regular fine thread for a retainer ring to lock the lens tube in place. Before final assembly and locking with this retainer, the sextuple thread must be well lubricated and should turn rather stiffly but with velvety smoothness. Otherwise close focusing is not possible. And if the lens tube has side play in the threads collimation cannot be maintained. Often it will be found that the sextuple threads must be engaged in one definite position at the start to get a proper fit. Also, it cannot be assured that parts are interchangeable; very frequently they are not, not even in the same make and model.

A knurled sleeve (called a ring by some and a diopter scale by others) drops freely upon a shoulder upon the outer end of the lens tube. It is provided on the lower end with graduations usually numbered 4–3–2–1–0–1–2–3–4 and there is a reference mark on the sleeve of the die-cast cover. This is the means whereby one can always focus the instrument in advance of actual use, at infinity, for example in night work. The diopter scale is not usually made fast in position in overhaul work until after collimation has been completed but the process will be described here for continuity. The top face which rests on the shoulder of the lens tube is drilled and tapped 0–80 for a short, headless set-screw. When the instrument is focused on infinity, the diopter scale is rotated until the zero mark rests on the reference mark of the outer sleeve, the position of the tapped hole is marked on the lens tube, and a recess is drilled there part way through. The screw is run down flush and the lower end projects into the recess, thus providing a means of locking the elements together (albeit a flimsy one) and a driving device for focusing. Another ring, threaded inside and out, is then screwed down tight against the diopter scale and serves to provide further anchorage. When secure, it also is locked with a headless set-screw. A Bakelite eyecap is then screwed on this outer ring.

All these threads should be lightly greased to postpone corrosion as long as possible. Since the parts are usually made of aluminum base alloy they are not stable to salt solutions. Even perspiration from an observer's face will seep in around the threads, corrode them, and the products of corrosion are very detrimental. Frequently they freeze the threads so that disassembly is impossible without destroying some of the parts. Then, if some of the corrosive materials reach the lenses or prisms, the glass surfaces are eaten away to a considerable depth. Sometimes the corrosion can be polished off with a pitch lap but more often only grinding will remove it.

In the earlier models, made from about 1939 to 1942, the cover plate for the body casting was not die cast but was made of a stamping from sheet stock. In this case the sleeve with the internal sextuple thread for the lens tube was a separate piece which screwed into a threaded part of the body casting. In assembly, the cover plate was first screwed and waxed down to the body and then the ocular sleeve was screwed and waxed into place. Since the threads on the body casting did not make a complete circuit, beginners found it very difficult to prevent cross threading of the ocular.

Prism Assembly: As stated in the description of the body castings, there are three inside lugs which are very accurately machined on the upper surfaces and are drilled and tapped for 4 × 48 screws. These lugs support the prism plate which, in turn, has the prisms mounted upon it. Two of the lugs have additional holes drilled for dowel pins which are accurately located in the plate and position the assembly.

The prism plates are roundly triangular in shape and are not interchangeable between barrels. Two openings, slightly smaller than the hypotenuse face of the prism but the same shape and at right angles to each other, are milled through and recessed on opposite sides. The prisms seat in these recesses with just enough clearance on the sides so that they can move parallel to the hypotenuse plane a few thousandths of an inch. It is, however, extremely important that the prisms be firmly seated, because the slightest tipping will make collimation impossible unless there be a very large error in one angle in exactly the right direction; this is not likely to happen at random. Prisms vary in size by more than the tolerance allowed in machining the recesses of the prism seats. Therefore, when replacements are required, it often happens that either the glass must be ground off slightly or the recess must be enlarged by scraping. During the war many had more difficulty in getting the prisms properly seated than in any other part of the assembly of the binocular.

Much ingenuity has been expended in devising methods of holding the prisms on the frames of modern binoculars. The original or prototype method will be described first. Two stud posts were threaded 4 × 48 and screwed into each side of the frame, close beside the prism seats. The outer ends of the studs were drilled and tapped 4 × 48 and the heights were equal to or slightly less than the height of the prism, hypotenuse face to truncated apex of right angle. A crossbar was attached to the tops of the studs; it was bent so as to put pressure on the center of the prism, a thin strip of cork being mounted between to prevent metal-to-glass contact. This is a simple arrangement and, once completed with prisms squared, it answers for most civilian use. However, many of the soldiers, sailors, and marines found that most of the time a binocular was just an additional burden to carry and did not consider it to be the delicate optical instrument that it is. In the tossing around process prisms mounted as described were jarred out of position under the tie-down straps; the slightest movement sidewise on the seats is sufficient to destroy both squaring on and collimation. This usage was so rough that literally tens of thousands of prisms were chipped on the hypotenuse faces.

A model was then brought out in which a triangular wire was bent around the prism after it was seated and the wire was held in place against the glass by four small flat-head screws. It is apparent that, by tightening the screws on one end in turn, the tapered shoulder of the screw against the wire will

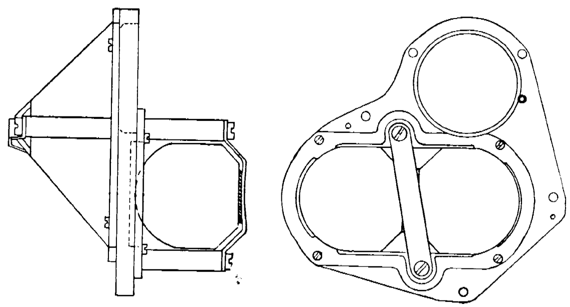


FIGURE 4

Top and side views of a prism shelf (or plate), showing one of many methods of securing and squaring prisms.

shove the prism slightly sidewise. In this manner the final squaring adjustment was effected. This method was later abandoned but a great many of these instruments will doubtless eventually fall into the hands of the public.

The next step (Figure 4) was to place a metal collar, stamped out of material about 0.0625 inch thick, around the prism and fasten this to the plate with four screws. Clearance was provided for the studs, and the inside edge was supposed to be scraped or filed exactly to fit each prism. The actual metal-glass contact was in the form of four pads, relief being provided elsewhere. Screw holes were oversize so that there was slight adjustment for the prism for squaring, and the metal section was weak enough so that it would spring a little in case of pressure due to poor fitting or jarring in use. In later models, in which this collar arrangement was used, the stud posts were omitted entirely and a saddle strap was bent to shape from one piece of flat stock fitted completely over the prism. It was provided with screw holes for fastening to the plate.

In the very last development before the close of World War II hostilities, the stud posts were revived but the prism was locked in place by four small

excentric rollers. Each was fastened to the plate with a screw so positioned that, on rotation of the roller, the prism could be shoved slightly sidewise. In this manner the prisms were squared. The method is simple and seems to be good sound engineering practice.

In a 6×30 model, several millions of which were manufactured and distributed during World War II, the prism plate was machined in the usual way and an over-riding strap held the prisms down on the seats. The prisms were squared and locked into position by a process which jewelers call "staking." The metal of the plate was forced over against the glass in at least four places with a chisel. This is rather a rigorous way to treat a piece of optical glass and many of the prisms could not stand it. Evidently, strains were put in the glass opposite the chisel marks and temperature changes or jarring often caused chips to fly out of the hypotenuse faces. It was not unusual to find all four prisms broken in new instruments as received at points of distribution.

In most binoculars, sheets of thin black metal are fastened underneath the hold-down straps for the prisms. These are shaped approximately the same as the right-angle polished faces and serve as light shields to prevent reflections. If not handled carefully in assembly they will cause scratches on the glass. For most civilian uses they will not be missed if omitted.

Covering and Finishes: Before the development of artificial and synthetic sheetings, leather was the standard covering material for hand telescopes of all kinds. The only other material seen has been wrappings of string and fancy knots put on their instruments by seafaring men, some of whose work was very ingenious and beautiful. The leather process was revived during the war on a commercial scale for one model of 16× quartermasters telescope.

Later, artificial synthetic leather and synthetic sheeting was used almost entirely. This material is usually black and embossed on the outside with a pebble finish. Vinylite was extensively used during World War II. The sheeting was cut to pattern size and cemented to the body casting by a rather elaborate process. Special synthetic adhesives were used and one or more periods of oven baking were required. The result, however, was a covering which rarely failed. Sometimes pieces were knocked off by accident and on such occasions the margins were trimmed in the overhaul shop and a patch was put on. The cement used in our shop was called Cordo 2055, manufactured by the Corrosion Control Corporation, 34 Smith Street, Norwalk, Connecticut. No doubt there are other satisfactory materials but it is not known by the writer whether any are available in quantity small enough for the individual worker.

One model of 7×50 which was manufactured in large quantity had no covering at all. Instead, a coat of fine-grained, dull black wrinkle finish was applied. This produced a very pleasing result, and repairs of scars were easy. Many manufacturers make this finish. (That produced by Sherwin Williams is known to be very good.) It must be applied with a gun and requires baking.

Exposed metal parts other than in that one model are normally finished with a dull black enamel or lacquer, baked on. Unless aluminum surfaces are very clean, good adhesion is usually difficult to obtain. Therefore, in overhauling, it is customary to completely disassemble an instrument, and all metal parts which have been exposed are degreased by one method or another. Often vapor phase trichlorethylene is used. Products of corrosion are either scraped, sanded or buffed off with a wire brush and loose paint is removed. Very frequently this means the removal of all paint. Many commercial fluids are satisfactory for this purpose. When thoroughly cleaned the instrument is partially reassembled for painting. Objective caps are screwed on, hinges and oculars are loosely assembled. All glass is left out. The lacquer or enamel is applied with a gun in a hood or booth and the instrument goes to the oven for baking. A commonly used lacquer had a baking schedule of two hours at 250°F. If time permits, two coats are desirable.

After disassembling the freshly painted parts the first task is to monofil the lettering and graduations on body covers, diopter scales and interpupilary scale. For this, a white wax known as "monofil" is used. Since it was not available for overhaul shops for a long time, most of them made their own fill. We melted a pound of paraffin wax, the type sold for home canning purposes, added half an ounce of castor oil and stirred in titanium oxide until the mixture was very thick to the stirring rod. Samples were tried from time to time as the oxide was added until, when cool and rolled into a stick, it would not crumble and was not sticky to the fingers. The material was rolled into pencils about ⅜ inch in diameter and issued to the assemblers. The pencil is rubbed vigorously over the lettering or graduations and the surface is wiped off with a clean cloth. If the engraving is already filled with either old paint or old Monofil, this is removed by going over the markings with the point of a scraper or a stylus.

Tolerances: It is believed that a statement of some of the manufacturers' mechanical tolerances of important parts will be of interest. Those which follow are for one of the earlier 7×50 models issued during the second World War, one which was made in large quantity but which, because of later improvements, became obsolete. However, the improvements did not lessen the number of parts or permit wider tolerances.

Body Castings and Hinges: A top view of one of the body castings shows 67 critical measurements, all within 0.003 inch and many within 0.001 inch. In side view there are many more. Even the length of the body is kept within 0.002 inch. The machining of the hinge lugs is very close. The taper of the barrel which carries the hinge pin is 0.500 inch per foot. Obviously the diameter must be reamed the correct amount or the pin will go through, either too far or not far enough; it should seat in the taper so that the top is almost flush with the top hinge lug of the left body casting. The bottom of the hinge pin will then not extend quite to the outer face of the lower lug. Thus, in assembly, the lower retainer screw pulls the hinge pin down into its seat, thereby making the movement stiff or loose. When properly seated, a hole, half in the hinge pin upper end and half in the hinge lug, should line up exactly. This hole is for a dowel pin, 0.0780 inch diameter, which serves to lock the

hinge pin to the lugs of the left body casting, thereby forcing it to turn in the tapered tube which is pressed or dowelled or both into the lugs of the right body casting. Very often when hinges go bad this dowel pin works loose in the upper end of the hinge pin. This is caused by the freezing of the hinge pin in its taper tube and many times it results in a broken hinge. If the dowel pin hole has become enlarged it should be abandoned and a new one made. In drilling it, care must be taken to center the drill exactly on the junction plane between the hinge pin and the casting.

Objective Fittings: Tolerances of most of these parts are 0.001 inch to 0.003 inch. There must be freedom of rotation so that the fits will fall within the class called "slip" by machinists.

Ocular Parts: There is much close work on the metal parts of an ocular. For example, in the lens tube alone, for the model being considered, there are 18 measurements, the maximum error permissible being two of minus 0.005 inch. In most of them deviation of 0.001 inch is allowed and one way only. It should be noted that the sextuple thread for focusing has a 9.5 mm lead; this is the only metric dimension found on any of the metal parts of late American-made binoculars.

Prism Plates: These are the most accurately machined parts in the instrument. As an example, a correct prism plate has 39 critical dimensions. The recesses for the prisms are milled at right angles ±5 minutes. Spacing of screw holes and dowel pins is accurate within ±.001 inch.

It may seem that these close tolerances are unnecessary refinements but they are not. Even with them parts are not strictly interchangeable from one instrument to another and much hand fitting is required in assembly work. After all, an attempt is being made properly to locate optical elements of two identical telescopes so that they will be adjustable to the user's needs, yet will remain in precise parallelism.

Optical System: All the binoculars that are being considered in the present account have essentially the same optical system. This is shown in Figure 5. Light from the object enters the objective, an achromatic doublet, is doubly reflected to the second prism, and the beam is offset to the axis of the collective lens of the ocular; it passes to the eye of the observer through another doublet. Thus there are seven pieces of glass in each barrel, or 14 in all, not counting various sunshades or filters or reticules which may or may not be placed in the beam. The prisms are so arranged, hypotenuse to hypotenuse, that the image is erected by the four reflections and they take the name "Porro" from the French designer who first used them this way. The over-all distance between objective and eye is considerably shortened by the four reflections. Other arrangements of various types will accomplish the same result and some of them are used for special purposes but Porros have certain advantages for mass production. Even mirrors have been used but they are difficult to anchor in precise position with sufficient security to withstand the rough usage to which binoculars usually are subjected.

The most important optical data for the elements of two models of 7×50 instruments follow. One of these models was made in large numbers early in the second World War but later was considered obsolete; the other is a later model, many extra parts for which were unused at the close of the war and were acquired by salvage companies for disposal to the public. The various lenses are assumed to face the object, as shown in Figure 6, and surfaces are numbered in the same order, object to eye. In the earlier model:

Objective, Crown Lens: Double convex, borosilicate crown glass; index (n_d) 1.5113±.001; *V*, 63.5±0.2; diameter 52.0 mm; thickness, 10.0 mm +.2−.4; radius 1, 130.1 mm; radius 2, 70.73 mm; surfaces polished to 2 fringes.

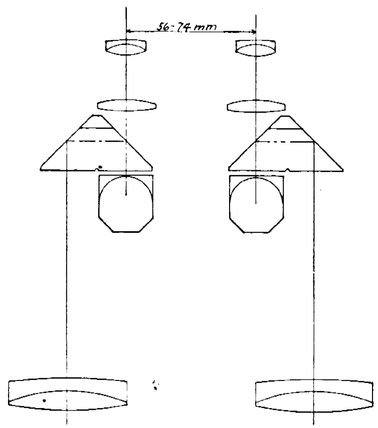


FIGURE 5
Diagram of the optical system of a prism binocular.

Objective, Flint Lens: concavo-convex, dense flint glass; index 1.6166±.001; *V*, 36.7±0.2; diameter 52.0 mm; thickness 4.5 mm ±.2−.4; radius 1, 70.73 mm; radius 2, 219.9 mm. Equivalent focal length of cemented combination 193.0 mm ±2.0; back focal length 186.0 mm.

Prisms: Light barium crown glass; index 1.5725±.0015; *V*, 57.4±0.5; projected length to sharp ends, 54.2 mm +0.0−0.4; actual length to rounded ends 52.1 mm +0.0−0.1; thickness 25.05 mm +0.0, −0.1; radius of rounded ends 12.5 mm +0.0−0.04; truncated right-angle corners ground off equally and 45°, leaving 14.1 mm +0.0−1.0 width; crosswise V-groove, ground on hypotenuse surface 1.5 mm ± 0.2 wide and without chips; not more than one bubble 0.2 mm diameter permitted; right angle faces flat within 1 fringe; hypotenuse face flat within 2 fringes; tolerance on all angles 5′.

Ocular Collective Lens: Borosilicate crown glass, index 1.5170±.0015; *V*, 64.5±0.3; diameter 27.0 mm; thickness 5.3 mm +0.2−0.6; radius 1, 73.88 mm; radius 2, 34.69 mm; surfaces polished to fit gage; glass must be free of bubbles and striae.

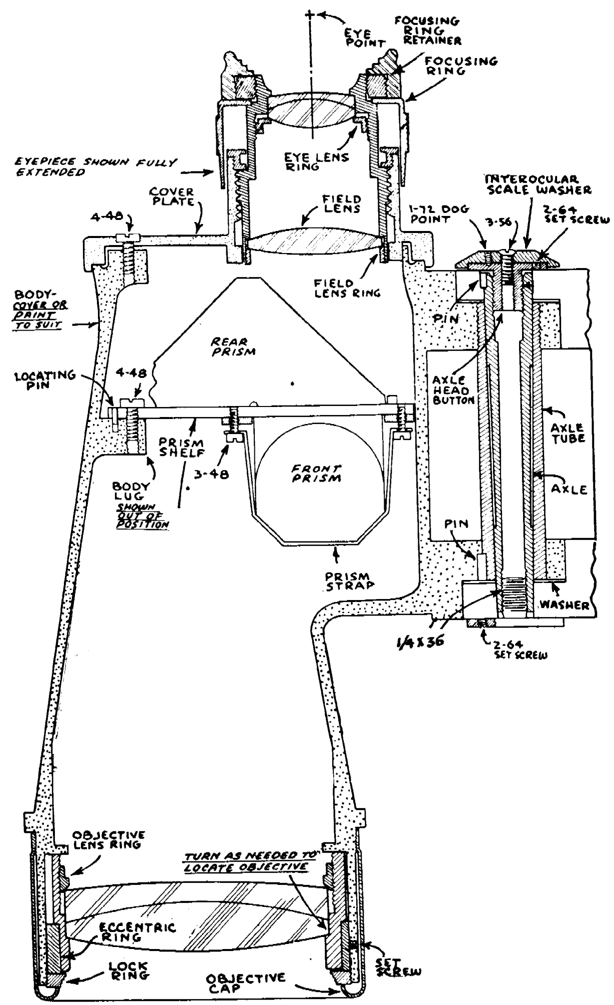


FIGURE 6
Section through left barrel of late model of 7 × 50 binocular. Adapted with permission from Edmund Scientific Corporation, Audubon, N. J., circular "How to Adjust and Collimate Binoculars."

Eyelens, Crown: double convex, light barium crown glass; index 1.5411 ±.001; *V*, 59.9±0.3; diameter 17.5 mm; thickness 6.0 mm +.01−0.5; radius 1, 20.15 mm; radius 2, 15.12 mm.

Eyelens, Flint: concavo-convex, dense flint glass; index 1.6210±.0013; *V*, 36.2±0.4; diameter 17.5 mm; thickness 0.6 mm ±0.2; radius 1, 15.12 mm; radius 2, 107.2 mm; glass must be free of bubbles and striae; thickness of combination cemented 6.6 mm +0.3−0.5.

In the later model, the specifications were almost identical in every respect with those given. The only changes or additions of importance were as follows: On the prisms the permissible error in the right angle was reduced to 3′ from 5′, while on the 45° angles it was raised from 5′ to 8′. Pyramidal tolerance was lowered to 3′ and the over-all deviation of the image was not permitted to exceed 10′. The error in curvature (deviation from a sphere) of the flat curve of the collective lens was held to 3 fringes while the steep one of both it and the crown of the doublet was allowed to be 5 fringes off. The same error was permitted in the steep curve of the flint but the flat one was held to 2 fringes.

In the process of overhauling many binoculars of many makes and models, occasion often arose when it was necessary to measure accurately the optical constants of all elements. In no other way could replacements be made. In this work it was found that the figures as given above had not been adhered to very closely. Apparently much wider deviations do not disturb color correction and definition sufficiently to be objectionable to the average user of the instruments and only a critical or fastidious person would complain. Certain deviations from the ideal can be corrected in assembly, to some extent at least, and it is believed that this is common practice.

It is, of course, desirable that the optics of the two barrels have somewhere near the same magnification or over-all focal length. Now this can be approximated in two ways, even though there may be considerable variation in the focal lengths of the individual lenses. All lenses can be matched together in pairs so that the two objectives, two collectives, and two eye doublets have close to the same focal lengths, respectively. When a large stock of glass is available this procedure is entirely practicable. The other way of equalizing focal lengths seems not to have been generally practiced. If two objectives, for example, have considerably different focal lengths, this can be compensated for by choosing ocular lenses accordingly.

It is believed that right-angle errors and pyramidal errors up to 18′ of angle were permitted in prisms by even some of the best manufacture and it is known positively that errors up to 24′ were frequently permitted by some. Many thousands of these have been measured and corrected. It is well established in assembly that, if either of the errors mentioned amounts to more than 3′ in each prism of one barrel, the instrument cannot be collimated without matching the errors so that those of one cancel those of the other. Next to the adjustment of the hinge, this is about the most important step in assembly, so it has been described in some detail under a separate heading.

The matter of matching can be standard routine in a factory having thousands of parts to choose from but when there are few extra parts, as in overhauling, trouble is at once encountered. If a prism or lens has to be replaced, it is inconceivable that one selected at random or taken from a junked instrument will be a duplicate. It would be much better if all optical parts were interchangeable in one model but evidently mass manufacture does not permit maintaining the close tolerances required. In a small shop, making prisms in batches of 100 and 200 of a particular kind at a time, there was not the slightest difficulty in holding angle and pyramidal errors within 1′ and the cost was no more than those produced in mass.

Further, tolerances permitted in some specifications required the optical and geometrical centers of cemented lenses to coincide within 0.05 mm. Also the tolerance in focal lengths of all lenses was 2 percent. Probably the necessity of haste and a limited amount of skilled help in war manufacture made it difficult to adhere to these figures.

Checking and Matching Prisms: In addition to the services already mentioned which prisms perform in a binocular, their arrangement at right angles to each other permits the separation of the objectives by more than normal interpupilary distance. Thus, stereoscopic vision is somewhat extended.

However, there are certain disadvantages connected with using them, some of which apply to all prisms. There is some loss of light through the comparatively massive pieces of optical glass. There is further loss of light due to reflection and scattering at the four glass-air interfaces through which the beam passes in each barrel. The scattering produces a haze which is not ordinarily noticed without critical inspection; it can be eliminated to a large extent by coating the two hypotenuse surfaces with a layer of magnesium fluoride one fourth wavelength thick, the so-called non-reflection coating.

Another disadvantage connected with the use of prisms is that if they are not set at exactly right angles to each other on their frames, the image will be out of square. The individual worker can easily check the squaring in several ways. One is to hold the frame to one eye in such a way that some square object such as a door or window frame can be seen through the prisms. The other eye views the object direct. If two prisms are squared properly the two images can be made to line up. If out of alinement, no rotation of the frame as a whole will correct them; one or both prisms must be shifted on the hypotenuse planes. Many overhaul shops make squaring blocks for this task. A piece of black Bakelite about 3 inches square is scored with lines at right angles to each other and spaced about ¼ to ½ inch apart. The lines are filled with white monofil and three posts are provided for the prism frame to rest upon. If, upon looking down through the prisms, the lines change direction from the squared net, adjustment must be made. Factories have well-constructed collimators which project a squared pattern of parallel light, especially for this important task.

Conrady, in "Applied Optics and Optical Design," page 33, aptly stated that a reflecting prism is optically a plane-parallel piece of glass and can be treated as such. [See Selby, "Eyepieces," appendix.—*Ed.*] It is obvious that, if the "right angle" of the prism is obtuse or acute or if the three polished faces are not mutually parallel, the sum total is not plane-parallel. As a consequence a light beam, upon passing through, will not emerge parallel to itself. The beam will be split up into a spectrum; objects viewed against a bright background will have fringes of color. The deviation of the right angle from 90° is conveniently called the "angle error," and the failure of the three polished faces to be mutually parallel is "pyramidal error."

A method of accurately determining these errors has been worked out and used for years; the apparatus is not beyond the capability of the average amateur telescope maker to construct. But for the present it will be assumed that the individual assembler has only a square for checking and only four prisms.

The square should be a good one, such as machinists use, or better. Use one of the ground ends for a reference face and hold the prism toward a fluorescent tube or other strong light. Lower the blade of the square to one of the polished faces. If light can be seen between the blade and the glass, that face is not square with its reference end. Note the error and try to evaluate it. It will of course be obvious that the light is strongest at the outer or inner edge of the polished face. Pass to the next face and do the same. The errors may both be in the same direction, in which case try to add the two together and at least get a mental picture of the total. If they are of opposite directions, subtract them. Pass to the third face and if there is no pyramidal error in the prism, this last one will cancel the sum or the difference of the other two. In other words, pyramidal error is the summation of three separate errors. The three surfaces are almost never parallel except in master or especially constructed prisms, but if the three planes are so inclined with respect to each other that they cancel out exactly, they will not deviate the final emergent beam. It rarely happens that they do cancel out in commercially made prisms and it is necessary to try to evaluate the resultant error. If projected far enough the three planes would intersect and form a true pyramid. [See ATMA, printings since '44, p. 76, Figure 1, center.—*Ed.*] Try to picture which end would represent the apex and mark the opposite or basal end with a cross or star. Obviously a light beam, in passing normally through the prism, will be deviated toward this base upon final emergence.

Place the square on the right angle faces and it will at once be apparent whether it be obtuse or acute. Try to evaluate the amount. It is not difficult to see an error of one minute if the illumination be good. On the end of the prism with the star, write an estimate of the angle error and whether it is obtuse or acute. Also write the estimate of the pyramidal error. The same procedure should be followed with all four prisms. If the right angle be obtuse, more than 90°, it will deviate the beam outwardly toward the rounded end of the prism; if less the opposite results.

Now if two prisms be placed on a frame it will be obvious that the right angle error of one will add to or subtract from the pyramidal error of the other, and vice versa. That is why matching prisms is so exceedingly important in assembly. It is definitely possible to select two prisms having pronounced errors, and so to arrange them on a frame that they cancel out and

the resultant error is not over 3′ deviation from parallel. But they have to have the right kind of errors and be arranged in a prescribed position with relation to these errors.

The problem is difficult to visualize and explain. Perhaps it can be made clearer by a few concrete examples. Prism *A*, next to the ocular, receives the beam from the objective, has a pyramidal error of 3′ and no angle error. Therefore it deviates the beam sidewise by 3′ either toward the wall of the barrel or away from it. Assume that it is toward the wall, the star mark on the prism to the outside. Prism *B* has 3′ angular error and no pyramidal error; it can make no difference which side is placed toward the barrel, since in this case there is no sidewise component to the deviation. If the angle of *B* is acute it will straighten up the beam exactly, the beam that *A* has thrown sidewise with its pyramidal error. If the angle of *B* is obtuse, its 3′ will be added to *A*'s 3′, the total deviation will be 6′ and the instrument probably cannot be collimated without recourse to shims. If, however, *A* is reversed, end for end so that its deviation is thrown inwardly instead of outwardly, then the obtuse angle of *B* will be canceled out and a perfect result will be obtained.

It is highly desirable that a person who assembles only one or a few binoculars should try as best he can to evaluate these errors in the prisms. Accuracy cannot be obtained with a square but an approximation can be approached. Four prisms taken at random can hardly be expected to collimate. Furthermore, one perfect prism cannot be paired with one which has an error of more than 3′. In replacing one prism of a pair it is often better to grind an intentional error into the one being made than to correct its mate when a new one must be made anyhow.

Even though the four prisms available cannot be expected to collimate when mounted haphazardly on a plate, a few rules may help to obtain a passable result. Most probably, each one will have both pyramidal error and angle error of variable amount. An acute and an obtuse prism should not be mounted together; they should both be one or the other and the pyramidal error on the one near the angle error of the other. If the pyramidal error of prism *A* is 6′ and the acute angle error of *B* is 4′ they will cancel within 2′. Then, if the acute angle error of *A* is 9′ and the pyramidal error of *B* is 8′, they will cancel within 1′ and the over-all deviation will be only 3′, well within the collimating range of the instrument if there be no mechanical faults.

The construction of a model of a binocular using cardboard, modeling clay, and wires, is well worth while. With this, the light path can be followed easier than from a drawing and a method of matching and notation can be worked out which is different from the one here given. Probably each large factory has its own system and its special apparatus for determining permissible errors without actually measuring these errors in minutes. Often projection type instruments are used and the workman merely has to read off two arbitrary figures to represent the errors and classify the prisms so that they can be put into their proper categories for matching. The autocollimating telescope forms the basis for such instruments. The one described in the next chapter and which has a well corrected spherical mirror for an objective has many points in its favor and is readily constructed with few tools. Almost any accuracy desired down to small fractions of seconds can be readily obtained and everything necessary to know about a Porro prism can be learned in less than a minute. It is convenient in using one of these instruments to record the errors in actual minutes and fractions, rather than arbitrary numerals. With the above as a basis a set of well tried rules may be set down for matching prisms accurately.

1. Cancel the angle error of the eye (top) prism against the pyramidal error of the objective (bottom) prism, and vice versa. Add the two results together; they should not equal more than 3′.

2. Determine whether the angle error is obtuse or acute.

3. To determine this, move the eyepiece and prism of the tester toward the mirror; if the two images from the right-angle faces approach each other, the angle is acute; if they separate, the angle is obtuse.

4. Place prism on tester stand so that when the reflected images, viewed through the eyepiece, have the single brightest image, the one from the front hypotenuse face, on top, and mark the top of the prism with a star. Adjust the prism table so that the two angle spots are on the horizontal line of the crossline. If the crossline is calibrated in equal divisions and these represent one minute of deviation each, count the number of divisions up to the single hypotenuse reflection and record the result on the prism. It is convenient to record the amount of angle error and whether it is acute or obtuse on the same end with the star. Due to the double reflection within the prism, the crossline divisions will have only half the value they do for pyramidal deviation.

5. In all cases place the top prism with the star toward the outside of the binocular.

6. If the angle of the top prism is obtuse, place the bottom prism in the instrument with the star toward the outside of the binocular.

7. If the angle of the top prism is acute, place the bottom prism with the star toward the middle of the binocular.

8. Match only acute angle prisms together and obtuse angle prisms together. Do not try to match one which is acute with one which is obtuse.

Additional notes of importance may be found below under the description of the tester. It may be noted here, however, that the definition of the prism is readily determined qualitatively and the flatness of the polished faces is at once apparent from the appearance of the various images as seen in the ocular.

The length of the light path through the glass of the prisms is important. Specifications for a recent model call for 54.0 mm ±0.2 for each prism. If it varies much from this there will be no room in the focusing mount of the ocular to bring the instrument to focus. Consequently, in regrinding and polishing, either to remove scratches, pits or chips or to correct errors, the minimum amount of glass should be removed. In an emergency an objective can be moved forward or backward a small distance to compensate for alteration of the amount of glass in the prism but it is a practice which is not recommended otherwise.

Centering and Cementing Lenses: The optical axis of a good instrument should be a straight line unless it is offset by prisms or mirrors; it should not be zig-zag due to lenses being tilted or by having their edges ground so that the axis is not in the center of the circumference. In manufacture, a lens is made slightly oversize and after grinding and polishing it is mounted in a machine which is so constructed that the optical axis can be made to coincide with the axis of rotation. It is then a simple matter to grind the edge down to the prescribed diameter. Soft wheels of grade J or K (of Norton nomenclature) are usually used but one or a few lenses can be edged to diameter by several simple methods which are well described in the literature.

The task is readily accomplished on an ordinary lathe, preferably one with a hollow spindle. The lens is mounted on a short length of brass tubing, the diameter of which is slightly less than that required for the finished product. The tube must be machined on the end, square with the axis, and sharp corners should be chamfered off. Sealing wax or blocking wax is used to stick the lens to the tube and while it is still warm the glass is shifted sidewise until the reflection of a distant light remains stationary on rotation of the tube chucked in the lathe.

This method is not especially accurate, for several reasons. In some shops a notched stick, held on a support in the tailstock or on the crossfeed, is pressed against the outer surface of the lens during slow rotation. This likewise is not very accurate and there is risk of scratching the lens.

In mass production both of the above methods are extensively used on especially built edging machines in place of lathes and it would seem that the results they produce are sufficiently good for the purposes required. It may be expected that one person who wants to assemble one instrument from a miscellaneous lot of parts, or even a small overhaul shop, would not have such a machine available, and perhaps he might want a more nearly accurate result. Two methods will be outlined, in both of which the only special equipment required is a lathe with a hollow spindle.

With the lens to be edged mounted in the lathe, an illuminated target such as a crossline, a pinhole, a piece of fine screen or the filament of a low-voltage, clear-glass light bulb is mounted to the left of the headstock so that the beam passes through the spindle. This can be centered sufficiently by sighting through the spindle from the opposite side before the lens is chucked. If the lens be positive an air image of the target will be projected somewhere to the right. The position is readily found by trial with a white card. If the lens be out of center this image will rotate when the spindle is turned. The tube should project far enough from the chuck so that it can be warmed with some kind of burner to soften the wax. The lens is then shifted sidewise until rotation of the spindle produces no perceptible movement of the image. Extremely close centering can be obtained if the image be projected upon a piece of clear glass and is then examined with a magnifier or microscope.

It is believed that a still better method is to mount an auxiliary lens, such as a 7×50 objective, on the crossfeed of the lathe and adjust it close to the center of rotation of the lathe spindle. By moving the crossfeed along the bed of the lathe it is possible to project the air image formed by the lens in the chuck to a distant wall or screen in greatly magnified form. In this manner the slightest discrepancy can be disclosed. Or, if one chooses, the direction of the beam can be reversed and to the right of the auxiliary lens there is placed some sort of target. A fine screen illuminated with a back light through a ground glass is excellent for the purpose. An air image of the target is produced by the auxiliary lens in the focal plane of the lens to be edged. Therefore this last will project the image of the target to infinity through the lathe spindle. It can be examined with any small telescope previously focused on infinity, and on rotation of the spindle very slight errors can be detected.

The actual grinding of the edge to diameter can be accomplished in many ways. A soft wheel (such as Norton No. 37C180-K8V) mounted on a toolpost grinder and fed with water is probably the fastest. However, equally good results can be obtained with loose abrasive grains and a piece of flat metal mounted across the lathe ways. This strip should have a slight spring and it should be hinged at the far end; a screw is provided so that it can be elevated against the edge of the lens by small stages. Another way is to mount the piece of flat metal on the crossfeed in an inclined position. The diameter of the glass is reduced by merely advancing the crossfeed.

A task which frequently confronts most workers with lenses is the cementing of two or more elements together or the renewal of the cement in damaged combinations of lenses. Formerly Canada balsam was used exclusively for this purpose. Sometimes the liquid form was used but, in order to remove the solvent, it was necessary to heat the glass slightly for a protracted period. Consequently stick balsam was nearly always preferred. However, it was found that sudden and extreme changes of temperature encountered in military operation frequently caused the elements to part. This led to the development of a synthetic resin cement, a methyl-methacrylate, by the research department of Eastman Kodak Company. This is tougher than balsam but has about the same index of refraction. It has been available in stick form only.

Many special appliances have been developed for mass cementing of large numbers of lenses of one size. But when the sizes vary greatly or when only an occasional cement job is encountered good work can be accomplished with relatively few accessories. A heavy cast-iron disk is heated on a hot plate; the carefully cleaned lenses, resting on a piece of black paper, are warmed up to the melting point of the cement on this disk. A drop of the cement is melted into the concave lens and the convex lens is dropped on. It will gradually settle into position but it will usually be found that there are some bubbles present. These can be worked out with slow rotation of one lens upon the other and pressure. A chamois-covered stick or a piece of soft rubber is usually used because the glass is too hot to be handled more than momentarily with unprotected fingers. A set of squaring blocks, made of cast iron ¾ inch thick, as shown in Figure 7, with a 7×50 objective lens in place, can now be used to line up the circumferences of the lenses. If the

original centering was done accurately this will usually suffice but it must be insisted that there is no substitute for good optical centering.

Elaborate and well constructed instruments are available in larger shops and factories and while the cement is still warm the lens is transferred to one of them. A very accurate scroll chuck centers the lens mechanically while the image of the crossline is projected from below. The beam is focused into a small telescope which is also provided with a crossline. This last usually has a circle in the center to represent tolerance; that is, the two lens elements must be so adjusted upon each other that they project the image of the lower crossline into this circle. Provision is made for rotation of the chuck with the fingers and the lower crossline can be adjusted up and down to accommodate lenses of great differences in focal length. The best

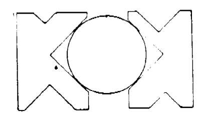


FIGURE 7

V blocks used to center achromatic lenses during cementing operation when lenses have already been edged to correct diameters.

instruments are provided with a penta prism in the telescope to turn the image out horizontally for ease in use.

Collimation: In any binocular telescope it is of the utmost importance that the optical axes of each half of the instrument shall be parallel to each other with a permissible deviation of not over about two minutes of arc in any part of the swing. If it exceeds this amount the observer's eyes will be looking in different directions and he cannot look through an instrument for a long period of time if his eyes are strained to bring the axes into alinement, without much fatigue, headache, or other evidence. He may see through the same instruments with one eye only, and this is a very common occurrence with privately owned instruments. If the axes are in alinement, the binocular may be used continuously for hours without the slightest strain and the observer soon forgets that he is looking through an optical instrument at all. The problem is to put them in alinement, or collimation, as it is usually called.

It will be readily apparent from a casual examination of an ordinary binocular that when the two light beams emerge from the oculars their projected paths may be parallel in one plane and not in another at right angles to it. Furthermore, a slight adjustment of interpupilary distance by revolution around the hinge may alter the direction of one or both beams. That is why the hinge was called the "heart" of the instrument earlier in this chapter. Thus it becomes evident that there are three distinct units which must be brought simultaneously into strict parallelism and they must remain so for all adjustments which may be made, such as for change of focus and interpupilary distance. Also, once the goal has been reached, the provision made for collimation should be locked as securely as possible to prevent displacements which would result from the ordinary use of the instrument. The very delicate nature of this piece of equipment will be readily apparent to anyone before he finishes the task of bringing two telescopes and a hinge axis into mutual parallelism.

To do this without an accessory piece of apparatus, called a collimator, is almost impossible if precise results be desired. However, few individuals either have access to a collimator or would care to spend the time and money required to make one. Therefore, an effort will be made to give a procedure whereby a passable result can be obtained.

It is assumed that the disassembled instrument has been put back together and that the focusing adjustments and the rotation of the barrels on the hinge are velvety smooth. If there be the slightest catch or "jump" in the latter, good collimation can never be attained. This point cannot be too strongly emphasized.

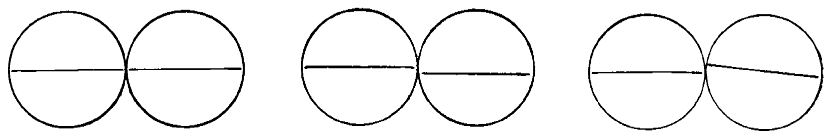


FIGURE 8

Appearance of horizon line through both barrels of binocular. Left: As seen when squaring and collimation are perfect, irrespective of movement on hinge axis or distance of instrument from eyes. Center: One or both barrels are out of collimation. Right: Prisms of right barrel out of square.

Hold the binocular before the eyes in normal position and look at some object which has a horizontal line, such as a picture molding indoors or a building outdoors. There should be no offset (often called a break) in this line as seen by the two eyes (Figure 8, left). Slowly move the binocular outwardly away from the eyes, and at the same time rotate the two barrels on the hinge to keep both images in view, all without relaxing close observation on the junction point of the horizontal line. If it continues to appear without an offset, throughout the swing of the hinge, the instrument is in collimation. A newly assembled one can hardly be expected to be in this condition. Probably the view will be as shown in Figure 8, center. This procedure should be repeated by every user of a binocular until it becomes standard routine irrespective of the one he uses. In no other way can he quickly evaluate the correctness of the adjustment or collimation.

If, during the process, the two parts of the horizontal line as seen by the two eyes do not remain strictly parallel to each other, even though they may be offset, then the prisms of one or both barrels are out of square (Figure 8, right). There is no cure for this except to remove the prism plate and square the prisms properly.

Each objective cell in modern binoculars has a loose excentric ring around

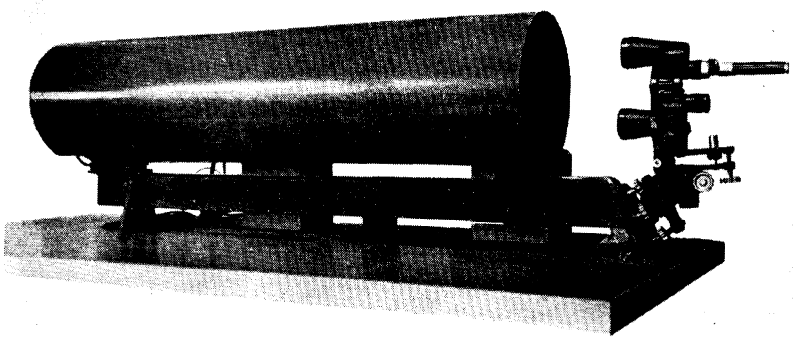
it, free to rotate but a good fit both on the cell and in the barrel. The cell itself is likewise excentric, the amount in each case being .020 ±.002 inch in most cases. Now the separate rotation of these two elements permits the oscillation of the axis of the objective in a circular plane normal thereto and .040 inch in diameter. This is sufficient to collimate any instrument if the parts have been made and assembled within the specific tolerances. All that is required is to rotate the two elements in each barrel the correct amount and lock them there. The difficulty is to determine which one to move, how much, and which way.

If possible, a rigid support for the instrument should be provided so that it can be worked upon without disturbing its direction of pointing toward the target object by even as much as .001 inch. An outdoor object, distant 1000 yards or more, should be chosen. This done, the best advice which can be given here is to just try. It is likely to be a long experiment but it may be well to remember at all times that the object sought is to bring the two images into superposition at all points of rotation of the hinge. Eventually an adjustment may be obtained whereby one may be able to use the instrument for short periods without undue strain, but only by accident will real collimation be attained.

By the use of a standard collimator, this process becomes simple routine after some practice. A great many special instruments have been made for the purpose, some of which are described in the literature. All these possess in common, two collimators of small size, say with 3-inch objectives, one for each barrel, or one small collimator with provision for moving either it or the binocular horizontally. Much ingenuity has been expended in devising means for holding the binocular in position and for viewing and interpreting the two images of the target. In some cases these images are projected upon a screen which is properly ruled and divided so as to tell the operator when the adjustments are within tolerance. In *Scientific American,* Oct., 1951, pp. 81–83, Felix A. Luck described a simple means of obtaining a reasonably close collimation, using the sun, a large reading glass lens and a wooden mounting on a camera pan head.

One collimator, Figure 9, top, which is in wide use in Naval shops, has numerous features to recommend it. After having made several, it can be stated with confidence that it is not beyond the capabilities of many individual workers. The essential parts are shown schematically in Figure 9, bottom. The tube may be of wood or metal, round or square. The length is determined by the focal length of the lens to be used. At *a* is an ordinary frosted bulb of about 60- or 75-watt capacity. Then comes the target unit which may be made up as follows. At *b* is a sheet of opal or ground glass. At *c* is the target shown in Figure 10, preferably made by printing directly on Kodalith a full-size drawing of this target. At *d* is a disk of red cellophane and at *e* is a disk of clear glass. These four elements, *a, b, c,* and *d,* are all made the diameter of the collimator lens *f,* to be used, and are bound together like a lantern slide and fitted into a cell which can be adjusted back and forth a small distance in the tube. The collimator lens *f* is ordinarily a single piece of glass and may be

8 to 12 inches in diameter. Ordinary plate glass of sufficient thickness should be satisfactory. The latter diameter is better for 7 × 50 binoculars but the first can be used. A plano-convex is satisfactory but the least aberration is obtained if it is double convex, with one radius about seven times the other. The focal length is not critical; 48 inches is a good figure to strive for. Once



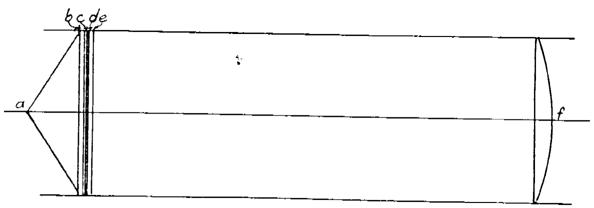


FIGURE 9

Above: A binocular collimator used extensively by the Navy. The instrument in the clamp at the right is a Spencer 7 × 50 with auxiliary telescope attached to the free-swinging barrel. The rhomboid prism is shown, its tube foreshortened, at the objective end of the telescope. Below: Diagram of the optical system of the same collimator.

it is known, the crosslines of the target (Figure 10) can be divided to represent ten-minute intervals and the circles represent degrees. Then the angle of field, the magnification and something of the aberrations and definition of each barrel of the binocular being worked upon can be determined.

The fixture shown in Figure 9, for holding the binocular, comes next in line and it must be rigid. There are many ways to make it. In addition to rigidity it must be possible to move the binocular as a whole because its purpose primarily is to aline the hinge axis parallel with the optical axis of the collimator within very close limits, that is, .001 to .002 inch.

Unless a projection method is to be used, an auxiliary telescope (Figure 9, top) is required for examining the position of the image of one barrel while adjusting the objective and the holding fixture at the same time. The telescope should be of low power; 2× to 4× is best. It has no crossline but is provided with a rhomboid prism mounted in front of the objective (seen foreshortened in the half-tone illustration). Threaded rings are usually provided to attach the telescope to the ocular of the binocular or it may be mounted on a separate fixture of its own. It is adjusted to infinity focus.

Upon looking through the telescope two images of the target will be seen, one through the binocular and one around the binocular by means of the rhomb. The problem is to make these superimpose throughout the length of the arc of swing on the hinge. There are two ways of doing this. One is to move the

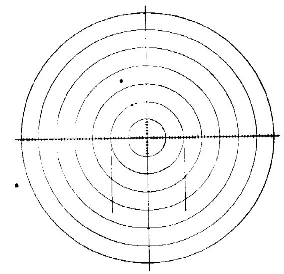


FIGURE 10

One type of target used extensively in collimators of the form shown in Figure 9. The details of the design are calculated from the focal length of the collimating lens. Each circle represents 1° of field. Each small division represents 10′ of angle. With this form of target it is possible to compare the sizes of the fields of view of the two barrels of the binocular as well as the comparative magnification. A general idea of the chromatic aberration is also readily obtained.

magnified image of the center of the target (the one through the binocular) halfway to the direct image (the one through the rhomb) and the rest of the way with the fixture. This is done at one end of the swing and the process is repeated at the other end of the swing. By going back and forth a few times in this way the two images of the center of the crossline will come to exact superposition and remain there no matter what the position of the barrel on the hinge. This means merely that the optical axis of that particular barrel and the axis of rotation of the hinge are exactly parallel to the optical axis of the collimator; therefore, they are parallel to each other.

Now, without disturbing the fixture at all, if the auxiliary telescope be transferred to the other barrel, which in normal practice is rigidly clamped in the fixture, and the magnified image be brought to the center by moving objective ring and cell alone, the entire instrument will be in collimation. Both optical axes will be parallel to the hinge. All that remains is to set the retaining rings, lock them with their set-screws and make a final check to see whether this has produced any maladjustment. If not, the diopter scales of the oculars can be set on zero (for infinity focus) at once and the work is completed except for waxing, which has already been described.

The other method referred to is very similar but somewhat faster. In this the axis of rotation of the hinge is first set approximately on the axis of the collimator. This is done by adjusting the fixture alone until, upon rotation of the free barrel with the auxiliary telescope attached, the magnified image of the target center travels about the stationary one in a circle. Then the two images are brought into superposition with the excentrics. After some practice an operator can do this in only one or two trials and collimation then becomes simple routine. The second barrel is adjusted the same in both cases.

Obviously it is necessary in this type of collimator to have the target mounted exactly at the focal point of the large lens. Then the image of the target is projected to infinity. To make the adjustment, a telescope with considerable magnification, 10× to 20× preferred, is focused upon a distant object out of doors, say the moon or a star. Then the target of the collimator should be moved back and forth in the tube until it is in best focus in the telescope and there is no parallax; that is, the image of the target does not move when the eye of the observer is moved up and down and crosswise in the exit beam of the telescope.

Telescope makers like to grind mirrors. Therefore, attention is called to the possibility of making a superb collimator by the use of an off-axis paraboloid instead of a lens. Probably this is greater refinement than is necessary for binoculars and an ordinary 8 to 12 inch $f/8$ Newtonian mirror would suffice. The target might be full size and offset; it might be smaller and mounted on the axis approximately in line with the hinge axis, or it might be projected to the mirror by means of a full aperture piece of clear glass inclined at 45°. Such a construction has not been made, so far as the writer knows. It is a modification of the prism testing instrument described in the next chapter.

Special telescoping tube wrenches are usually made for adjusting the objective cell and excentric ring of a binocular simultaneously. They must be made especially to fit each particular make and model and, since considerable labor is involved, they are not usually provided for a single instrument or even a few. The same adjustments can be effected, but not so easily, by using two hooks, one in each hand.

Finally, the habit should be formed of always looking backward through each barrel of the binocular toward a strong light. In this way internal optical defects can be spotted instantly, especially if the instrument be pointed not quite directly toward the light, so that slight oblique illumination is obtained. Scratches, pits, dust, smudges, bubbles, etc., stand out brilliantly, but the adjustment of the instrument cannot be evaluated in this manner.

II. Semi-Modern Binoculars

This is the type of instrument used so extensively in the first world war. A great many of them bear the serial numbers of the Signal Corps, U. S.

Army. They do not differ fundamentally from those which have been described but the details of construction have been changed radically since they were made. Nearly all are 6 × 30. The lighter alloys had not then come into extensive use in instrument making, so most of the parts are made of brass and zinc die castings. For this reason they have withstood corrosion very well and many of them are still in excellent mechanical condition.

The hinge has a straight pin instead of a taper, a construction which has much in its favor, although the method of producing resistance to rotation of the hinge by tightening bearings seems unsound in either case. The straight pin rarely freezes and consequently there are relatively few broken hinges.

Objective cell and ocular both screw into the body casting, so there are stamped metal covers on each end. In assembly, these are waxed down. Oculars are individually focused. There were many modifications in construction but the forward and backward motion is produced by multiple threads as in the later designs. The use of a key and spiral slot had disappeared.

Prisms are mounted on each side of a milled shelf, cast integral with the body, and are held in place by an overriding spring clamp engaged in two internal slots in the casting. The prism seats are considerably oversize.

Collimating rings were not in general use when these instruments were made. Therefore, adjustment is made by shifting the prisms on the shelves. For this purpose there is a series of headless screws, 2 × 64, threaded through the body casting from the outside. These are located in such positions that they can be made to shove the prisms back and forth on the seats and also rotate slightly for squaring purposes. In this manner collimation is effected.

It is highly desirable, before this is attempted, that one become thoroughly familiar with the function of each screw. The disassembled barrel with only the prisms in place should be studied in detail. A diagram for each prism, made at the time, will aid the memory. Ordinarily the screws are so arranged that each one has another to oppose it. Therefore, collimation is effected with two screwdrivers, the one working against the other. It is good practice to be absolutely sure ahead of time that all screws work freely in their threads and that the driver slots are not in bad shape. There is a very good reason for this. The points of the screws bear directly upon the glass of the prisms and at the most vulnerable positions, the thin edges of the 45° angles, or near the hypotenuse face. It takes very little excess pressure on one of these screw points to chip the glass, and replacement prisms are not regularly manufactured. It is also good practice to back off each screw a very slight amount each time it is tightened, just for safety's sake.

If a collimator is not available, adjustment must be made by trial and error, as has already been described. The best results cannot be expected but after a period of experimentation a usable instrument should be obtained. If a collimator be available, the binocular is attached to the fixture, the auxiliary telescope is put into position and the second method described will be found to be advantageous. Until the operator becomes thoroughly familiar with the exact function of each screw he will have difficulty but, once this is mastered, these instruments do not give much trouble. They have a much wider range of adjustment than modern ones with excentric collimating rings and, as a consequence, larger prism errors can be tolerated. However, if they much exceed those given in the preceding chapter, bad color effects begin to appear.

All that remains to be done after collimation has been completed is to set the diopter scales of the oculars to zero and fill the screw holes with black wax. In general overhaul all the rules and precautions already mentioned should be followed, such as greasing, sealing, painting, etc.

A great many minor modifications of construction were made, especially in the design of the hinge and the ocular. It will be found very difficult to match the old hard rubber eye guards on the oculars. Many different designs were used. In many cases it will be found better and quicker to discard the old ones entirely, make new retainer rings to fit the brass mount and use a couple of modern guards.

The semi-modern binocular has many points in its favor. Its greatest fault is the likelihood of the collimating screws chipping the prisms.

III. Binoculars with Central Focusing Devices

The number of makes and models of these is legion. Some are cheap and some are expensive while some are outright fakes. In this last category fall such things as those articles which were widely distributed some years ago and which looked outwardly like binoculars yet they contained no lenses, prisms or mirrors but only two plain disks of window glass in each barrel. These did not even have a central focusing screw but there was an imitation of one.

Thus the general public has been "educated" into the belief that a properly made binocular should have a central knob, the turning of which moves the oculars inwardly and outwardly simultaneously. This design is unsound, both optically and mechanically, yet it persists in expensive models as well as the cheap ones.

The basic construction is similar in all of them but details vary within wide limits. There is a central tube connecting the hinge lugs and a large knurled knob somewhere along the line. This is free to rotate but not to move up and down on the hinge axis. Attached to this knob, or integral with it, there is another tube which rotates within the first and this has a multiple internal thread. A short section of rod bears this same thread on its lower end and projects above the upper hinge lugs. It is milled square on its upper end. By turning the large knob, the rod is made to move inwardly and outwardly. The arms which bear the oculars at their outer ends are attached to the outer end of the rod. Often there are blind screws holding the various parts together, so great care should be exercised in disassembly that no injury is done to the mechanism. The ocular lenses are mounted in tubes in various ways and the tubes are secured to the outer ends of the arms. One ocular is usually made to be focused independently so that adjustment can be made for difference in the two eyes. The lens tubes are supposed to slide freely up and down in sleeves attached to the body castings when the central knob is turned.

This type of construction is open to criticisms from many directions, only a few of which will be mentioned. It is not possible to mount optical parts securely on the outer ends of crossbars and these in turn to a small movable central post so that they will remain in adjustment. The connection to the post must be a hinge joint to permit rotation of interpupilary separation, and this further complicates the construction. The lens tube must slide freely in the body sleeves; otherwise they will bind. We know that these ocular assemblies should not have their axes tipped at an angle to the axis of the instrument more than about 2′. We also know that they should not move at right angles to the main axis more than .002 inch. If they do, collimation is destroyed.

It is not possible to have two freely sliding elements such as this, and which will remain in strict alinement, without extremely heavy and rigid construction. If the central movable post were made from 1-inch solid stock and if all machining operations were of the highest quality there might be a chance; but this post, or rod, is often brass, not more than ¼ inch in diameter.

As a consequence of these difficulties the ocular lens tubes are extremely sloppy sliding fits in the sleeves. Sometimes a thin strip of felt or leather is glued to the inside of the sleeve to try to help the situation but this often causes too much friction and, as a result of the operator trying to focus the binocular, the hinge joint at the tip of the rod is ruined. That is, a stress has forced it so that there is .001 inch or more play. If there is any perceptible movement in this joint, if either ocular will move up or down independently of the other, or if there be the slightest side play of the lens tube in the sleeves when adjustment is made for interpupilary distance, it may be taken for granted that collimation is impossible and the observer must resign himself to the use of one eye only when looking through the instrument. Much dirt and dust also sifts into the interior of such a binocular around the lens tubes.

In some of the better makes and models the objectives have excentric collimating rings and, while the exact adjustment described in Section I can rarely be effected, it can be approached. Others, mostly older models, have screws through the body casting for sliding the prisms around for both squaring and collimation. Others, chiefly cheap European and Asiatic models, have no real provision for bringing the two optical systems into parallelism. All that can be done is to take the instrument partly down, shove the prisms around with a stick or screwdriver, then reassemble and note the result.

It may be stated with confidence that no binocular can be made light or cheap with a central focusing device and which can compare in accuracy with one having individually focusing oculars. And it is significant that, in military operations where the performance of this instrument meant life or death, the latter type was used exclusively. If weight and expense are important factors in the making of an individual selection the writer would strongly recommend that a choice be made between a monocular and a Galilean field glass.

Attention may now be directed to a binocular which was designed late in World War II but which, up to the time of writing had apparently not come on the market. It was a 6 × 42, had a plastic body, no hinge, and no focusing devices at all. Thus, in one swoop, most of the things which have been criticized in this chapter were discontinued. Interpupilary distance was taken care of by choice of one of three models. Apparently no focusing was provided, in the belief that if an object were so close that focusing be necessary, the observer would not need a binocular. This is doubtless true in many cases but occasion may arise, as in bird study, when magnification at close range is desirable. Such an instrument would be sturdy, dust-tight and watertight. It is hoped that the idea will not be forgotten.

IV. Galilean Type Binoculars (Field Glasses)

The optical parts of these instruments are extremely simple; therefore construction may be relatively inexpensive and they have wide distribution. In many ways they are superior to all other types within their range. Both advantages and disadvantages are here indicated.

In each barrel there are two lenses only, an objective and an ocular. In the best models both of these are achromatic doublets. The objective is a positive lens of wide aperture. Focal lengths vary greatly, so that over-all magnification may be from 2× to 6×. As magnification goes up, difficulties are encountered; best performance is said to be in the range 3× to 5×.

The ocular is a single negative lens or combination. It may be a cemented doublet or even a triplet, the additional lenses being for the purpose of aberrational corrections.

The mechanical construction is likewise simple. The objective is mounted directly in the end of the body tube. The ocular is mounted in a separate tube which is either a sliding or a multiple screw fit in the upper end of the body tube. In use the focal points of the two lenses coincide; therefore, the image of the object is projected to infinity. And, because of this, usually no interpupilary adjustment is provided, the exit pupil being the diameter of the aperture of the ocular. Furthermore, there is no critical eye point; the instrument can be used close to the eyes or several inches distant if need be. Images are erect and very brilliant if the optical elements be good and clean.

Two methods of focusing will be found in the various models. In one, each ocular is independently adjustable; these have multiple threads, as in modern military binoculars and are much to be preferred. The other has a central focusing device which suffers from all the ills described in Section III. These ills are equally incurable but they do not do as much damage as in prism binoculars. The sliding ocular tubes are difficult to maintain in strict alinement but they are free to move inwardly and outwardly. If they move too freely, dust will gather in the interior of the instrument. If too tight, the cross-hairs will work loose where they are attached to the central focusing post.

Only in the higher powers is a hinge provided for interpupilary adjustment. In the lower powers the ocular is large enough to take care of all ordinary eye separation. The hinge lugs are usually of weaker construction than in prism binoculars. Therefore, when the instrument is dropped, the tubes are likely to be bent out of alinement.

No provision is made for adjustment for collimation, at least not in the models which are in most common use. Usually the two barrels are brought parallel to each other by straightening the parts which have been bent. In many cases this can be done by a twisting motion while at the same time the operator has the instrument focused on a distant object.

Many "field glasses" of superb construction and performance have been made and are still in service after 50 or more years. As might be expected, however, with an instrument of such simple construction, much useless junk has been foisted upon the public. This may take the form of faulty mechanical construction, or the optics may be disgraceful, or both. In some widely distributed models, the objectives were doublets all right, but in each case both lenses were made of the same glass, and green bottle glass at that. Needless to say, an object viewed with one of these had all the colors of the rainbow.

Opera glasses usually are Galilean type instruments and of about 2× magnification. Many of them are works of real art and are much sought as collectors' items. Decorations on them run through the range of human ingenuity but in the interior there are only two lenses in each barrel. Gold plating on the metal parts is very common. One widely distributed model has the outsides of the barrels covered with pieces of pearl shell, properly fitted together. All such instruments seem to get the roughest kind of usage and many things happen to them. They are obviously made more for ornament and show than for utility. Repair and overhaul are difficult, especially if the ornamental decorations be injured. The fancy metal parts get bent and scarred and replacement is expensive.

If a person with his own workshop feels that he must construct a binocular, the Galilean is by all odds the most simple to make. He need not use tapered tubes. Care should be taken to maintain strict alinement. If the objectives and oculars be well matched for focal lengths, and are reasonably well corrected, a very useful instrument will result. For athletic contests a 4× Galilean has no peer.

Evaluating a Binocular: In order that the reader may be in a little better position to evaluate a prospective instrument, it is suggested that he examine it backward first; that is, look through from the objective and toward a strong light. If the angle of vision be slightly oblique every optical surface in each barrel can be examined in turn. Dust, dirt, chips, finger marks, scratches, poor polish and even the larger striae and bubbles are at once apparent if present.

The instrument should be shaken to detect loose screws or other parts which may have been inadvertently left there during assembly.

The hinge should be tested for smoothness of rotation; there should not be the slightest catch or grinding.

Oculars should move in and out with velvety smoothness.

The collimation and the squaring of the prisms should be checked by looking through the instrument normally at a distant horizontal line, such as a part of a building, first with one eye and then with the other and then with both. Move the binocular away from the eyes, keeping close watch of the two images and keeping them tangent to each other by rotation of the hinge. The horizontal line should remain continuous through the two circles in all positions.

If it does not, the instrument is out of collimation or the prisms are out of square.

Color correction is best checked by focusing upon a small object such as a twig, a telephone wire or a ball on the end of a flagpole, against a bright background, first with one eye and then with the other. In the better instruments color is barely detectable under this test and is not objectionable.

A Reflecting Autocollimator for Precise Measurement of Prism Angles

By G. Dallas Hanna
California Academy of Sciences

In the development of the instrument described in the following pages I am deeply indebted to many persons. If my connection be considered merely that of a reporter of facts and circumstances and if the credit for ingenuity displayed be given to the individuals mentioned, a correct picture of the actual situation will result.

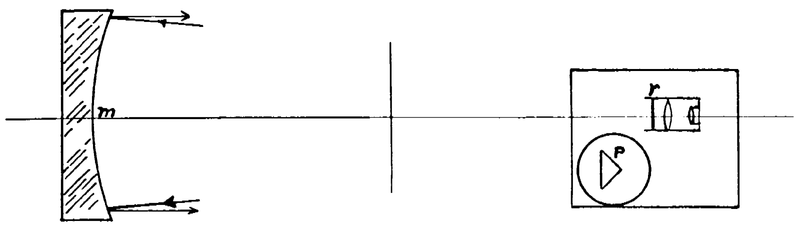
The original suggestion of the possibility of using a mirror for the objective of an autocollimator, so far as I am concerned, was made by Dr. D. H. Rank in July, 1942, at Frankford Arsenal. My immediate problem was the acquiring of technic in the manufacture of roof prisms, for which other and adequate means of testing were available. A year later, after the completion of the roof prism program, we at the Academy were deeply engaged in the overhaul of Naval optical instruments, received directly from incoming ships. Testing equipment was unobtainable and speed was imperative. Many instruments, and prism binoculars especially, came to us in large numbers with reflector prisms broken. An autocollimator was needed to rapidly check the angles of replacement parts being made. There were no suitable lenses available but we had an abundance of mirrors from previous activities. Therefore, the reflector type was decided upon.

In the actual design of details and the carrying of them out to completion, much of the work was done by Mr. A. S. Getten of the Academy staff and Mr. Daniel Brower of the Optical School, Mare Island Navy Yard. The instrument became the pride of the small group of amateur telescope makers who gathered in the Academy shop during spare hours from an otherwise busy career, throughout the war, to keep the crew of overhaulers of instruments supplied with prisms. These men are J. A. Steinback, D. A. McLaren, and L. A. Parsons. Two others who aided in the work during considerable periods were Carl Wells and Karl S. Bailey. Three non-telescope makers of great skill belonged to the group, Allyn G. Smith, a telephone personnel expert, C. C. Church, a micropaleontologist, and Edwin Over, a mineralogist. All these men used this versatile instrument as a part of the regular routine the same as a straightedge or an optical flat, and in the many discussions of its principles and possibilities nearly every one of them has had constructive suggestions to make.

Two of the instruments were made. The first had a 6-inch $f/8$ mirror for an objective and the second a 5-inch $f/4$. The last is lower power and was suggested by Mr. McLaren because errors in many commercial prisms were so large that they could not be measured with the $f/8$.

The general construction is shown in Figure 1, top, and a photograph of the original instrument is reproduced in the same figure. More than 25,000 prisms were tested on this device, the first being a batch of head prisms for periscopes which were made. It is just as accurate for plane-parallels, wedges, penta prisms, rhombs, and roof prisms. We have not had a prism that we could not test on this set-up.

The position of the mirror in its wooden cell is obvious. It was made by the late William M. Grant, a meticulous workman; it was aluminized in 1935



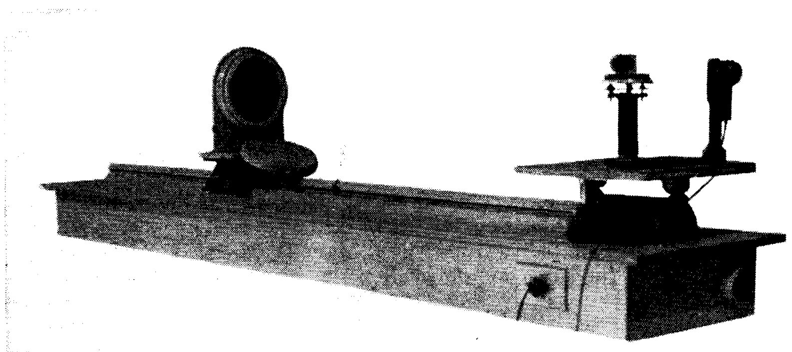


FIGURE 1

Above: General arrangement of optical system for reflecting autocollimator, from above. m: *mirror; in this case a 6-inch f/8 of 1212 mm focal length.* p: *Prism; normally this rests on a loose disk of glass for ready rotation, and the disk rests on a universally inclinable prism table.* r: *Reticule of Ramsden ocular. The light source in this case was located immediately below the ocular. If it be located to one side and be reflected to the mirror by means of a small prism or a semi-reflector many interesting possibilities for additional uses of the instrument open up, especially if a monochromatic source be used. Below: The original f/8 instrument.*

in our home-made outfit and the coating is as perfect as when first put on. The mirror cell is attached to a base, which slides, saddle fashion, on a triangular cast-iron bar. This is not necessary and resulted merely from the fact that a base for a large photomicrographic outfit was available. Adapting it to the purpose was quicker than constructing a table which would have served equally well.

At the right end of this pseudo-optical bench there is another sliding fixture, the flat top of which serves as a support for light source, ocular, and prism table. The only accessory not visible is a 6-v transformer to step the current down for the flashlight bulb which was used as a light source.

Light from the filament of this bulb passes directly to the mirror, the distance between the two being the focal length of the mirror. Therefore a full aperture beam of approximately parallel light comes directly back toward the operator.

The prism table and prism are located in this beam. If the prism be an ordinary right angle one with the hypotenuse face toward the mirror it is obvious that light rays striking it will be reflected back toward the mirror from each air-glass surface. A series of images results and the mirror brings them to a focus in the ocular. If there be no error in the prism, all images will superimpose as one. This condition rarely exists; usually there are five, variously separated depending upon the errors present.

The prism table itself, in this particular case the original construction, is very simple. A hollow post is permanently fixed to the base plate and has a flange on top. This flange is drilled and tapped for three screws which have large knurled heads or plates near the top. These are made exactly like leveling screws used on such instruments as transits and levels. The prism table itself rests upon the upper ends of these three screws, recesses being provided on the lower side for positioning. A coiled spring, inside the post, is attached to the base plate and to the center of the table; this pulls the latter down on the heads of the three screws. Thus the table is inclinable in all directions and this is necessary because no two prisms are likely to have the ends ground in the same relationship to the reflecting sides. The construction is essentially that of most spectrometers.

The light source must necessarily be located at the focus of the mirror. This is easily adjusted because light source, ocular and prism table are attached to the same base plate which is free to slide in any direction on the table. Obviously, light source and ocular could be in a fixed position and only the prism table movable but this first instrument was not made that way.

The five images of the filament which come back to the ocular have the relationship shown in Figure 2 or they may be reversed, with the single spot below, depending upon direction of pyramidal error. The single spot (I) is the direct reflection from the hypotenuse face. Upon rotation of the prism on the table this spot moves across the field of the ocular. The next two spots, II and III, which are usually oriented on the horizontal crossline, are reflections from the right-angle faces. Light enters the prism from the mirror, strikes each of these faces, is reflected to the other, back to the mirror and thence to the ocular. If there be no error the two images are exactly superimposed, the same as in a good roof prism. The separation of the images is a measure of the right-angle error which can be read off on the graduated crossline. And these two images remain stationary upon rotation of the prism.

Two fainter images, IV and V, more widely separated, will be located below the crossline. Their separation is double the distance of the angle images but they move across the field when the prism is rotated. Therefore they are internal reflections of the hypotenuse glass-air surface, each one quadruply reflected from the right angle faces. They are located the same distance below the crossline as the single image is above. The pyramidal error can be read off directly on the vertical crossline by taking the distance from the upper single image to the mid point of a horizontal line connecting the lower faint images. In practice, however, it is more convenient to read only half this distance; that is, from the horizontal crossline up to the single image, and ascribe to this double the value in minutes, which is used to measure the angle error. That

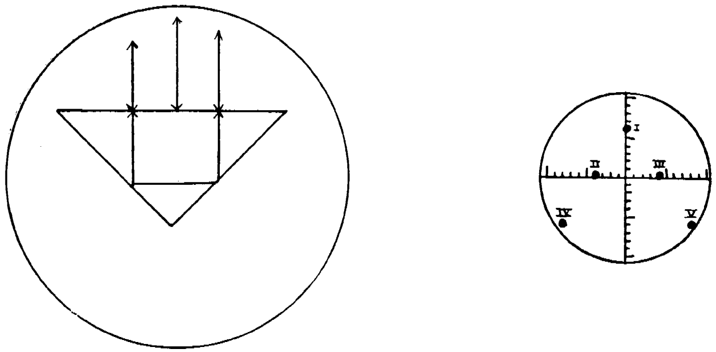


FIGURE 2

Left: Diagram of light paths using an ordinary right angle prism. Right: Appearance of the images as brought back to the crossline of the ocular. I: Single reflection from hypotenuse face. II and III: Reflected images from the right angle faces. IV and V: Internally reflected images of the right angle beams.

is, if the angle images are separated by six divisions and each division is equivalent to ½ minute, then a division of equal length on the vertical crossline would represent one minute of pyramidal error. This follows, since the image from the hypotenuse face has been reflected only once while each of the angle images is doubly reflected. Actually, there are more internal reflections from this hypotenuse glass-air surface, some of the light from each escaping toward the mirror, but they are usually so faint or so far apart that they cannot readily be detected. The most I have ever seen is nine.

The paths of the light rays are shown in the diagrams. The optical principles involved are of the most simple nature. The focal length of the mirror needs to be known as accurately as possible. Facilities, however, are not ordinarily available for securing this closer than in even millimeters. We measured from the knife-edge of an ordinary Foucault tester to the center of the mirror and took half the result as the focal length. The index of refraction of the prism likewise enters the calculations, as shown in the formula $s = f \times 4nr$ where $n =$ the index of refraction of the prism; $f =$ the focal length of the mirror, $d =$ the separation of the images on the crossline in millimeters; $s =$ the angular separation of the images; and $r = 1$ minute of arc, radian measurement $= .0002909$. This formula applies to the separation of the images produced by the reflections from the right angle faces.

As an illustration, the particular instrument described may be chosen; here $f = 1212$ mm and the index of refraction of the prism may be assumed to be 1.516.

1 minute $= 1212 \times 4 \times 1.516 \times .0002909 = 2.14$ mm on the reticule. Or 1 mm division on the reticule $= .468$ minute angular deviation.

If the instrument be used as we found it most convenient; that is, if the two images from the right angle faces be oriented on the horizontal crossline of the reticule, then the formula must be slightly modified for determination of the pyramidal error in angular measurement. It then becomes $s = f \times 2nr$. If the pyramidal error be measured as the vertical distance between the direct reflection from the hypotenuse face and the two faint, widely spaced, internally reflected images, which are likewise from the hypotenuse face, the first formula applies. We did not do this because it so often happens with prisms made on a mass production scale that these two faint images fall completely out of the field of the ocular due to large right angle errors.

It is obvious that, with a separation of the images from the right angle faces of 2 mm on the reticule for one minute of error, very minute deviations from a right angle can be detected with even a low power ocular. It is convenient, but not necessary, to have the divisions of the crossline represent even minutes or fractions thereof for some standard glass such as borosilicate crown. Such special reticules can be made in several ways. We used a diamond chip mounted on an accessory apparatus which was attached to a low power objective of an ordinary compound microscope. The spacings and lengths of lines were obtained by means of the mechanical stage. Lines of any desired fineness can thus be obtained and, while the accuracy of spacing is not great, it will suffice for many purposes.

Various oculars have been used with the tester but the one which served our particular purpose best is a wide field one from a 7×50 Spencer binocular. The magnification of the ocular does not enter into the formula because it serves only to magnify the crossline on which the air images of the light source are focused by the mirror. At one time, for some close work, a filar micrometer was used for an ocular. The divisions on the scale were millimeters and the drum was divided into 100 parts. With this particular mirror one drum division figured out as equivalent to an angle error of one seventh second for borosilicate crown glass, but we never attempted to work closer than two seconds.[1]

[1] As an illustration of the method of computing the distance between divisions of the reticule, consider first the pyramidal error which is a reflection from the front surface of the prism and it is desired that one division shall equal one minute. The length of this division is the tangent of twice the angle subtended from the mirror (because of double reflection) $= d/f$ where $d =$ the length desired and $f =$ the focal length of the mirror. Focal length times the tangent of two minutes angle equals the length of the division. The tangent of 2′ angle, taken from a table of natural tangents, is .00058178. Multiply this by the focal length of the mirror, say 1200 mm, and the result is .698 mm between

It is obvious from the diagram that, if the prism and light source be moved toward the mirror, the angle images will go out of focus but they will also either approach or separate from each other. If they approach, the angle of the prism is acute, if they separate it is obtuse. This is important information in routine shop work where corrections have to be made.

This optical arrangement has no erecting system; therefore the apparent pyramidal error is reversed. When the single image from the hypotenuse face appears above the horizontal crossline and the angle images are on this crossline, the light beam is actually inclined downward toward the prism table. Therefore, it is good practice always to use the same system in orienting prisms; we put the single image up, or else assumed that it was up and wrote the characteristics of the prism always on that end. This or some similar system is important in matching prism errors for binocular assembly.

If the pyramidal error be excessive, say over 8 minutes, the angle images will show pronounced spectral colors; the greater the error, the greater the dispersion. Thus, in making corrections, suppose a prism taken at random out of an instrument has an angle error of 5 minutes and a pyramidal error of 25 minutes, not an unusual occurrence by any means; then it will be difficult to find the reflection from the hypotenuse face; it will be out of the field when the angle images are in view. The spectral colors, however, as Mr. McLaren learned, tell at once whether it is above or below the crossline. If the red color of the angle images be down, the single pyramidal hypotenuse image is also down and, in order to correct the error, a wedge-shaped slice of glass must be taken off one face, the thick edge of the wedge being up.

If these notes have been followed closely it is believed that they will give the workman all the information needed to correct a reflecting prism. Thus he learns the amount of error in the right angle and whether it is obtuse or acute; he also learns exactly what to do to move the pyramidal spot toward the horizontal crossline where it should be.

All these errors are of prime importance in binocular construction. If they be left uncorrected, then the prisms must be matched in pairs in a particular manner so that the angle error of one cancels out the pyramidal error of the other; otherwise they will be additive, spectral colors will be bad and the instrument cannot be collimated.

Since a single reflecting prism is optically a plane-parallel, as Conrady[2] so brilliantly explained, if one be used individually the errors need to be reduced in accordance with the use to be made of it. That is, if no magnification of the image be anticipated, as in tank periscopes, very large errors can be tolerated. However, in such places as diagonals for Newtonian telescopes, where high magnification is often employed, only superb prisms will suffice. An error of a few minutes would be intolerable if sharp crisp images be desired. Many a mirror has been condemned when the fault lay in the prism. Furthermore, the surfaces in such applications must be exceptionally flat. In the specifications of prisms for binoculars the surfaces are indicated as flat within one fringe for the reflecting faces and two fringes for the entering and exit faces. And the magnification in this case is only six or seven. Increase the magnification to 75 or more and the result is obvious. Such accuracy as is required is rarely found in commercial prisms at any reasonable price. Therefore, in our opinion, a fine optical flat is ordinarily superior for a diagonal.

divisions for the reticule. Each division on the vertical line will then equal one minute of pyramidal error. On the horizontal line the two images from the right angle faces will be separated double this amount, because of two additional reflections, so that a division of .698 mm will indicate half a minute of error.

[2] Conrady, A. E., "Applied Optics and Optical Design," Part 1, 1943, p. 32.

In the manufacture of reflecting prisms, all three polished faces are variously inclined to either of the end faces which may be used as a reference. This can be checked with an ordinary square or on such a tester as is here described, by revolving the prism on its table. If the single image from the hypotenuse face be oriented on the horizontal crossline, then a single image should also appear on the same line from each of the angle faces on revolving the prism on the table, if all three faces be mutually parallel. This almost never happens except in especially corrected prisms. And it is not necessary for ordinary use if the three inclinations balance each other out. Suppose the hypotenuse face be five minutes acute with a reference end. Now if one angle face be eight minutes acute and if the other be 13 minutes obtuse, all will cancel out and there will be no resultant pyramidal error. Or one angle face may be four minutes obtuse and the other two minutes obtuse and the result will be one minute of pyramidal error.

From this it will be obvious that both right angle error and resultant pyramidal error can be removed from a reflecting prism simply by taking glass off of one right angle face. It does not matter which one, but the one with the greatest error or poorest surface is usually chosen. In making such prisms it was common routine in our shop that after the hypotenuse and one right angle face were block polished, the third was given a flash polish (about five strokes on a hand pitch lap) and tested. If either pyramidal or angle error be over one minute the correction was made at once by hand with fine abrasive, the surface flash-polished again and tested. After a little practice this was a matter of only a few moments. Therefore, the last faces were blocked for machine polishing with all errors reduced to one minute or less. Careful blocking on specially made plates prevented drifting of more than one minute, so that it was rare indeed that a prism came out of the block with an error greater than two minutes. If it did it was again corrected on one right angle face and rerun and there were practically no discards.

Nothing has been said thus far regarding the 45° angles. Ordinarily, comparatively large errors can be tolerated and checking with accurate squares is sufficient.

It is not possible to secure readily interpreted data regarding these angles with this tester in its original form. If a light beam strikes one of the right angle faces normally, it is apparent that a portion will be reflected back to the mirror and thence to the ocular. Another portion will enter the prism, strike the hypotenuse face internally where it is totally reflected to the other right angle face. Most of the beam will then escape and be lost but a portion will be reflected backward (because of the glass-air interface) to the hypotenuse and thence to the mirror and ocular. The two images both rotate when the prism rotates on the table. As they appear in the ocular one may be vertically displaced relative to the other; this indicates the amount of pyramidal error between the two right angle faces alone. One image, that internally reflected, will usually appear fainter than the other and not so well defined. The horizontal separation of the two images will remain the same irrespective of the orientation of the prism. That is, it does not matter which right angle face acts as the entrant and which the exit. If the right angle be truly 90° then the horizontal separation is a measure of the deviation of the small angles from 45°. When the internally reflected image is on the same side of the direct

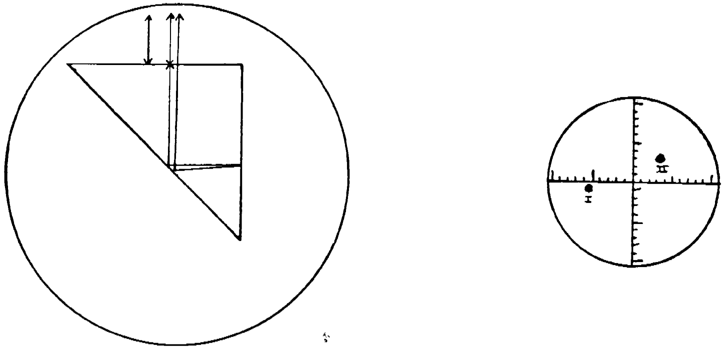


FIGURE 3

Left: Diagram of the light paths when a right angle face is oriented toward the mirror. Right: Appearance of the images as brought back to the crossline of the ocular. I. Direct reflection from the right angle face. II. Internally reflected image from the other right angle face. The images appear the same when a wedge is tested, one being from the front surface and one from the back and the vertical displacement indicates the direction of the axis of the wedge.

image, as in Figure 3, as the reflecting surface, then that angle is more than 45°. The error is of course doubled because of the two internal reflections.

If the right angle is not 90° complications arise which make interpretation laborious. There must be taken into consideration the nature of this angle, whether it is obtuse or acute and how much, and this figure must be used in a final calculation. Even then it is not satisfactory because of the difficulty in determining which of the 45° angles is off most. It is obviously possible to have a near right angle prism in which one of the small angles is exactly 45°. The separation of the two images would then be the same as in the regular test for the right angle.

The chief usefulness we found for the tester in connection with the 45° angles was in the making of highly accurate master prisms where there must be no appreciable error in any of the angles. In this work it always seemed best to make the right angle first by testing in the usual way and at the same

time reduce the pyramidal error of the two right angle faces to near zero by testing through one right angle face. Then any residual pyramidal error has to be on the hypotenuse face and in removing it the two 45° angles can be exactly equalized, so that the final result is a prism in which all images can be superimposed irrespective of the orientation of the prism on the table.

In 1923 G. W. Moffit[3] described an achromatic refracting type of autocollimator which has some very advantageous characteristics but which does not seem to have come into general use. Its construction is such that the facilities of a good optical and machine shop are necessary. In the explanation of the performance of the instrument, methods are given for testing right-angle reflecting prisms especially but ways of testing Dove, penta, roof and 60° prisms are included. In his Figures 10 and 11 are shown four ways of testing the 45° angles of reflecting prisms, all of which are applicable to the present instrument. In one case the prism is set on the table as in Figure 2. One of the right angle faces faces the objective, and opposite the other right angle face there is another right angle prism placed so that the light from the first enters the hypotenuse of the second and is reflected back. This second prism should preferably be well corrected. While very accurate results can be obtained in this manner the method is somewhat laborious and due allowance must be made for error in the right angle of the prism being tested.

In the operations for which the tester herein described was constructed it was found that a very large percentage of prisms taken out of instruments had errors so great that the images fell outside the field of view, which was 12 minutes. Therefore, Mr. McLaren made another with a 5-inch $f/4$ mirror for an objective, so as to get less magnification. The field in this case covered 20 minutes and this instrument made an ideal workshop tool standing beside the hand correction plate and the hand polishing lap. The field was still not large enough to take in many commercial errors but beyond its capacity a carpenter's square would suffice.

After cessation of hostilities, there was time for experimentation and the testing out of certain suggestions which had been made from time to time regarding changes and modifications. Also there appeared in print, Dr. Rank's[4] illuminating article on the same subject.

Mr. Parsons made a 6-inch mirror of 180-inch focal length to test the possibility of using much higher magnification and therefore reading much smaller errors. From a preliminary study of this it seems apparent that air currents in the room become disturbing and defects of the prism, such as departure from flatness and internal striation and stress, offset to some extent the advantages of great separation of images because of minute angle errors. From this, we suspect that an $f/8$ to $f/12$ is the ideal range for routine testing of fairly well made prisms, although the longer focal length has some fascinating possibilities.

In most work the concentrated filament of an ordinary flashlight bulb makes

---

[3] Moffit, G. W., "An Instrument for the Testing of Prisms." *Journal of the Optical Society of America and Review of Scientific Instruments*, Vol. 7, No. 10, Oct. 1923, pp. 831–852, 14 figs.

[4] Rank, D. H., High Precision Achromatic Collimator. *The Review of Scientific Instruments*, Vol. 17, No. 6, June, 1946, pp. 243–244. 1 fig.

an excellent light source, or target as it is sometimes called. It is easy to find, gives an abundance of light and the coils of the filament give an excellent object to use for appraisal of definition of the prism, qualitatively. If they cannot be resolved crisply in the images from the angle face reflections, one or more surfaces are far from flat. Bands of light extending outwardly from the image in best focus show that the edges are turned down. This is not a serious defect in such an instrument as a binocular but might be fatal when most or all of an entrant or exit face is exposed.

For extremely close work, such as rhomboids, plane-parallels, master prisms and wedges, it was found desirable to mount a pinhole, a slit or a crossed slit in front of the light source. A secondary flat, such as Dr. Rank shows in his diagram, was not found necessary in the making and testing of the wedges and parallel plates which we made. Two images of the target are received in the ocular, one from the front and one from the back surface. One will be slightly out of focus if the plate be thick. The back surface image will be readily identified by "breathing" on that surface. The alinement of the two images is the axis of the wedge and the thick edge is opposite from the back image. The separation of the two images is a direct measure of the angle of the wedge, there being no double reflection. The second formula therefore applies. Definition again is a function of flatness of surface.

After considerable discussion it was decided that the instrument could be made more versatile by making a special prism table equipped with divided circle and vernier. The only circle available at the time was divided into 30-minute intervals and could be read to one minute with the vernier. The prism itself is mounted on an accessory central table provided with leveling screws. The machine work was done with ordinary spectrometer accuracy and the result is essentially a spectrometer table. With this accessory, any prism angle can be measured within the accuracy of the divided circle. All that is necessary is to focus the images from successive faces on the crossline of the ocular and read the circle properly. In fact, the optics of the instrument are superior to ordinary divided circles and, therefore, the errors of these can be checked by using prisms, wedges and plane-parallels of known or easily determinable accuracy. Of course, in this form the apparatus is nothing more than a spectrometer equipped with a superior collimator which acts as its own telescope.

The set-up led Mr. Steinback to devise a method whereby any prism angle can be measured without a divided circle at all. The requirements are the instrument as originally made, except with a special table, and a series of test pieces which can be made and measured with it. Of course it presupposes that the operator has the skill to make these test pieces and it may be stated with confidence that anyone who has corrected roof prisms to two-second tolerance would have no difficulty.

The table is made to spectrometer accuracy with taper bearings. There are actually two tables, a lower one and an upper one, capable of independent revolution; or the lower one can be locked and the upper one rotated separately. The upper one is fitted with the usual universal tilting top.

Suppose it be desired to measure the right angle of a piece of glass, there being no hypotenuse face. This cannot be done by the method already described for reflecting prisms in general. The directly reflected images, and these alone, are available.

A plane-parallel piece of glass, a bar for example, is mounted on the lower table and the image from it (actually two images superimposed if it be parallel) is oriented on the crossline of the ocular. The glass to be tested is mounted on the upper table and tilted so that the image rests immediately above the first. Now if both tables be rotated together, the image from the other face of the piece being measured will come into view and can be stopped on the vertical crossline. The lower table is locked. The upper table is rotated back until the original image from the specimen is on the crossline. The lower table is unlocked and both together are rotated until the image from the plane-parallel is on the crossline. If the piece being tested is exactly 90° its image also will be on the crossline. If not, the deviation is twice the actual error.

Suppose a 45° angle is to be checked on a prism. An accurate 90° prism is mounted on the lower table and the piece to be tested on the upper. The procedure is then exactly the same as before.

A 60° prism can be checked as follows. The plane-parallel bar is mounted on the lower table and the image centered on the vertical crossline of the ocular. The prism is mounted on the upper table and the image from one face is likewise centered. The tables are rotated together until the image from an adjacent face of the prism comes into view and is centered. The lower table is locked and the upper table is rotated back until the image from the first face appears and is centered again. The lower table is unlocked and both are rotated until the second face is again centered. The lower table is locked and the upper is rotated back to center the first image. Then both together are rotated until the image from the plane-parallel is on the crossline. This will be exactly 180°. If the image from the second prism face is not on the crossline, the amount it is off is 3 times the actual error.

The remaining two angles are measured in the same way and the sum should equal 180°. Errors of measurement should not be over two seconds each if a narrow slit or small pinhole be used and, even if they are cumulative, the final result should be well within half a minute.

It will be noted that, in this method of measuring, the index of refraction of the glass does not enter into the calculation at all. Therefore one minute error will require that the division marks of the crossline be 1 mm apart when the focal length of the mirror is 1718 mm.

This process of stepping and dividing can be carried to almost any refinement within reason. Wedges of various angles are not hard to make and check to extreme accuracy if they are within the range of the instrument.

It might be supposed upon first consideration that it would be possible to build up angles accurately from pieces of known angle by cementing them together. It is doubtful whether the layer of cement can ever be made sufficiently close to parallel to eliminate its wedging effect.

Making Rhomboid Prisms

By G. D. Hanna

Rhomboids are very desirable prisms and probably would be used more frequently were it not for difficulty in construction. We have had some experience in making them and the following notes are set down for guidance in future work.

The size most often needed, apparently, and those we have made, are about ¼ inch square and 1½ inch long. They are best made in a block of three or four, this block being sawed into the individual prisms when figuring is completed.

1. Choose a rectangular piece of optical glass of suitable size and thickness. Grind and fine grind the two large surfaces parallel to micrometer.

2. Fine grind the two edges and square with flat faces. Mark one for a permanent reference edge.

3. Make a jig of a rectangular cast iron block 3 by 1¼ by 1 inch thick. Grind one face flat and one edge flat and at right angles to the face. Bevel one end 45° as accurately as possible and at 90° to the flattened edge. Screw a stopper block (previously flattened on one side) of brass or iron to the flattened edge.

4. Rough grind by eye the 45° angles on the glass slab.

5. Finish fine grinding the 45° faces in the jig.

6. Carefully check all angles. They should be just as accurate as it is possible to make them with squares.

7. Polish one flat face within ¼ to ⅒ fringe.

8. Give the other face a brief rub on the hand lap for a temporary slight polish and check for wedge effect in prism tester. (The tester we use will give a deviation of 2 millimeters for one minute of error.)

9. If the wedge is 15 seconds or more, fine grind off the thick part and repeat the test. The two surfaces should be made almost exactly parallel by fine grinding them.

10. Finish polish the other flat face within ¼ to ⅒ fringe, keeping the face parallel with the first one. In parallelizing the plate a definite procedure must be followed after the first face is finished. Number the corners and mark one face for reference. After a flash polish on second face check in tester. The image reflected from the front, flat and polished surface will be bright and sharp. That from the flash or back surface will be more or less diffused, thus permitting the identification of this surface. Its image is always displaced toward the thick part of the wedge. As the error is lessened by grinding and polishing, the two images approach and become very difficult to distinguish. They should be made to superimpose as nearly as possible.

11. Briefly polish the two 45° ends and check for pyramidal error on 25-power telescope.

12. Eliminate all pyramidal error by fine grinding in the jig, using shims

next to the stopper plate if necessary and checking frequently with 25-power telescope. Reduction of pyramidal error or elimination of it also eliminates any deviation of the two 45° faces from right angles to the flat faces.

13. Finish polish one 45°, keeping it flat to ¼ to ⅒ fringe and holding the pyramidal error to zero. (The other 45° has its preliminary polish.) The pyramidal error shows as a displacement of horizontal lines vertically. At this stage or up to this stage little attention need be paid to horizontal displacement of the vertical lines.

14. Finish polish the final 45° face.

The figuring of the prism is done on this last 45° face, assuming of course that the first one is accurate as to angle and pyramidal. If it is not, the two 45° faces must be worked alternately to eliminate the errors. We have found that the best method of testing during construction is to use a 25× telescope

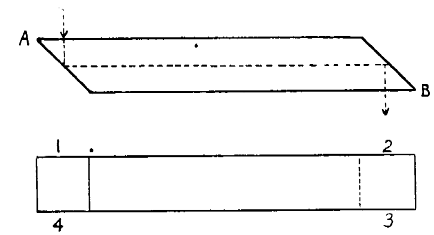


Figure 1

and the Arsenal roof prism target at 30 feet. Since this target furnishes divergent light, the image through the rhomb can never be made to coincide with the main image so far as the vertical lines are concerned. If the horizontal lines are displaced there is pyramidal error in the 45° faces and this should be removed. If the work has been done carefully it can be corrected by polishing alone. When the pyramidal error is removed the angle error can then be eliminated. It shows up as an unequal displacement of the rhomb image from the center line of the target, when the rhomb is reversed end for end. Assume angle *A* (Figure 1, top) is 45° even but angle *B* is 45° 0′ 10″. The displacement of the vertical lines will be unequal when the prism is reversed so that the light enters at *B* instead of *A*. Whether it is the toe or the heel that needs to be taken off can be learned by a few trials on the polishing lap. The correction should be continued until the displacement of the vertical lines is exactly the same when the prism is turned end to end. Then, and only then, if the telescope be focused on an object at infinity, will there be no doubling of the image due to the rhomb. When it is all completed the rhomb can be tested again before a collimator with any kind of telescope. Or it can be tested on our type of prism tester (the autocollimator described in the preceding chapter) by sticking a small silvered mirror to the emergent flat face, thus directing the beam backward along its path through the prism; if perfect there will be only one image at the eyepiece.

15. When the rhomb meets all these tests, grind one protector plate for each of the flat faces. This protector should be very close to the same size of the prism block and have good 45° angles. Grind two strips to protect the 45° polished faces and wax all three protectors around the prism block and down on a piece of $\frac{1}{4}$-inch plate. Then saw into strips, making as many rhombs out of the block as had been provided for. All that remains is to chamfer the sawed edges.

In order that the exact procedure to be followed in correcting the 45° faces shall be available, the following supplementary notes are supplied. If they be adhered to very carefully then it becomes unnecessary to do any of the work by trial and error.

It is assumed that the blank is now in the stage when the two broad faces are strictly flat and parallel within very narrow limits; also that the 45° faces have been ground and fine ground in the jig (or with squares) so that all angles are as close as they can be made.

Give the two 45° faces a flash polish on the hand lap and stand in front of the 25× telescope focused on the Arsenal target. One end face must face the target, the other the telescope, the latter being about even with the center of the objective. Telescope and target must be horizontal and the support for the rhomb must be placed so that it cuts the optical axis at right angles.

Superimposed on the main image of the target there will be a faint one which comes through the rhomb. It will be more or less poorly defined, depending upon the flatness of the 45° faces and the extent of the polish. Note carefully the position of this faint image (ghost, we call it). That is, the vertical lines should be displaced to the right of the main image, assuming that the prism was inserted into the beam from the right. The distance of displacement depends upon two factors. One is the deviation of the 45° face which is across the objective from 45°; the other is the length of the prism.

Reverse the prism end to end and front to back. Again note the position of the displaced ghost. Have the corners of the prism marked 1, 2, 3, 4, or in some other definite manner (Figure 1, lower). If when 1–4 is in front of the objective the displacement is less than when 2–3 is so placed, this means that the heel of 1–4 must come off; the angle is too obtuse. The correction can be made by polishing. Test frequently because, as the heel is taken off, the distance of displacement becomes less and less and it is very easy to go too far. Endeavor to get 1–4 flat at the same time. If when polished it is convex, local correction with a small rectangle or oval of stiff leather is very effective.

When 1–4 is flat and polished and the displaced image is not far from the same distance as when the prism is reversed, note the position of the displaced horizontal lines. If they are above the same lines of the main image, pyramidal error of the 1–4 face is such that the uppermost end (1) of the 45° face must be taken off. If below, the opposite or lower end (4) must be taken off. Polish until the horizontal lines of the ghost coincide with the main image.

The prism is now ready for the final correction on the 2–3, 45° face. Place it in front of the objective and, if the displaced ghost vertical lines are not exactly the distance from the center line as when 1–4 was there, make the correction while polishing if possible. If the 2–3 image is farther away than 1–4 take off the toe; if closer take off the heel. At the same time correct the pyramidal error, remembering that if the horizontal lines of the ghost are above the main lines, take off the upper corner, if below take off the lower corner.

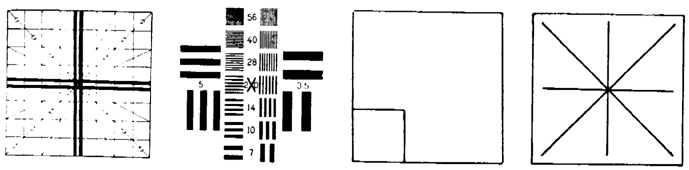
This procedure does not produce exactly 45° angles at the ends of the rhombs but it does make the error exactly equal, plus and minus, and the faces parallel. Slight deviation from 45° does not affect the performance of the prism optically.

The figuring of these 45° surfaces calls for the highest skill of the optical worker. Only one method is known to us and this should be followed meticulously unless a better procedure should be discovered. This is the method. Flash polish the two surfaces on the hand lap well supplied with rouge. We use 6-inch laps (5 parts Bergundy pitch, 1 part W W rosin) dummied flat. Work the angle and pyramidal errors down as close to zero as possible. This can be done only approximately with rouge on the lap because the rhomboid image will be quite fuzzy. Then figure and finally correct one face. The lap for this should be dummied to work the loose rouge into the pitch. Score crosswise $\frac{1}{8}$ to $\frac{1}{4}$ inch apart, using light pressure on the razor blade. Wash off all loose rouge. This is very important. Put one drop of water on the lap, spread it around with a finger. Then and only then can figuring be started. Glass will be removed slowly by this lapping process but it is entirely in control. The surface should be flat to the very edges well within a quarter of a fringe. The angles of course should be checked as figuring proceeds and if by removal of convexity it develops that several seconds must come off a certain end or edge, it is better to go back to loose rouge again. When one 45° face is completed the procedure should be repeated on the other.

The rhomboid images through the completed prism are quite sharp. All horizontal fine lines of the target should be resolved. The 40 lines vertical should be resolved or just on the point of resolution. The resolution of these is determined by the size of the 45° faces crosswise and the flatness crosswise. Obviously, the aperture being very small, the highest resolution cannot be expected.

[EDITOR'S NOTE: The method of making rhomboid prisms described above was worked out by the late J. A. Steinback and the author when they were engaged in optical instrument activity for the U. S. Navy in World War II. Their rhomboids were made to 2-second tolerance. Purchased on the open market rhomboids are expensive. So far as is known, these instructions are the only ones in print as this book goes to press in 1953. A rhomboid prism was also used in the auxiliary telescope in the chapter on binoculars. See Figure 9 of that chapter.

Reference in the above chapter and elsewhere in this volume to "the Arsenal roof prism target," also to "the 40 lines vertical," calls for elucidation while those familiar with the details are still on the scene. There was no official Arsenal target in World War II but at the Frankford Arsenal many thousands of prisms were tested with a composite target that may easily be re-created in essential form, thus: Redraw the design in the first square to scale 8 inches wide. Make the heavy lines 1/4 inch wide, the little circles 1/4 inch in diameter. Buy from the Gov't Printing Office, Wash., D. C., National Bureau of Standards "Circular 533, Supplement," "Lens Resolution Charts," by Irvine C. Gardner. Clip out one of the charts (similar to the one shown greatly reduced in the second square, whence the "40 lines vertical") and superimpose it on the first target as in the third square. Hang these on a wall and illuminate with a 150-w frosted bulb shielded from the tester's eyes. Some Frank-



ford Arsenal prism correctors liked the one target better, some the other, some used both. The test charts are printed from precise plates engraved with a dividing engine—crisp. Actually, there is no need to reproduce the whole detail in the first square; the one in the fourth is as good. However, since there seems to be a human (or ape) desire to have things "just like Uncle Henry's," the chart, copied from the original at Frankford Arsenal by the artist A. H. Johns of the wartime Roof Prism Gang of amateurs, is reproduced here. Even he omitted many of the frills of the original, said to have been over-elaborated by a pre-war arsenal employee on a rainy afternoon. Fred Ferson made his target (see ATMA, p. 75) by scratching the fourth design above on a ten-cent looking glass with a razor blade and illuminating it from behind. Dr. Hanna combined the Arsenal type of chart on Kodalith at full scale and again at half scale (for a job requiring even finer resolution than roof prisms), mounted the two "negatives" behind clear glass, and placed opal glass and a fluorescent lamp behind it, all in a box.]

Separation of Abrasives on a Laboratory Scale

By G. Dallas Hanna
California Academy of Sciences

What we think are good and passable optical surfaces are produced by the use of common abrasives. There is no particular difficulty with the coarse grades as supplied by the producers but nearly everyone who has ground glass has had the misfortune to encounter scratches when these were least wanted. In desperation, many discouraged individuals have then dumped their powder in water, trying thereby to rid themselves of the coarse grains that do the damage. They try separation by settling, but it may be said most emphatically that a segregation cannot be made so easily.

The problem involves the classification of a mixture of grain sizes of powder into a series of batches each of which contains grains of only one size or within a comparatively narrow size range. References to the subject are common in the literature dealing with the technic of producing optical surfaces, but no detailed account of how to accomplish it has been found. It is reasonable to suppose that some methods may have been worked out and published in books or periodicals that deal with ceramics, soils and cements; these sources have not been searched.[1]

The establishment of an efficient procedure and routine became a necessity for us in the early part of World War II because the finer finishing grades of abrasives were unobtainable. No success was had until it was learned that a dispersing agent, or deflocculent, was an absolute necessity. Thereafter, the problem narrowed down to the selection of a suitable one among many that were available and the determination of most suitable sizes of grains for the purposes required.

The technic as finally worked out is the result of the combined efforts of the small group of amateur telescope makers at the California Academy of Sciences who in wartime were temporarily detached from their favorite pastime to engage in the production of military optical elements of many types.

The process pertains especially to silicon carbide and aluminum oxide grains because these are the materials most commonly used in preparing optical surfaces for polishing. The grains are available commercially and are sold under various trade names. Different "grades" bear numbers which appear to have been established arbitrarily but which seem to this writer to bear no very definite relationship to each other. In general, however, the higher the number the finer the grade. A classification based upon a series of screen wires has

[1] After this chapter was written, Mr. A. G. Ingalls came across a mimeograph report published in 1937 by the U. S. Bureau of Mines and entitled "Short-column Hydraulic Elutriator for Subsieve Sizes," by S. R. B. Cooke, U. S. Bur. Mines Report of Investigation No. 3333, Ore-dressing Studies, pp. 37–51, figs. 5–19, Feb. 1937. [Out of print. —*Ed.*] This is a thoroughly scientific account of the separation of various sizes of ores and rocks which are strictly within the size ranges used by glass workers. The apparatus described is not too difficult for the average worker to construct and it would seem that results can be made 100 percent efficient or nearly so. In the same report are numerous references to previous literature.

been suggested as the key to the grades and may have had some connection with commercial grade numbers but such a system is highly unsatisfactory and fails to convey any special meaning as to the size of grain. For example, a statement that 80 grain size will pass through a screen of 80 meshes to the inch is meaningless unless the diameters of the individual strands of the wire be given. This is rarely, if ever, done. Furthermore, a given 80 mesh screen may pass most or all of a batch of 80 grade grains when these are dry, yet fail completely to pass them when they are wet. Grade 150, the coarsest we use, will pass through a Monel metal screen we happen to have. It will not pass through a 100 mesh Monel screen but will pass a 150 mesh bronze screen readily because the wires are smaller.[2]

Attempts have been made (see Twyman, F., "Prism and Lens Making," 1942, pp. 34–36) to base a classification upon the average size of grain as measured with a microscope but this does not completely satisfy the needs of the optical worker. At best only an infinitesimal portion of the grains in any one batch can be seen in a few fields of the microscope. Furthermore the average size of a grain is only one of three highly important factors. Another is the proportion of undersize grains that do no work, yet are in the way of those that are cutting. A third is the proportion of oversize grains and erratic "cobblestones" which produce scratches or excessively deep pits. It should not be overlooked that these grains do not actually cut in the same sense that a diamond-impregnated wheel will cut glass, but that they roll between the glass surface and the tool, thereby producing a more or less uniformly pitted surface.

Commercial grades of abrasives down to about 320 in fineness are satisfactory to use as supplied. They are relatively inexpensive and remove glass rapidly. Angles on prisms[3] can be roughly generated with them but surfaces cannot be made truly flat unless especially adapted tools be made to grind upon. For all grades finer than 320 we have attempted to use a classification based upon time required to settle through a column of water 8 inches deep. A better standard might have been chosen but we were obliged to use equipment already available. Consistent, reproducible results have been obtained

---

2 Commenting on the above paragraph, S. R. B. Cooke (see footnote 1) states in a private communication: "Many of the manufacturers' grade numbers do not conform to the Tyler screen scale but in all modern scientific research on the sizing of grains (ores, etc.) the Tyler screen scale is adopted as standard. This is based on a 200 mesh screen having 200 openings per linear inch, each opening being 74 microns (0.074 mm) in size. The openings are square. The size of wire is adjusted to give 200 openings per lineal inch with this size of opening. Now the Tyler scale is based upon a geometric progression of $\sqrt{2}$, so that the next coarser screen in the standard series has a linear opening of $\sqrt{2} \times 74$ microns or 104 microns (approximately). The size of wire is then adjusted so that in a screen of this aperture there are 150 openings per linear inch, that is, a 150 mesh screen. Similarly, the next coarser screen has an opening of $\sqrt{2} \times 104$ microns or 148 microns: 100 mesh. So we now have, in decreasing size of screen opening and for practical sizes in grinding: 65 mesh, 208 microns: 100 mesh, 148 microns; 150 mesh, 104 microns; 200 mesh, 74 microns. By using the $\sqrt[4]{2}$ series, intermediate sizes are available. With regard to dry screening versus wet screening, all results are reported in terms of dry screen analysis, even if wet screening has been performed to remove very fine material."

3 Originally, this chapter was prepared for use in connection with the production of roof prisms in wartime.

and scarcity of finishing abrasives has been no hardship through several years of semi-commercial operation. The only grade regularly purchased is 150; more than enough of the finer ones are recovered from the slush pans of the grinding wheels.

Many brands of the finer commercial grades have been tested and in all cases the classification of the grains has been extremely poor. This applies not only to those grades which are not claimed to be carefully separated but also those which have been sold for optical finishing purposes at relatively high prices.

An excellent way to test a finishing abrasive is to take two small pieces of plate glass and grind them together, wet, for a few moments with the powder in question. Pressure is placed on the upper plate at one edge, not in the center. Examine the ground surface under a microscope. If the grains were uniform in size the ground area will meet the remaining polished area as a gradual thinning outward of the milky white surface; there will be no scratches, only pits. No commercial abrasive has yet been found by us that will meet this test.

The problem of separating these materials into a reasonably uniform series of sizes of grains may be divided into two parts. First, consider a commercial grade such as 600 aluminum oxide; this contains particles ranging from near colloid size up to a few which are as coarse as grade 80. A large percentage, however, fall within several valuable size ranges. Put about two pounds or less of the abrasive into a two-gallon jar, add about an ounce of solution of sodium metasilicate[4] and fill the jar with tap water, stirring thoroughly. Sodium metasilicate is not the only dispersing agent or deflocculent[5] that will work with these materials but it was chosen because it is so widely used in drilling oil wells to keep the circulating mud (clay minerals) in suspension. The solution used here at the Academy of Sciences is made up by adding an ounce of the silicate to a gallon of water. Proportions are not critical.

The jar is allowed to stand 30 minutes. Then the liquid is siphoned off to within an inch or two of the layer of settlings on the bottom. The liquid taken

---

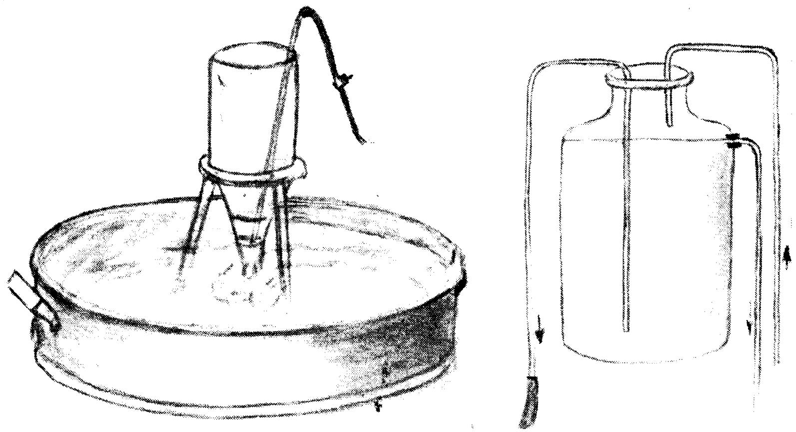
4 "Or orthosilicate (water glass). Another excellent dispersant is *quebracho*, an impure tannic acid, American Cyanamid Co., 30 Rockefeller Plaza, New York, N. Y., also ordinary gelatine in dilute solution."—S. R. B. Cooke, personal communication.

5 At this point the editor has asked for the inclusion of "an explanation of what a deflocculent or dispersing agent actually does. That is, does it root in and elbow the particles apart? If so, how? What forces?" It should be borne in mind that the particles with which we are dealing in finishing abrasives are of extremely small size. Because of the very large surface area in relation to mass they do not sensibly follow in their behavior the laws that govern larger particles such as sand grains. Attractive and repellant forces that are not ordinarily operative from a visual standpoint become of paramount importance. For example, the particles are individually in constant motion (Brownian movement) due to molecular bombardment. Surface energy, adsorption, wetting properties and viscosity of the field, concentration of solids, electrical properties of both particles and fluid and numerous other things enter into the theories and laws that govern the motions of suspensions. The subject becomes immediately highly involved in mathematics and in part in the field of thermodynamics. If the student be interested in further research upon the various analytical problems involved it is highly recommended that the following text [largely mathematical.—*Ed.*] be consulted: J. M. Dallavalle, "Micromeritics, the Technology of Fine Particles," Pitman Publishing Corp., New York. This work contains an extensive bibliography.

off contains only those grains that failed to reach bottom in an 8-inch column of water in 30 minutes. It is saved in a five-gallon jar.

Another ounce of metasilicate solution is added to the first jar and it is again filled and stirred, allowed to stand 30 minutes, then siphoned off into the second jar.

The process is repeated until the second jar is full.



Drawings by the author

Left: A simple elutriator for separation of coarse grades from finer ones. The volume of water is controlled by the pinchcock on the rubber hose. Right: Apparatus arranged for constant pressure on the stream of water to the elutriator shown at the left. The bottle is set on a high shelf and water from the main enters through the tube at the right. The next tube to the left is the overflow and the one on the extreme left is the siphon which connects to the elutriator.

The second jar, if the column of fluid is 16 inches high, is allowed to stand for two hours; that is, four times the settling time of the smaller jar. If available vessels have other proportions different times would result.

The object aimed at is to secure on the bottom of the larger jar all material that remained in suspension in the 8-inch column of water for 30 minutes but would settle in a similar column in 60 minutes. Everything finer than this is discarded for abrasive purposes because it has been learned through long experience that it does not grind away glass sufficiently rapidly to be useful in correcting prism angles. Furthermore, the 30 minute grade produces a surface that can be brought to a perfect polish on a one inch square surface in not more than five minutes by anyone who has learned the technic of the hand polishing lap. The time interval includes that necessary to figure the surface flat to within a tenth of a fringe with no turned down or rolled edges. As a finishing powder this 30 minute grade removes glass very slowly, too slowly except for

special purposes. But in separating it the use of a suitable dispersing agent such as the one suggested is absolutely necessary.

It is astonishing how much of the commercial grade, 600 or finer, will be discarded by this process because it did not settle in the one hour allotted. In all cases tested it has amounted to 25 percent or more of the original bulk. If the commercial grade be used directly as received this fine mud serves a useful purpose in one way: it "cushions" the mixture on the grinding plate so that the cobblestones cannot produce such deep scratches as they otherwise would. Operators often accentuate this effect by adding a few percent of bentonite clay, precipitated chalk, or some similar substance. The obvious answer is to remove the large, erratic grains so that they cannot produce scratches.[6]

If, when one five-gallon jar full has been decanted from the original mixture, there still appears to be a supply of 30 minute grains present, the process is continued until the smaller jar becomes reasonably clear at the end of that period.

When this stage has been reached and the 30 minute material in the larger jar has been washed a sufficient number of times to get rid of most of that which floats an hour, this 30 minute grade is removed, dried and bottled for general use. Or, in order to be doubly certain that it is absolutely free from injurious particles, it may be re-run. We often do this with the 15 minute grade.

The process is next carried through in the same manner for a grade that will float in the 8-inch jar for 15 minutes. This time and for subsequent separations there is no finer material to discard.

This 15 minute grade is the most generally useful finishing powder we have found; with no mud and no large grains, scratches are almost impossible to produce. The resultant ground surface is considerably finer and more uniform than that produced by any of the commercial grades we have tested.

The metasilicate should be used for each decantation.

The next succeeding grade is that which will float for 7½ minutes. This becomes a very excellent grade for hand correction of prism angles preparatory to block polishing. Pits made with this grade are too deep to polish out readily by hand; they are about the coarseness of those left by grade 904 as marketed by one firm.

Following this a 1 minute grade is removed. It removes glass rapidly and is especially suited for removing pits from coarser grinding and to complete the roughing out of various prisms and plates. It is also useful for chamfering edges. The pits it leaves are about the size and depth of those produced by the original unclassified 600 grade.

The material left is a problem. Microscopical examination will show something concerning the nature of the contaminating coarse grains. A better test is to use some of it to grind a dummy piece of polished glass. Further separation by decantation is not practicable. Often, after drying, it is put into the

[6] "If bubbles have been formed due to agitation or evolution of dissolved gas due to a rise in temperature, they may raft coarser particles to the surface, and if these are decanted they will foul the decanted and sized abrasive."—S. R. B. Cooke, private communication.

container with some coarse grade such as 320 or 150. However, in order that proper evaluation of commercial grading can be made it is interesting to make two or more additional separations by elutriation as described below. This gives the operator an opportunity really to see the cobblestones that are not supposed to be present.

The next part of the problem is concerned with the reclassification of the material which accumulates in the slush pans, "gunk" to many operators. This consists of a mixture of all grades of abrasive from the coarsest used down to impalpable, useless powder, together with such glass as has been removed in grinding and a small percentage of iron from the plates, or "wheels" as they are often called. The method finally adopted here is to first screen the general mixture through a 40 mesh sieve to remove trash of any kind that may have fallen into the pans. The actual separation is begun by removing first all grains coarser than 320 grade. This is accomplished by elutriation. A clear glass bottle with gradually tapering neck, such as the type in which ginger ale is marketed, makes an excellent elutriator. The bottom is cut off with a hot wire and a cork is inserted in the top. The elutriator is used as shown in the left-hand sketch; that is, it is placed upside down in a chemist's tripod. It is filled about one fourth full of the abrasive mixture, and a glass tube with a hose connection to the water supply is run down inside until it reaches the cork. A gentle stream of water is started, the fine material rises, overflows the top and is caught in a large pan in which tripod and all are standing. For a given height of elutriator a given stream of water will leave as too heavy all grains coarser than a definite size. It is possible to work out the constants on a time-volume basis, and therefore extremely accurate grading of coarse material can be effected by this means. We learned through trial and error the approximate size of stream necessary to leave grade 150 in the elutriator but did not further work out the details.

The coarse material thus recovered is dried for subsequent use. The fine is accumulated in the pan until there is sufficient for a batch in the two gallon jar where it is allowed to settle.

It now seems essential to remove all iron from the mixture, since if it is left a good classification does not seem to result and as the particles "rust" upon drying they seem to cement some abrasive grains together, forming lumps that will produce scratches. Attempts to remove the iron magnetically did not succeed, probably through insufficient effort. It is readily dissolved by adding about one ounce of commercial sulfuric acid to a gallon of fluid. Two hours or more are required, the completion of the reaction being indicated by cessation of hydrogen evolution. The material tends to flocculate after this treatment but this is an advantage, because it permits the making of two or three washings rather quickly. The bulk of the surplus acid and iron solutions are thereby removed.

The separation from this point on is done in the same manner as has been indicated for new material. The proportion of very fine particles is, however, higher. These consist of useless abrasive, glass and a small percentage of practically colloidal graphite from the iron of the grinding wheels.

Addendum: In 1946 the National Bureau of Standards published an account of a method for grading diamond powder for abrasive purposes. After testing a large number of dispersing substances, a solution of gelatin in water was finally used. Sodium metasilicates were not used. (See Steierman, B. L., Insley, H., and Parsons, W. H., "Size Grading of Diamond Powders," U. S. National Bureau of Standards Research Paper RP1716, *Journal of Research*, vol. 36, no. 5, pp. 469—478, 9 figures.) If one may be justified in appraising the methods described by the photographic reproductions of the fine powders, the separation of grades would not be considered suitable for producing finely ground surfaces in our laboratory.

[Editor's Note: While sodium orthosilicate should be obtainable almost anywhere in the form of water glass, any who wish to experiment with the metasilicate probably can obtain it in ten-pound lots at about twice the price of sugar from the Package Chemical Co., 218 W. First St., Boston 27, Mass.

In a private communication Hanna says, "We use our abrasive alongside roughing mills and never take any precautions such as taking a bath before fine grinding, yet it has been so long since any of us has had scratches on glass that we have forgotten." It may prove that flocculated brickbats have been the cause of scratches that have baffled some workers almost beyond endurance.

Most TNs have the scientist's intellectual curiosity about phenomena that surround their optical work, and to such the following extracts from a letter from S. R. B. Cooke, Professor of Mineral Dressing in the School of Mines and Metallurgy of the University of Minnesota, may be of interest. They are replies to questions that were submitted to him.

"Dispersants are essential for any kind of elutriation or sedimentation sizing. The law governing either method is Stokes' Law:

$$v \text{ (in cm per sec.)} = \frac{2}{9} \times \frac{g(d_2 - d_1)r^2}{n}$$

in which 2/9 is a constant; g is the acceleration of gravity (about 981 cm per sec²); d_2 is the specific gravity of the solid being elutriated; d_1 is the specific gravity of the fluid (usually water, 1.0); r is the radius of the particle assumed spherical; and n is the viscosity of the fluid (in poises, about 0.01 for water at 20° C).

For example, the falling velocity of a particle of Carborundum, sp. gr. 3.2, is given as follows

$$v \text{ (cm/sec.)} = \frac{2}{9} \times \frac{981(3.2 - 1)r^2}{0.01} = 47960\ r^2$$

provided water is used at about 20° C. Now take a particle of Carborundum about 5 microns in diameter [smaller than No. 600.—*Ed.*] assumed spherical (and there is not much else you can assume). The 5 microns = .0005 cm, but this is diameter, not radius as called for in the equation, so dividing by 2, we have v (cm/sec.) = 47960 (.0005/2) ² = 0.003 cm per sec., the falling velocity in water. In other words, the elutriator separating 5 micron and finer particles from coarser stuff would have a rising current of water traveling at 0.003 cm per second. Now, suppose the particles are flocculated, that is, clumped together. They would have a velocity much greater than the above and no separation could be effected. Hence the necessity for deflocculation."

Some years ago S. R. B. Cooke developed but did not patent what became known as the "Cooke Elutriator" and which he states can be home-made for perhaps $50, provided the builder uses typical TN ingenuity and resourcefulness.

Asked to distinguish between elutriation and sedimentation he replied, "In sedimentation the particles fall, in elutriation they rise."

Further to bring out the philosophy of deflocculation discussed in footnote 5, he was asked, "Why don't the flocculated particles fall apart at once when put under pressure between two surfaces being worked?" Reply: "Because in the finer sizes the surface forces are greater than the gravitational and fluid forces." It remains difficult for human beings to think in terms of the microscopic world where the forces with which we are familiar exist in different proportions; forces trivial to us outweighing gravity; ask an insect or even a bacterium, which knows from experience in a world of forces we are little aware of. Also see cognate considerations in D'Arcy Thompson's classic work "Growth and Form," chapter on "Magnitude."]

The Barlow Lens

By C. R. Hartshorn

When this chapter was first submitted for criticism, one man suggested that the material in it might be found insufficinetly explicit by some readers, and superfluous by those who already knew enough about optics to be able to understand it. It is the author's belief that most readers of this book will fall in the latter category insofar as their receptive abilities are concerned, but that among them will be many who have not previously given much attention to the Barlow problem. To those, and to all who are interested in telescopes for visual observation, these notes, based on one man's experience, are offered in the hope of laying a foundation for more adequate development of this neglected subject.

The Barlow lens is no new arrival on the optical scene, its inventor, Peter Barlow, having been born at Norwich, England, in October, 1776. He was a renowned physicist and mathematician who, besides writing a number of important scientific books, was professor of mathematics in the Royal Military Academy at Woolwich for 40 years. The lens that bears his name seems to have found considerable early acceptance, and was strongly recommended by Webb and Espin in the old classic for star-gazers, "Celestial Objects for Common Telescopes." That book is the authority for the statement that W. F. Denning, the great double star observer, always employed the Barlow lens and invariably found it an aid to the ordinary eyepiece. Other references to the Barlow occur here and there in astronomical literature, but usually without any description of the lens itself.

Briefly, the device is a negative lens placed a short distance inside the focus of a telescope objective, generally in the eyepiece tube, where its function is similar in principle to that of a Cassegrainian secondary mirror. But, instead of reflecting the incoming light rays, the negative lens bends them slightly outward by refraction, projecting the elongated secondary cone of light with its increased magnifying power away from the objective instead of back toward it. Thus, since the setup is still that of the Newtonian in the case of a reflector, the observer looks toward the mirror instead of toward the open sky. In this form of telescope the tube acts as a shield to keep out unwanted skylight, and faint objects stand out with greater contrast.

Unfortunately, however, the Barlow lens is inferior to the Cassegrainian secondary mirror in the matter of achromatism. No lens can be made perfectly achromatic. Moreover, the Barlow, unlike an objective but like any eyepiece lens, has to work off axis when objects are viewed that are not in the exact center of the field. That is, the images of all off-axis objects are afflicted by some of the same kind of chromatic aberration that can be produced by stopping off one side of an achromatic objective. The saving factor in the situation is that, since the focus of the Barlow is negative and that of the eyepiece positive, the one may be so constructed as to compensate partially for the shortcomings of the other.

A practical focal length for a Barlow lens intended for use in the adapter tube of an ordinary Newtonian telescope would be about minus 5 inches or a little more. Such a lens about doubles the magnifying power of the telescope, and with it an $f/8$ Newtonian can be made to produce about the same magnification as an $f/16$ refractor of the same aperture. The stepped-up Newtonian will work well with Huygenian eyepieces, something it could not do unaided.

The writer has a Barlow lens of this type which has performed so well that the specifications are given here for what they may be worth, although other amateurs may have solved the problem differently, and with still better results. This lens is 1¼ inch in diameter, with a focal length of −5¾ inches. It works well at a distance of 2½ inches inside focus when used with mirrors of about $f/8$, but it will stand a little change of position to obtain more power. Here are the working data (Table 1).

TABLE 1

	n_D	n_{555}	n_F	n_C	v
Flint *	1.6174	1.6206	1.6294	1.6126	36.6
Crown	1.5230	1.5247	1.5293	1.5204	59.0

	Flint	Crown
r_1	+44.1 inches	
r_2	−2.28	
r_3		−2.28 inches
r_4		+2.28
t	.200	.105

* The flint lens here is the leading component, nearest to the objective.

It is not very difficult to design an efficient Barlow for moderate amplification with telescopes of ordinary focal ratios, but it is another matter when extremely powerful lenses are attempted. The writer once tried without success to make a Barlow of −2½-inch focal length for use with an $f/4$ mirror. The resulting lens performed splendidly as long as the object was kept in the center of the field, but otherwise it was practically useless, because of a severe case of coma. Even so, the time spent was not entirely wasted, for it demonstrated some interesting points, including the ability of such a small lens (less than 13/16 inch in diameter) to transmit a fairly wide image without stopping down the objective. This is an important point to be considered when determining the diameter needed for any telescope secondary, whether a negative lens is used for the purpose or a small mirror as in a Cassegrainian or Gregorian.

Suppose, for example, that we are going to make a negative lens powerful enough to double the magnification when used as a Barlow stationed 2 inches inside the primary focus of a telescope (Figure 1). If our telescope is an ordinary 6-inch Newtonian reflector of 48-inch focal length, and our largest eyepiece has a ¾-inch field lens, the Barlow will need to have an effective diameter of only .61 inch; not the .97 inch diameter that one might compute by doubling the telescope length in recognition of the increased magnification

and drawing straight lines from the opposite sides of the objective to the edges of the ¾-inch field lens by the method described on page 381 of ATM. That method is correct for a simple telescope, but here we are dealing with a compound telescope, and it is not actually the equivalent in all respects of a simple telescope 96 inches long. Rather, we have started with a simple 48-inch telescope which produced a relatively small image of any given object. Then we have interposed a negative lens near the small primary image and magnified the latter to double its former size. Instead of a simple telescope of twice the original focal length, which would have produced light paths straight from all parts of the objective to points in the final image plane, we have a compound telescope in which the light paths first converge into a narrow cone and then bend out to form the final image.

It will be seen from the foregoing discussion and diagram that a Barlow lens may sometimes be made smaller than the eyepiece with which it is to be

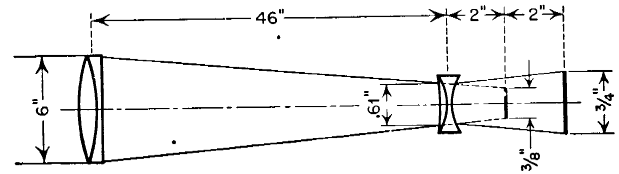


FIGURE 1

In the example given the objective or mirror is a 6-inch, the secondary image is ¾ inch in diameter, the working diameter of the Barlow is only 0.61 inch, and the primary image is ⅜ inch in diameter, or only one half the size of the required secondary image since in this case the Barlow doubles the power.

used, without causing any loss of resolving power due to stopping down the objective. It is only fair to the reader to state, however, that this theory, when affirmed by the writer, has sometimes met with considerable scepticism or downright disbelief.

The ability of the Barlow lens to work efficiently in smaller sizes than one would normally expect has an interesting and useful corollary. When a Barlow is employed, the proportions of the diagonal in the telescope may be correspondingly reduced. It has been suggested by some that the lens could be put just ahead of the diagonal, placing the latter near the primary focus, and reducing it to very small dimensions.

It is common practice to mount Barlow lenses in such a manner that they can be moved toward or away from the objective, in order to vary the magnifying power of the telescope. This procedure has been followed sometimes in the manufacture of hand telescopes, but it should be used sparingly in instruments of higher power, especially when short focus Barlows are employed. In the latter case, even a small movement is sufficient to produce noticeable aberrations, assuming that the lens was properly designed for its former position. This is apparent when we remember that the usual rule for an achromatic combination is to make the spherical aberration zero for center and edge, and to achromatize the pair in the zone that is 70.7 percent of the distance from the center to the edge. Obviously, the effective edge of the Barlow depends on its position in the telescope, since moving it nearer to the objective widens the cone of light which it has to transmit to the eyepiece. Similarly, the aperture ratio of the objective influences the degree of correction of the Barlow, both for chromatic and spherical aberration. Thus it will be seen that both the position of the Barlow in the telescope and the focal ratio of the objective are conditions that can be met to the best advantage only with a lens that is custom built to suit the particular case.

In this connection it seems worth while to inquire whether the ordinary rules for obtaining maximum chromatic and spherical corrections, i.e., achromatizing in the .707 zone and eliminating spherical aberration as between center and edge, are quite applicable in the case of the Barlow lens, which has to transmit cones of light that are eccentric with respect to the optical axis for image points not in the center of the field. Would it be better to work for the best possible definition on the axis, or to try for a compromise solution more favorable to the rest of the field? The question may be merely academic if we intend to limit our work to designing Barlows of moderate power, such as the one already described, since lenses of that type improve the field of a medium focus reflector. It has been the writer's experience, however, that trouble is likely to be encountered if more powerful lenses are attempted for use with short focus objectives. Whether a sort of negative orthoscopic lens can be designed for the purpose is problematical, in view of the deep curves required in these smaller Barlows. Perhaps the ideal solution could be obtained by designing the Barlow lens and eyepiece together as a unit. Another interesting possibility is that coma and other aberrations might be eliminated by leaving the lenses uncemented and giving the adjoining surfaces different curvatures, or by using more than two components in the combination.

Ordinarily, two cemented components are used, and the flint is placed ahead of the crown because that permits the use of somewhat shallower curves. The simplest way to design a lens of this type is by application of the thin lens equations as given in ATM or ATMA for the elimination of chromatic aberration in a refractor. If this method is chosen, the first surface of the flint may arbitrarily be made nearly flat, in order to approximate the form most suitable for the elimination of spherical aberration. Such a procedure cannot be expected to produce a lens that will function to the best advantage at some predetermined distance from the objective, but good results can be achieved with lenses of moderate focal length by first determining the best position for the Barlow with regard to achromatism according to actual trial in the telescope and then figuring the first surface on the polishing tool to eliminate the remaining spherical aberration.

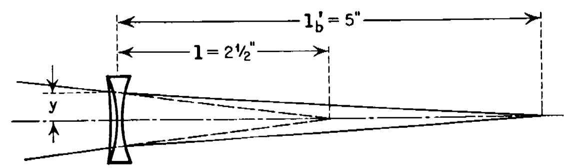
In applying this method, or in using any Barlow lens, it should be borne in mind that as long as any large amount of spherical aberration is present a good color correction is impossible. This is true of any so-called achromatic lens, because the color correction depends on all the light from a given object

point coming to a focus in the same place. Whether the spherical aberration results from a poorly designed or figured Barlow lens or from a poorly figured mirror, if the light from some zone is out of focus it will cause a noticeable amount of color.

Testing may be done on a star, with the Barlow in its place in the telescope, by means of a Ronchi grating or knife-edge as the worker may prefer. If the Ronchi wires appear barrel shaped when inside focus the center and edge of the Barlow should receive the most polishing, and if the wires appear to converge toward the center the intermediate zone of the Barlow should be depressed. The appearance of a raised or depressed doughnut under the knife-edge test would indicate the presence of spherical aberration. Whatever test is used, it should be remembered that the optical surface being dealt with is limited to that area bounded by the marginal rays from the telescope objective. The doughnut does not necessarily extend to the actual edge of the Barlow lens.

It is a good plan, if one likes to work with figures, to compute the curves beforehand that will, if spherical, produce the least amount of spherical aberration as well as a minimum of color. An approximate solution of this problem is possible by the so-called analytical, or algebraical approximation, method. The example that follows is adapted from the form of computation presented in Conrady's book, "Applied Optics and Optical Design," pages 220 to 223.

The problem is shown in Figure 2.



OPTICAL CONSTANTS

	N_D	N_F-N_C	V
FLINT	1.6225	.01729	36.00
CROWN	1.5407	.00910	59.4

FIGURE 2

A sketch for the design of a Barlow lens of minus 5-inch fl with the flint ahead, for use with an f/8 objective at a distance of 2½ inches inside focus. Optical constants: Flint N_D 1.6225; N_F—N_C .01729; V 36.0. Crown 1.5407; .00910; 59.4.

The solution is based on two similar algebraic expressions which indicate the longitudinal spherical aberration of the flint and crown lenses respectively. The powers of the flint and crown, which have previously been determined by thin lens formula to correct for chromatic aberration, remain constant, but changes in the shapes of the lenses are permitted by variations in the value of c_2, which stands for the reciprocal of the radius of the cemented surfaces. If the sum of all the terms in the two expressions is taken as zero and the resulting equation is solved for c_2, we can determine the shape of lens that would be corrected both for longitudinal spherical and for longitudinal chromatic aberration for the case of infinitely thin lenses with truly spherical surfaces.

The formula and its application for the flint lens follows. The indicated multiplications are accomplished here by the use of logarithms. A calculating machine may be preferred if one is available.

$$y^2l'^2_b(G_1c_a^3 + G_2c_a^2c_2 - G_3c_a^2v'_2 + G_4c_ac_2^2 - G_5c_av'_2c_2 + G_6c_av'^2_2)$$

Explanation of symbols:

f' = focallength of Barlow, = -5 inches

c_a = net curvature of flint lens, $= \dfrac{1}{f'(V_a - V_b)(N_F - N_c)_a} = .49432$

c_b = net curvature of crown lens, $= \dfrac{1}{f'(V_b - V_a)(N_F - N_c)_b} = -.93923$

c_1, c_2, c_3, = reciprocals of r_1, r_2, and r_3, respectively.

l = distance from Barlow to primary focus = $2\frac{1}{2}$ inches

l'_b = distance from Barlow to secondary focus, $= \dfrac{lf'}{l+f'} = 5$ inches

v_1 = reciprocal of distance from Barlow to primary focus, = .4 inch^{-1}

$V'_2 = V_3 = (N_a - 1)c_a + v_1 = .70771$

y = $\frac{1}{2}$ the effective aperture of the Barlow, = .15625 inch (for axial points)

$$G_1 = \frac{N^2(N-1)}{2} \qquad G_2 = \frac{(2N+1)(N-1)}{2} \qquad G_3 = \frac{(3N+1)(N-1)}{2}$$

$$G_4 = \frac{(N+2)(N-1)}{2N} \qquad G_5 = \frac{2(N^2-1)}{N} \qquad G_6 = \frac{(3N+2)(N-1)}{2N}$$

The logarithmic tabulation is in Table 2.

TABLE 2—*LOGARITHMIC TABULATION*

	$+G_1c_a^3$	$+G_2c_a^2c_2$	$-G_3c_a^2v'_2$	$+G_4c_ac_2^2$	$-G_5c_av'_2c_2$	$+G_6c_av'^2_2$
log $y^2l'^2_b$	9.78558	9.78558	9.78558	9.78558	9.78558	9.78558
log G	9.91347	0.12099	0.26156 *	9.84194	0.30369 *	0.11973
log c_a^n	9.08203	9.38802	9.38802	9.69401	9.69401	9.69401
log v'^n_2			9.84986		9.84986	9.69972
log sum	8.78108	9.29459	9.28502 *	9.32153	9.63314 *	9.29904
Antilogs	+.06041	+.19706C_2	−.19276	+.20967c_2^2	−.42967c_2	+.19909

(Asterisks in the tables indicate logs of negative numbers, minus signs appearing at tops of same columns. Antilog would be positive if an even number of asterisks appears in the column. Conrady uses an *n* for the symbol.)

For the crown lens we have the formula

$$y^2l'^2_b(G_1c_b^3 - G_2c_b^2c_2 + G_3c_b^2v_3 + G_4c_bc_2^2 - G_5c_bv_3c_2 + G_6c_bv_3^2)$$

The logarithmic tabulation is in Table 3.

TABLE 3—*LOGARITHMIC TABULATION*

	$+G_1c_b^3$	$-G_2c_b^2c_2$	$+G_3c_b^2v_3$	$+G_4c_bc_2^2$	$-G_5c_bv_3c_2$	$+G_6c_bv_3^2$
log $y^2l'^2_b$	9.78558	9.78558	9.78558	9.78558	9.78558	9.78558
log G	9.80737	0.04274 *	0.18183	9.79330	0.25123 *	0.06521
log c_b^n	9.91831 *	9.94554	9.94554	9.97277 *	9.97277 *	9.97277 *
log v_3^n			9.84986		9.84986	9.69972
log sum	9.51126 *	9.77386 *	9.76281	9.55165 *	9.85944	9.52328 *
Antilogs	−.32453	−.59410c_2	+.57918	−.35616c_2^2	+.72350c_2	−.33364

Now we collect all the terms resulting from the two tabulations, and obtain a quadratic equation in c_2:

$$.14649c_2^2 + .10321c_2 + .01225 = 0$$

By the usual solution,

$$c_2 = \frac{-.10321 \pm \sqrt{.10321^2 - 4 \times .14649 \times .01225}}{2 \times .14649}$$

This reduces to two possible values for c_2, −.15120 and −.55335. The corresponding values for c_1 and c_3 follow directly from the relations, $c_1 = c_a + c_2$, and $c_3 = c_2 - c_b$, and by reciprocals we obtain the two solutions:

$r_1 = +2.9144$ inches	$r_1 = -16.941$ inches
$r_2 = -6.6138$	$r_2 = -1.8072$
$r_3 = +1.2690$	$r_3 = +2.5935$

Usually the prescription giving the shallower curves is preferable, so in this case we will elect to use the second solution with the slightly concave front surface. The last operation is to draw the curves to scale and assign thicknesses to the lenses, which may be given here as .15 inch for the flint and .10 inch for the crown.

The foregoing lens design has been tested trigonometrically by the writer and appears to be accurate. Such a result cannot always be relied upon, however, since the algebraic form of computation is based on thin lens formulas. For precise design work the trigonometrical ray tracing method is available, and it should be resorted to if one essays to make a short focus Barlow, or one for use with an objective of large aperture relative to its focal length. The trigonometrical method is explained elsewhere in this book, but some comments may be in order here with regard to its special application in the Barlow problem.

The usual example chosen for an illustration of ray tracing is an astronomical objective. In such a case the light rays striking the first surface of the lens are considered to be parallel to the optical axis, and the initial angle U, which the incoming light makes with the optical axis before being bent by refraction, is taken as 0. When tracing a marginal ray through a Barlow lens, however, we have to deal with convergent light at the first surface, and it is therefore necessary to compute the angle U' from the data pertaining to the aperture and focal length of the objective. Thus sine U' equals half the aperture of the objective divided by its focal length (approximately). For tracing rays through the .707 zone, sine U' equals half the aperture times .707, divided by the focal length.

While the trigonometrical method gives nearly exact answers as to the state of correction of a given lens, it does not automatically furnish the data for a perfected design. The latter must be approached by making several trial tracings using different sets of data, and then deriving the final solution by interpolation. The first step in correcting any lens is to trace rays in red and blue light through the .707 zone, and then adjust the last radius for color, repeating the last column of computations until a state of correction is obtained. Then tracings are made in brightest light for the marginal and paraxial rays, and these are repeated with lenses of various shapes until the spherical aberration is eliminated. In changing the shapes of the lenses, or "bending" them, the individual radii are altered but the powers of the lenses are kept constant. The latter condition is sufficient to maintain the color correction during the bending process with certain types of lenses.

In adjusting the last radius of a Barlow lens to eliminate color it should be remembered that the aberrations of a concave lens are opposite to those of a convex one. In other words, a Barlow consisting of a simple bi-concave lens would introduce both spherical and chromatic overcorrection into a telescope. Consequently, if the blue rays are found to be short, indicating chromatic undercorrection, the crown component of the Barlow should be strengthened by shortening the last radius. The operation will produce a positive spherical correction at the same time, however, and in a far greater amount than the related chromatic correction. The edge rays will be lengthened relative to the central ones, by several times the amount of the adjustment between the red and blue rays.

Bending a Barlow lens also affects both aberrations by significant amounts, as will be seen, and because of this it is hardly possible to make the final adjustments by means of either operation alone.

Which direction the lens is to be bent will depend on the shape of the Barlow with reference to the spherical aberration parabola. In our algebraic example we had two solutions giving a choice between two shapes, and such will normally be the case. About midway between the two will be the shape of lens corresponding to the vertex of the parabola, and this one, if used, would introduce a large amount of spherical undercorrection into the telescope. The situation may seem inconsistent with the rule, mentioned previously, that concave lenses produce overcorrection, but here we are talking about an achromatic doublet. A positive flint component has been added to annul the chromatic aberration of the negative crown, and its contribution with respect to spherical aberration is sufficient in this case to produce spherical undercorrection in the combination. When we say we are working at the vertex of the

parabola, we mean that our Barlow has the shape that gives the maximum undercorrection, and bending it either way will tend to eliminate the spherical aberration. Conversely, if the lens has overcorrection it should be bent toward the median shape, which will be either forward or back depending on which arm of the parabola the condition corresponds to.

If the Barlow approximates the form with the least bending of the edge away from the objective and it is desired to weaken the spherical correction, its edge should be bent away from the objective. Now, because the lenses have thickness, the effect of the bending on the amplifying contributions of the surface nearest the objective will be greater than the effect on the contribution of the last surface. Bending the lenses away from the objective will cause a shortening of the distance between Barlow and image, and reduce the relative effect of the crown component. A negative chromatic correction will be the result, amounting to a significant fraction of the corresponding spherical correction.

If our project were to design a small doublet objective of long relative focus, we might be able to correct for one aberration at a time, determining first the proper curvature of the last surface to give a good color correction, and then bending the entire combination into the shape that would give the best results with regard to spherical aberration. The bending would have little effect on the chromatic correction in that case. A Barlow lens is another matter, however, and the deeper the curves are made the greater is the effect of bending on the chromatic correction. Since the chromatic tolerance is only one quarter of the spherical one, it is apparent that the final correction has to be made by adjusting the last radius and bending the Barlow at the same time; or perhaps it would be more correct to say that the contributions of the two operations, both as to spherical and chromatic aberration, have to be employed in the final correction simultaneously. The writer's method is to estimate the two adjustments quantitatively from a study of the results of the previous trial solutions, and to continue the process until the required degree of accuracy is obtained. Graphs are helpful in estimating the various corrections, but the process is laborious, and no doubt it could be improved on by an experienced designer.

It may be worth while to review some of the statements that have just been made relative to computing the curves for a Barlow lens. The first way, which is by far the simplest, is to use the thin lens achromatization formula for powers of flint and crown, and make the leading surface of the flint nearly flat. Then the final corrections are obtained by shifting the position of the Barlow in the telescope and by changing the figure of its leading surface, or of both of the exposed surfaces if necessary. The final figuring operation is likely to be necessary, incidentally, no matter how scientifically the Barlow is designed. The second method of computation is by algebraic approximation, which is comparatively easy to carry out and fairly accurate. The third method must be used when a high degree of precision is required. It employs trigonometrical ray tracing, and is rather tedious when applied to a Barlow lens design. It is not very difficult, however, if one is in a position to spare the required time.

Since many pitch and rouge addicts do not possess either a table of logarithms or a calculating machine, it is probable that more Barlow lenses will be made by the first method than by either of the others, and there is no doubt that some of these will excel many of the more pretentiously designed lenses in performance. That can be predicted with assurance, because there are many factors affecting the degree of excellence of a Barlow lens beside the mathematical elimination of primary spherical and chromatic aberration. Probably the most important of these is the worker's skill in carrying out the grinding and polishing operations.

Two Direct-coupled Amplifiers for Use with a Stellar Photoelectric Photometer

By Gerald E. Kron
Lick Observatory

If a stellar photoelectric photometer is reduced to its fundamentals, it may be said to consist of two parts: the light-sensitive element, and the indicating meter. In this chapter one type of indicating meter will be discussed, a d.c. (direct-coupled) amplifier for furnishing the required sensitivity, followed by a meter for indicating the actual readings of light sensitivity.

The indicating meter part of a photometer must satisfy several requirements if it is to be a useful instrument. It must have sufficient sensitivity for its purpose; it must give a faithful, undistorted measurement of the input; it must be reasonably small, reliable, and inexpensive; and, if possible, it should be portable. A good galvanometer satisfies all these requirements except that of portability. An amateur astronomer can save himself a great amount of tinkering and trouble simply by using a galvanometer for his photometer. However, if it is impossible for the amateur to furnish a fixed, stable mounting for a galvanometer, or if the lure of the use of vacuum tubes is too much for him, he may find it necessary or interesting to attempt the construction of an amplifier type of photometer. One who is good at penny pinching, and who has a fairly good stock of electronic parts on hand, may even find it possible to build an amplifier for less than the cost of a good galvanometer.

The construction of a useful d.c. amplifier is not a simple or easy thing to accomplish. On the other hand, it is all too easy to make the construction of such an amplifier seem simple and straightforward. Thus, it is perhaps wise to sound a word of warning and to call to mind the old saying containing words about angels, etc. It is easy enough to fasten together a collection of parts according to a circuit diagram. Forcing this assembly to perform as a good d.c. amplifier should is something else, however. In other words, anyone can give instructions for the general assembly of a piece of equipment, but making this equipment work is a special problem that must be solved (or not) by only one person: you. It would probably be unwise for anyone except a person who has had at least the experience of the average licensed amateur radio operator to attempt the construction of a d.c. amplifier. Certain others, of great resourcefulness, doubtless can do it. Whether or not a given individual can do it frequently can be decided only by trial.

The general design of the amplifier depends upon the characteristics of the meter it drives, and of the amplifier in the light receiver. The amplifier receives a signal from the multiplier, and transmits it after the process of amplification to the meter. The amplifier must have sufficient amplifying power to make the normal dark "noise" level of the multiplier visible as a continual random twitching of the meter needle, else sensitivity will be too low for use of the photometer on the faintest stars of which it is capable. Such sensitivity will be too high for many uses, so the amplifier must also be equipped with a control of its amplifying power, or a "gain control" as it is commonly called. The r.m.s.[1] noise level of an average 1P21 multiplier operated at 70°F is about 10^{-11} ampere. If a meter is sufficiently sensitive to give an appreciable deflection on a current of this size, then it may be connected directly to the multiplier, and no amplifier is needed. If one happens to have a meter of such sensitivity that, let us say, 0.001 ampere (one milliampere) is required for full-scale deflection, then considerable current amplification is needed. Meters of this sensitivity are very common, and meters ten times this sensitive (100 microampere meters) are not difficult to obtain. The two amplifiers to be described are for use with such meters. The advantage of using this meter lies in its reasonably high sensitivity, and its general availability in several price ranges. In addition, the scales come divided into convenient units.

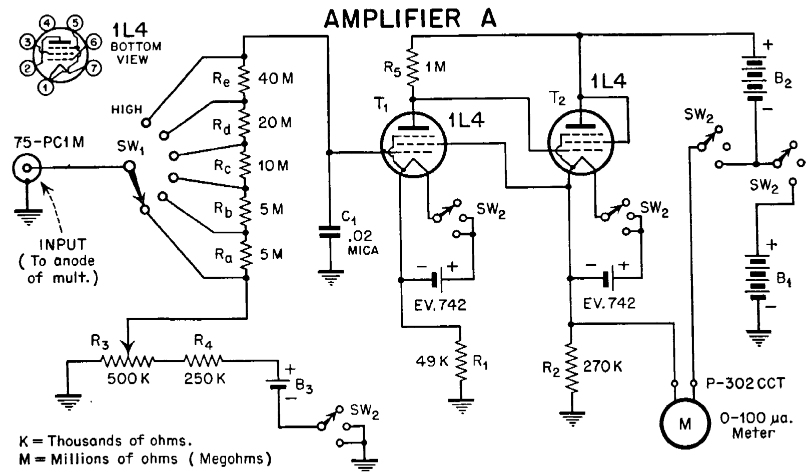
An amplifier may be either a voltage or a current-yielding amplifier. Because the most readily available meters are current-consuming devices, the amplifier may be designed to be current-yielding. Multipliers are also current-yielding; however, vacuum-tube amplifiers are always voltage-consuming devices. Thus, something must be done to the output of the current-generating multiplier to make it suitable for use with a voltage-consuming amplifier. Ohm's law [2] suggests a solution to the problem; simply connect a resistor across the output of the multiplier (where a galvanometer would be connected) and a voltage which may be computed by applying Ohm's law will be generated across the resistor.

Obviously, the larger the resistor used for the so-called "input resistor," the larger will be the available voltage. Certain circumstances limit the size of the resistor in practice. Experimental work has shown that the maximum practical input resistance is about 100 megohms, or 10^8 ohms. We can now compute, with the aid of Ohm's law, that the 10^{-11} ampere noise level of the multiplier will become a voltage of 10^{-3} volt, or one millivolt, across an input resistor of 10^8 ohms. If it is agreed that a convenient value for the indication of the noise level on the meter would be 1 percent of full scale, then the amplifier will have to have enough amplification to give 1 percent of full scale on one millivolt, or full-scale deflection on 0.1 volt. The amplifiers to be described give, at maximum sensitivity, full-scale deflection on 0.5 volt and 0.1 volt.

Further consideration of Ohm's law will make it plain that a reduction in the size of the input resistor will reduce the voltage input to the amplifier. Control of the input resistor thus provides an excellent means for controlling the sensitivity of the photometer, though it can become cumbersome if not augmented by some other means of gain control.

To aid in further discussion of amplifiers, reference will now be made to a specific example, a very simple and inexpensive amplifier. It is one of two amplifiers to be described in this chapter and will be used as a model for discussing several general features common to both. The simpler amplifier will be called amplifier A, while the other, more complicated, will be referred to as amplifier B.

The circuit diagram for amplifier A is shown in Figure 1. There you will see that amplifier A has two tubes, and that it operates entirely from batteries.[3] Battery operation makes possible the extreme simplicity of this amplifier, by virtue of the uniform voltage yielded by batteries during their useful life. The complexity of amplifier B, on the other hand, is caused almost entirely by the difficulties encountered in making an amplifier deriving its power from the ordinary lighting circuit operate properly in spite of line voltage variations. More will be said of this in the description of amplifier B.



Drawings by J. F. Odenbach after the author

FIGURE 1

Circuit diagram for a simple direct-coupled amplifier

Amplifier A

The two tubes in amplifier A have different functions, and they are used in different ways, though they are of the same type. T_1 is employed as a voltage amplifier. T_2 is a power, or driver, amplifier for coupling the voltage-amplifying T_1 to the current-operated meter M. The tube T_2 is employed as a cathode follower; that is, the meter is driven by the change in cathode current of T_2.

---

1 "Root-mean-square." This refers to a particular way of taking the average of random variations. You can get a good r.m.s. estimate by estimating the peak amplitude of the random "wiggles" of your meter needle, and dividing by the value 4.

2 Ohm's law states that $E = IR$, where E is a potential in volts, I is the current in amperes flowing through a resistance R in ohms.

3 I am indebted to Dr. John Hall for calling my attention to the simplicity and stability of a battery-operated amplifier designed to drive a 0–100 microammeter. Amplifier A was designed after inspection of a circuit kindly sent me by Dr. Hall and Dr. John F. Jewett.

This method of driving the meter is preferable to the more familiar method employing direct connection to the plate because of the resulting economy in the number of batteries needed, and because a cathode follower driver has a more nearly linear operating characteristic than a conventional amplifying stage. A linear operating characteristic means simply that the change in current through the meter is exactly proportional to a given change in input voltage applied to the grid of T_2.

The combined action of the two tubes may now be discussed in detail. T_1 operates almost as an ordinary pentode voltage amplifier; it is unusual only because of the low current and voltage conditions under which it operates, and because of the action of the cathode resistor R_1. The low current and voltage make for economy of battery power, and for reduced control grid current. More will be said later of the action and importance of control grid current in the first stage of a photometer amplifier. The resistor R_1 has three functions, it reduces the amplification of the first stage to an appropriate value, it introduces cathode degeneration and thereby improves the linearity of the first stage, and it furnishes grid bias without the necessity of employing an additional battery. Note that the screen grid voltage for T_1 is supplied from the cathode of T_2. This connection makes simple provision for the screen potential, and it causes a small amount of inverse feedback with a resultant favorable effect on the overall linearity of the amplifier. The first stage of the amplifier draws a plate current of 47 microamperes; it operates with 43 volts on the plate, 45 volts on the screen, and -2 volts on the control grid. It amplifies by a factor of 7. Because of the low currents involved in the operation of the first stage, none of the voltages may be measured accurately with an ordinary test meter (a vacuum-tube volmeter is required) but if the amplifier is properly built, exact knowledge of the voltages is unnecessary.

The amplified signal from T_1 passes directly to the control grid of T_2. The no-signal current of T_2 is carried entirely by resistor R_2; thus, for no-signal conditions, the meter M will have a zero reading. In other words, the cathode voltage of T_2 will just equal the voltage of the battery B_1, or 45 volts. By Ohm's law, therefore, the no-signal current drawn by T_2 must be 45/270,000, or 167 microamperes, plus a small amount for the screen current of T_1. The maximum-signal current will be, of course, the above quantity plus 100 microamperes required to give the full-scale deflection of the indicating meter M. The amplifier will take a negative input signal of about 0.05 volt to give full-scale deflection of the meter. The amplifier is not suitable for a positive input signal, because T_2 will be driven so close to current cut-off for full-scale deflection of the meter (which would have to be connected with reverse polarity) that linearity of the stage would be doubtful. A multiplier phototube gives a negative signal.

The input circuit to the control grid of T_1 performs several important functions. It acts as a loading resistor for the multiplier, and as such it really is more a part of the multiplier than it is of the amplifier. In addition, this circuit is employed as a gain control, as a no-signal zero control, and as a means for establishing the proper "time-constant" for the whole photometer.

Five resistors whose total series value adds to 80 megohms are connected from the input grid to the circuit consisting of R_3, R_4, and B_3. R_3 is a potentiometer which places an adjustable potential derived from B_3 into the input circuit for the purpose of setting the no-signal zero position of the meter. The switch Sw, allows selections of the portion of the total series value of $R_a + R_b + R_c + R_d + R_e$ to act as a load resistor for the multiplier for the purpose of gain control. Persons familiar with the usual type of gain control will recognize that the one here presented is connected backward by comparison. It is, in fact, an Ayrton shunt arrangement, and not a potentiometer. The potentiometer type of connection would place the total 80 megohms permanently across the multiplier as the load resistor. This would allow large voltage signals to be generated when the multiplier is used on bright objects, which, under some circumstances, could result in loss of linearity. The gain control shown in Figure 1 allows five steps of sensitivity by factors of two from full sensitivity to 1/16 of full. Plainly, this control may be constructed with as many steps as desired, in any ratios desired, as long as the total resistance is about 80 megohms, or, at least, no more than 100 megohms. The purpose of the condenser C_1 is to limit the response time of the entire photometer.

The concept of response-time is complicated enough and important enough to warrant discussion in a paragraph of its own. The response-time of any device is finite. That is, no machine, be it an amplifier or a meat grinder, can accomplish the purpose for which it was made unless it is given a certain amount of time in which to act. Some amplifiers are made deliberately to act in a very short time; for example, the video amplifier of a television receiver will give a useful contribution to the whole picture in less than one millionth of a second. The speed with which a photometer amplifier acts may be controlled by its maker to suit his desires. Previous experience with photometers indicates that they should be adjusted to give an answer (meter reading) in about 10 to 15 seconds after the starlight is admitted to the multiplier. During this time interval the meter needle will be moving toward a maximum value. A required wait of 10 or 15 seconds to get a reading may seem like a pure waste of time, but it really is not. During this interval, the amplifier is taking data for you; it is averaging, in a very accurate and effective way, the random fluctuations in light caused by "seeing" conditions, and it is relieving the operator of taking down and averaging any more numbers than necessary. The desired response time of the amplifier is determined by the condenser C_1. If the value of C_1 in microfarads is multiplied by the input resistor in megohms, a value for the input "time-constant" will be obtained in seconds of time. If the time-constant is multiplied by 2π, the result will be the indication-time of the circuit, provided that it contains no element that is slower acting. For amplifier A, the time-constant is $0.02 \times 80 = 1.6$ second. The indication-time is $1.6 \times 2 \times 3.14 = 10.0$ seconds.

Amplifier A may be built, including the batteries, on a chasis having as small an area as 64 square inches. Figure 2 shows the construction we adopted, a cubical metal box with all components panel mounted, except the batteries, which are mounted on the floor of the box. Our amplifier was made from salvaged materials, and is therefore somewhat untidy in appearance. The builder may select any type of cabinet he desires, and may "doll up" the amplifier as much as he pleases. If a plain black cabinet is used, amplifier A may be built for about $15, not counting the meter. Table 1 contains a schedule of parts.

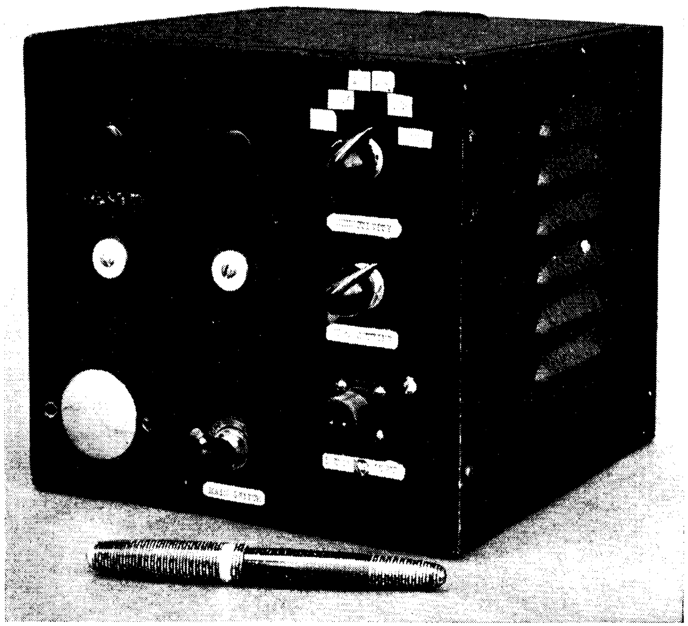


Photo by J. F. Chappell

FIGURE 2

External appearance of Amplifier A. The amplifier was built from salvaged parts, and the unidentified objects on the front panel are simply plugs for unused holes.

This amplifier may be built without the use of any instruments other than a soldering iron and drill. However, a standard universal test meter will be found useful for such purposes as testing batteries. Owing to the small currents drawn in the circuit, no voltages, with the exception of the battery voltages, can be measured with a conventional test meter.

In building the amplifier, first do all of the hole drilling and mount all of the parts. This may be done according to any parts layout that suits the

TABLE 1—*PARTS SCHEDULE, AMPLIFIER A*

1 Cabinet, type ICA 3925, 8 by 8-inch panel	$ 3.00
1 Input terminal, type 75-PC1M, Amphenol	.20
1 Sw_1, Gain control switch, type 1216L shorting-type Mallory switch	.80
1 Sw_2, On-off switch, type 3136J, 3-position, 6-pole shorting-type Mallory switch	1.20
2 T_1 and T_2, type 1L4 tubes	2.25
2 miniature 7-pin sockets	.25
1 output terminal, 2-prong Jones socket, S-302-AB	.15
1 output plug (for meter) Jones plug, P-302-CCT	.35
2 filament batteries, Eveready type 742	1.10
2 B_1 and B_2 "B" batteries, Burgess XX30E	3.00
1 B_3, zero-control battery, penlight cell	.10
1 C_1 condenser, 0.02 mfd., type ASG_2 Glassmike	1.00
1 R_3 0.5 megohm potentiometer, linear taper	.75
2 R_a and R_b 5 megohm, ½-watt resistors	.20
1 R_c 10 megohm, ½-watt resistors	.10
3 R_d and R_e 20 megohm, ½-watt resistors	.10
1 R_1 50K, ½-watt resistor	.10
1 R_2 270K ½-watt resistor.	.10
1 R_4 250K ½-watt resistor	.10
1 R_5 1 megohm, ½-watt resistor	.10
five feet of hook-up wire	.05
Total cost of amplifier A	$15.30
1 M_1 0-100 microampere meter, Simpson model 27	$15.00
or, better, Weston model 430,0–100 microammeter, ½ percent	$45.00

fancy of the builder. A d.c. amplifier of this type is not sensitive to the layout of the parts. The input and output terminals, zero control, on-off switch, and gain control switch may be mounted on the front panel according to a layout that is pleasing in appearance. The amplifier shown in Figure 2 has the input terminal mounted on the back; this may be a convenience, as a wire dangling from the front will be eliminated. After the parts have been mounted, all of the wiring may be done. Wiring should be neat and businesslike. Keep the wires and small parts such as resistors close to the chassis, regardless of how long some of the wires may become. Avoid a spiderweblike appearance. Heavy parts like the batteries should be strapped down in such a way that they are secure but may be easily replaced. Try to build the amplifier with the idea in mind that it might be dropped on the floor, and that it should be undamaged by such treatment; or that it might be carried for miles in the luggage compartment of an automobile, and must survive the vibration. No shielding of any kind within the amplifier is required, provided it is built in an enclosed metal box. The on-off switch is connected with three positions, an "off," an intermediate position that turns on the filaments and the zero-control potential, and an "on" position that turns on the B+ voltage. This type of switching is used so that the filaments may be brought to temperature before the B+ has been turned on, because experience has shown that the zero drift will be reduced by this practice. After the wiring is completed, check the circuit carefully for errors. An error in wiring may result in burned-out tubes or damaged batteries, and a glance at the prices in the parts schedule will show why this should be avoided.

It is a good plan to have the tubes in the sockets while the wiring is being done, to help with the alinement of the little connectors inside the sockets; however, do not insert the battery plugs until the circuit has been checked for errors. After the circuit has been checked and the battery plugs have been inserted, turn the on-off switch to the first position and look in the tops of the tubes to be sure the filaments are burning. This may have to be done in a darkened room, as the 1L4 filaments burn very dimly. The first test should be made with a wire connected across the input resistor; simply connect a wire—it can be one with alligator clip ends—from the input grid of the first tube (T_1) to the center contact of the zero-control potentiometer. Now turn the amplifier on, pausing a moment at the first position of the on-off switch. Insert the meter plug, and observe what happens to the meter needle; it will probably flash off scale. Try to bring the needle on scale by working the zero-control one way or the other; if you are very lucky you will be able to bring the meter needle on scale this way. If you are just an ordinary person, you are face to face with your first problem.

Now try changing the value of R_1; see if a 100K resistor will make the needle rush off scale in the opposite direction; if it does, then some intermediate value of R_1 may work, and you will have to spend some extra money on an assortment of resistors in order to find one resistor, or a combination of two or three in series or parallel, that will keep that meter needle on scale. Do *not* put a variable resistor or rheostat in the circuit for R_1, except temporarily as a possible aid in finding the correct value; the final resistor should be a fixed resistor, and its value should not be far from 50K, more or less. Extra variable resistance controls should be avoided; their use makes an amplifier messy, and encourages knob twiddling in order to correct such ills as bad tubes and worn-out batteries. In addition, most variable controls give contact troubles when used in circuits in such a way that current is drawn from the middle contact. The zero control, R_3, has no appreciable current drawn from it, and it should be the only potentiometer appearing in the finished amplifier.

If no reasonable value of R_1 will make the meter read on scale, test the batteries with a voltmeter, as one of them might be defective or may be connected with wrong polarity. If possible, find a friend who has an ohmmeter, and test resistors R_5 and R_2; sometimes resistor values are wrongly stamped in the factory. You can also buy a third tube, and try substitution of tubes if all else fails. *Don't* attempt to vary other circuit constants such as R_2 and R_5; this will not help, and will simply confuse both you and the circuit. If all parts are perfect, and if there are no mistakes in wiring, simple adjustment of R_1 should make the amplifier work properly. When you have achieved the result of getting the meter needle on scale, try the zero control, and observe how nicely you can put the needle any place you wish on the scale. If you run out of zero control, a small further change in R_1 may be necessary.

You are now ready to make final adjustments and tests of the amplifier. First, its polarity must be tested, and made correct; that is, you must be sure that the meter needle goes to the right when light falls upon the multiplier. To do this, remove the shunt from the input resistor and connect the positive end of a flashlight cell to the input; the meter should go off scale to the *left*. If it goes off to the right, reverse the polarity of the meter anywhere in the circuit where it is most convenient. Now replace the input resistor shunt, and try the zero-control again. For the sake of consistency, it is nice to have a right-hand rotation of the zero-control knob cause a right motion of the meter needle. If it does not, the condition may be corrected by interchanging the two wires to the outer terminals of the potentiometer R_3.

The amplifier may now be tested for its input grid current. With everything assembled and in working condition, set the meter needle to the approximate center of the scale with the zero-control knob. With any handy piece of wire, again shunt out the input resistor, making an attempt to contact the zero control potentiometer before input grid terminal in order to avoid a surge that will probably throw the meter needle off scale. The meter needle will come to rest in a new position on the scale, and when you release the shunt connection, the needle should go back to its former position. Note the amount by which the needle was displaced. The voltage sensitivity of the amplifier is about 0.05 volt for full scale, that is, for 100 divisions, making 0.0005 volt per scale division. The input resistor is 80 megohms, or 8×10^7 ohms. If the meter deflected ten divisions when you grounded the input, it means that 10×0.0005 or 0.005 volt had been across the input resistor. Applying Ohm's law, the current must have been $0.005/8 \times 10^7$ ampere, or close to 6×10^{-11} ampere. This current originated in the first stage of the amplifier, that is, in T_1. The effect of this current, known as the grid current, is to act something like a resistor in parallel with the 80 megohm input resistor. Unfortunately, it may exert a non-linear effect on the input signal, though the possibility of this is minimized by the large size of resistor R_1. A further safeguard lies in having the grid current so small that it can cause little trouble, whether it changes its size with the size of the input signal or not. The value of 6×10^{-11} ampere is typical. The exact size of the grid current depends upon properties of the tube and the conditions under which it is operated. If you find yourself with a bad tube in this respect, interchange the two tubes in the amplifier, or try an extra as a substitute.

Your amplifier, upon passing the grid current test, is ready to be tried out on the stars. Connection from the multiplier anode to the amplifier may be made with a piece of polyethylene insulated microphone cable or coaxial cable as long as several hundred feet without impairing the performance of the photometer in any kind of weather. A coaxial cable called RG-58-U is excellent for the purpose, and it will fit into the matching terminal of your Amphenol 75-PC1M input terminal. Most modern microphone cable is more flexible than RG-58-U, but not all of it is polyethylene-insulated. Make sure of this type of insulation before using microphone cable. When you plug in the multiplier, the meter needle may go off scale to the right, indicating a large "dark" current. This current may be caused by any of the following:

(1) A light leak; that is, the multiplier is not completely darkened.

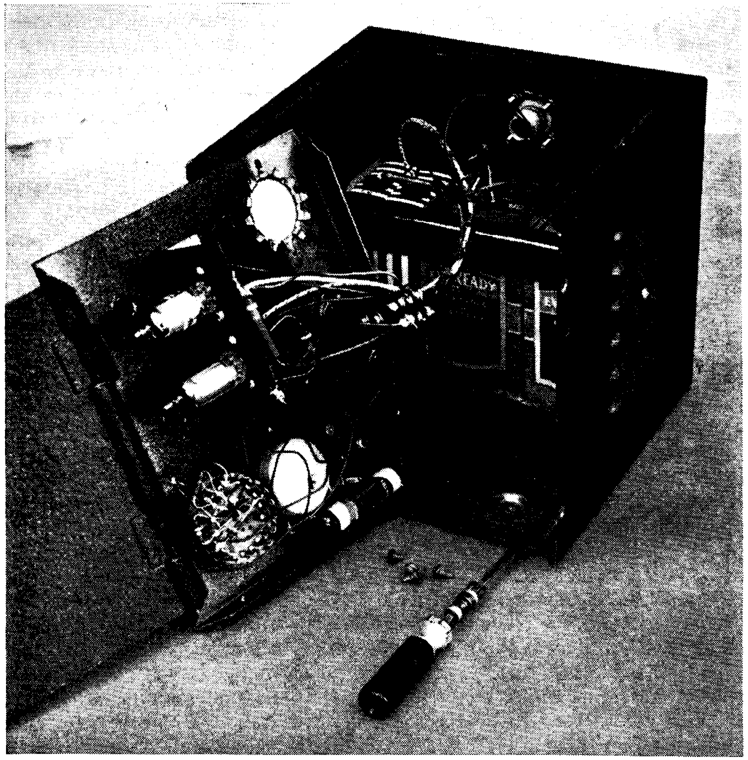


Photo by J. F. Chappell

FIGURE 3

Internal structure of Amplifier A. All parts except the batteries and the input terminal are mounted on the front panel.

(2) A "green" multiplier (one that has been on the shelf for a long long time).

(3) Current leakage in the cabling between the multiplier and the amplifier, involving the multiconductor cable that carries the dynode potentials to the multiplier.

(4) A multiplier that normally has a large dark current.

The remedy for (1) is obvious, (2) may be remedied by allowing the multiplier to remain connected for several hours. You may make a test for (3) by removing the multiplier from its socket and then connecting everything else. Any meter displacement will be due to cable or socket leakage. Sometimes black Bakelite sockets are badly "leaky" during damp weather and of course the only remedy for this is to replace such parts or use sockets and plugs made of brown mica-filled Bakelite. If your multiplier normally has a high dark current, there is nothing to be done about it except balance the dark current out by modifying your zero control circuit to suit your special case. By this time, you will know how to do this without detailed instruction. Keep in mind the fact that multipliers are very sensitive to heat; if they lie outside in the sunlight, even enclosed in a receiver, they are likely to be ruined. Try to keep your multiplier at a temperature below 80°F if possible, and of course don't ever leave one on a telescope that is standing in direct sunlight, or in a telescope dome that is likely to heat up badly during the daytime. Remove the multiplier and take it into the house, and even put it in the refrigerator if necessary during very hot weather. A good rule for the amateur is always to disconnect the multiplier when it is not in use, but connect the voltage an hour or so before placing it in service.

The performance of your photometer on the stars will depend upon the excellence of the multiplier. At the Lick Observatory we find we can do effective two-color photometry of stars of twelfth magnitude with a 1P21 multiplier on our 12-inch refracting telescope. We would do somewhat better with an aluminized reflector, because of gaining the ultraviolet light lost in the refractor. If the multiplier were to be refrigerated, still better results would be obtained, by one or two magnitudes, depending upon the properties of the multiplier. A really good type of 931A multiplier selected with great care from 20 or 30 samples might get to tenth magnitude, with luck. Remember that multipliers are extremely variable from sample to sample, just like persons. They may look alike, but some are fine while others are relatively worthless. The only really effective way to select multipliers for astronomical photometry is to compare them under actual service conditions. We have tried laboratory methods for comparing multipliers, and such methods work for eliminating the poorest ones from a group, but the finals are always run on the telescope. If you are the fortunate possessor of a really good 1P21 multiplier, you can make valuable contributions to astronomy with a 6-inch telescope, particularly if it is an aluminized reflector.

AMPLIFIER B

Amplifier B[4] is distinguished from amplifier A by being operated entirely without batteries. The circuit, Figure 4, is, by comparison, much more complicated, and the amplifier is correspondingly more expensive to build. The extra cost is justified in some cases by the saving in operating expense caused

---

[4] The circuit for this amplifier is derived from a circuit given in Vol. 18 of the Radiatron Laboratory Series (McGraw-Hill Book Co., New York), combined with a circuit of the author's design.

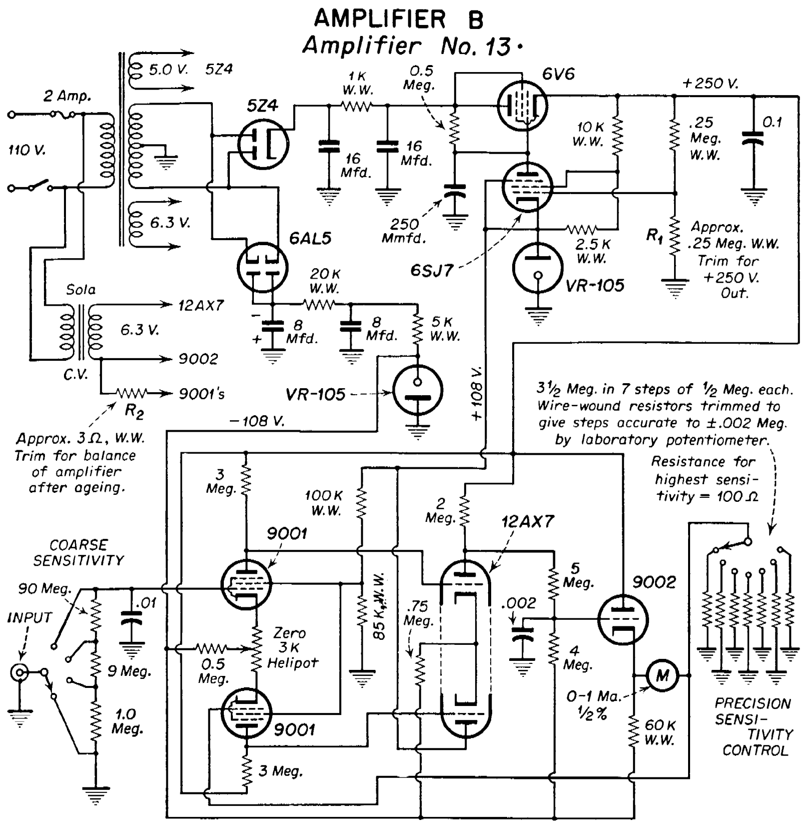


FIGURE 4

Circuit diagram for Amplifier B and its associated power supply. The upper part of the diagram portrays the power supply section, and the amplifier itself is to be found on the lower part of the diagram.

by the absence of batteries, by better stability and linearity of operation than that found in amplifier A, and by the greater reliability of an instrument which cannot surprise its user with a dead battery. Of course, amplifier B depends for its operation upon availability of standard 115-volt lighting circuit, and the failure or unavailability of such a circuit will render the amplifier useless.

The standard 115-volt lighting circuit has rather poor voltage stability.

Seldom are these circuits free from variations of less than 5 percent, and there are frequent cases of lines showing variations of as much as 10 percent. Direct-coupled amplifiers are notoriously sensitive to variations in their supply voltage, and the successful operation of a d.c. amplifier from a power source of varying voltage is a major problem. The usual effect of voltage variations upon a d.c. amplifier is to cause an unstable zero; that is, the zero reading of the meter will "wander" about in a very annoying manner that makes accurate readings difficult, and impossible if the variations are large and rapid.

Amplifier B is designed to decrease random wandering of the zero to a value so small that it is negligible. This is done by incorporating three design features into the amplifier, as follows:

(1) Parallel balancing of each of the first two stages.

(2) Electronic voltage regulation of the B+ voltage.

(3) The use of inverse-feedback enclosing all three stages of the amplifier. Feature (3) insures that the amplifier will have a high degree of linearity. The parallel balancing will be evident upon inspecting the circuit diagram, Figure 4. Note that each of the first two stages has two tubes instead of one, and that each of the two tubes is connected in such a way that its circuit is a mirror image of its companion. If the two tubes of each pair were identical, the parallel balancing alone would be sufficient to render the amplifier completely independent of all small variations in its power supply. Unfortunately, electronic tubes of similar type are not identical, and therefore the additional expedients (2) and (3) must be used.

The complexity of amplifier B makes any attempt at a complete description impractical here. I will therefore assume that he who contemplates building this amplifier has gained experience from sources other than these paragraphs, and I will describe the amplifier only in general terms.

Figure 4 shows a circuit diagram of amplifier B, and Figures 5 and 6 show respectively a close-up view of the amplifier with a Weston Model 430 meter and a view of the amplifier as part of a photoelectric installation on the 8-inch reflecting telescope at the Students' Observatory, University of California.

Amplifier B has two gain controls, one giving factors of 10 by selection of different values of multiplier load resistors, and one giving steps of ½ stellar magnitude by controlling the degree of inverse feedback of the amplifier. A factor of 10 is exactly 2½ stellar magnitudes; therefore, if the fine gain control, the one with steps of ½ magnitude, is given 2½ magnitude range, the fine control can more than "fill in" between the steps of the coarse control, and give the amplifier ½ magnitude steps in sensitivity over its entire sensitivity range.

The first stage of amplifier B employs two type 9001 tubes; these little tubes, as connected in this circuit, give an amplification of about 150 with an input grid current of about 5×10^{-11} ampere. The "active" tube is used as the input tube, while the control grid of the "passive," or balance tube, is used as the feedback injection electrode. The second stage requires a single tube envelope, but again consists of two elements, this time the two triodes of a type 12A x 7[5], in a balanced connection. This stage has a gain of about 60, and thus the first two stages have a combined gain of about 9000. The final stage is a triode, a 9002, used as a cathode follower in the role of a current amplifier to drive the meter, a 0–1 milliammeter. The meter is cathode fed from the last stage, in series with a resistor, selected by means of a selector switch, that determines amplifier sensitivity. The smaller the resistor, the greater the sensitivity. The signal appearing across this resistor is fed back to the control grid of one of the input tubes, resulting in inverse current

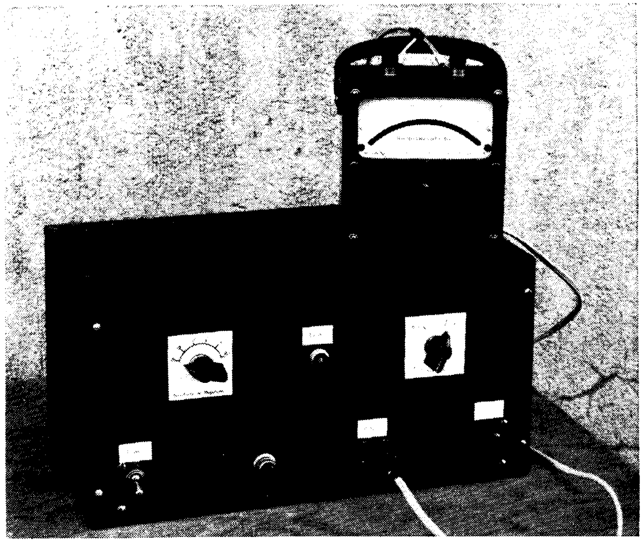


Photo by J. F. Chappell

FIGURE 5

External appearance of Amplifier B, with Weston model 430 milliammeter.

feedback. The current sensitivity of the amplifier is therefore almost entirely independent of the internal resistance of the meter, over a wide range. If the feedback resistors are of high stability, such as wire-wound resistors, the sensitivity of the amplifier will be highly stable with respect to time and temperature. The precision of the ratios of fine sensitivity, determined by the size of these feedback resistors, may, by careful trimming of the values of the resistors, be made as high as ±0.1 percent.

The quality of the parts in this amplifier should be high. The 9001 sockets should be made of a ceramic material, as should, also, the selector switch to

[5] The heaters of this tube may be connected in parallel for 6-v operation.

which are connected the high resistances used for multiplier loading and coarse gain control. The 90 megohm resistor is best obtained by connecting nine 10 megohm resistors in series. This will insure that the temperature coefficient of this high resistor is similar to those of the lower resistors, thereby insuring temperature independence of the coarse sensitivity ratios. Excellent resistors for critical high resistance applications are the Continental Carbon "Nobleloy"

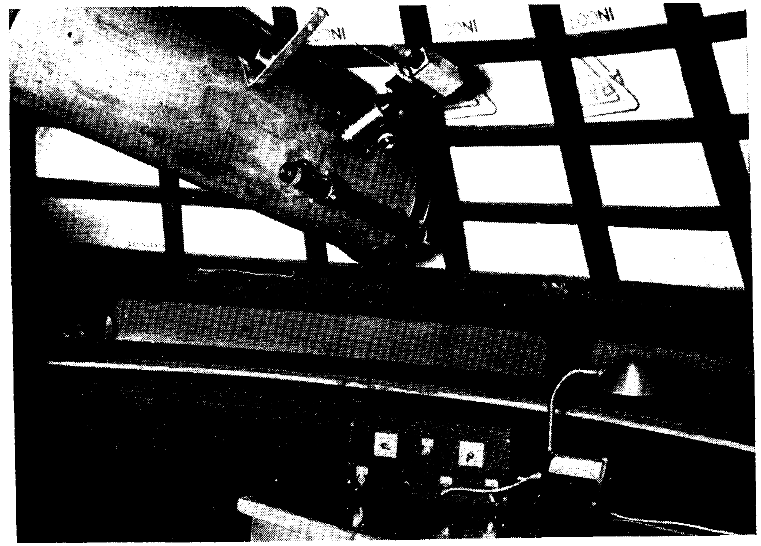


Photo by Jack and Mabel Chambers

FIGURE 6

Amplifier B operating with a photometer installation on an 8-inch reflecting telescope at the Students Observatory, University of California, Berkeley. Note the light receiver mounted at the Newtonian focus, and the filter slide just inside the receiver. Guiding is done with a 4-inch refracting telescope visible just above the 8-inch tube. Batteries for the multiplier are mounted on the 8-inch tube at the declination axis. Only the shielded anode lead trails from the telescope to the amplifier.

precision resistors. The time constant condenser should be of low leakage and low dielectric absorption. The last term is used to describe a propensity for most condensers to "soak up" an electric charge slowly, later to be yielded when the potential is removed. An excellent condenser of low leakage and low dielectric absorption is the Glassmike type ASG, made in a variety of capacities by the Condenser Products Company (1375 N. Branch St., Chicago, Ill.). The two input 9001 tubes should be of the same make to insure similarity. If, by bad luck, two quite unlike tubes are obtained, as indicated by a bad zero unbalance, it may be necessary to try another pair.

Amplifier B may be built into a chassis having an area of 120 square inches or larger. It is advisable to build the power supply and amplifier together on the same chassis, to avoid complication caused by external wiring to a separate power supply. If the cabinet is of metal, and encloses the amplifier, no additional shielding will be needed by any of the parts. Construction of the amplifier will require the use of a good 20,000 ohms-per-volt universal test meter, and any trouble-shooting may require the use of a vacuum-tube volt-

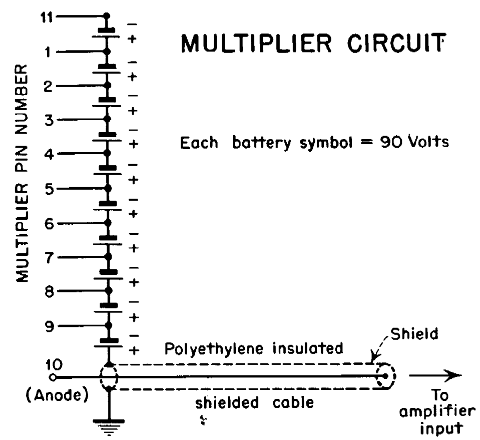


FIGURE 7

Suggested circuit diagram for a multiplier to be used with an amplifier. The batteries may be of the smallest available type of hearing aid battery.

meter to measure voltages at high impedance points such as the plates of the 9001's.

The regulated power supply should be built first, and the plus voltage supply adjusted to its proper value, 250 volts, by trimming the resistor R_1. A study of the circuit will show that the plus power supply is nothing but a self-regulating direct-coupled amplifier. The 6SJ7 amplifies the voltage fluctuations in the controlled part of the circuit and feeds the amplified signal to the grid of the 6V6 so as to oppose, by varying the 6V6 conductivity, the original variation. If the overall gain of the 6SJ7 and 6V6 stages is about 100, then the regulation of the power supply will be 100 times better than the unregulated voltage coming from the rectifier tube. The VR 105 in the cathode circuit of the 6SJ7 is employed as a reference source of steady voltage, with which the 6SJ7 compares the controlled voltage. The negative voltage supply is a simple one, with regulation furnished by a VR 105. A tendency for the heater insulation of the 6AL5 rectifier to break down to the cathode, caused by too high a-c voltage from the power transformer, can be eliminated by

inserting resistors in series with each cathode, of such size that the d-c voltage at the 6AL5 plates stands at −250 volts under load. The Sola constant voltage transformer specified for the amplifier heaters may be 6.3 volts output, either No. 30492 or No. 301002. A 6 volt storage battery may be substituted.

After the power supply is working, you may build the amplifier itself. The chassis layout is not critical. It is important that the feedback coupling from the feedback resistor to one of the input grids be to the correct input grid, otherwise the feedback will be regenerative instead of degenerative. This amplifier is not highly sensitive to properties of any of its parts, provided, of course, that parts are not defective. If properly wired free from errors and defects, it should, when finished, operate with no trouble shooting. The 9002 cathode should, of course, be at ground potential, whereas its grid should be at about −8 volts. The plates of the 12A x 7 should both be at about +108 volts, while the cathodes should be at about +35 volts. The 12A x 7 grids (and therefore the 9001 plates) should be at a slightly lower potential than the 12A x 7 cathodes. The 9001 cathodes should be at about +2.7 volts; a value much below +2.5 may cause high grid current in the 9001 stage. The input grid current should be less than 10^{-10} amps, and may be as low as 10^{-11} amps for some tubes.

After an initial aging by operating for about 50 hours, the zero should be extremely stable even at full sensitivity. Random variations of the zero may indicate leakage between the heater and cathode of the 9001 tubes. Such leakage may develop after many hundreds of hours of use and may be corrected by replacement of the tubes. It may be corrected permanently for any tubes by operating each heater of each input 9001 from a separate heater transformer winding (which may be of 5 volts, thus eliminating series resistances). If the cathode is now connected to one end of the heater, heater and winding will "float" at proper cathode potential, and insulation needs will be transferred to the transformer winding. Needless to say, nothing else should be operated from these heater windings, and the use of this system precludes operation of the heaters from a storage battery. The use of these separate heater transformer windings is standard practice in our professional equipment. We make our own transformers for this purpose from small standard heater transformers.

[EDITOR'S NOTE: The preceding chapter describes an amplifier for use with a stellar photoelectric photometer but does not describe the photometer itself or its uses. Photoelectric photometers are used by professional and amateur astronomers for making highly accurate measurements of light as faint as starlight, as in studying cepheid variable stars, long period variables, and eclipsing binaries. There are organized amateur programs for this work. The Kron photometer with which the Kron amplifier just described may be used has been described in detail in Harvard Circular 451, titled "The Construction and Use of a Photomultiplier Type of Photoelectric Photometer," written by the author of the preceding chapter as a publication for the Panel on Orbits of Eclipsing Variables, Commission 42 of the International Astronomical Union. It is available from the Harvard College Observatory, Cambridge 38, Mass.

A blueprint essential for building the optical column for the photometer described in the circular is obtainable inexpensively from the Chairman of the Commission, Professor Z. Kopal, Department of Astronomy, University of Manchester, Manchester, England. Circular 451 explains the principles of photoelectric devices with special reference to photoemissive cells, the amplification of photocurrents, the construction of a photometer (optical system, light receiver, voltage supply, galvanometer and sensitivity control), and observing technic—all from the practical point of view of the constructor.

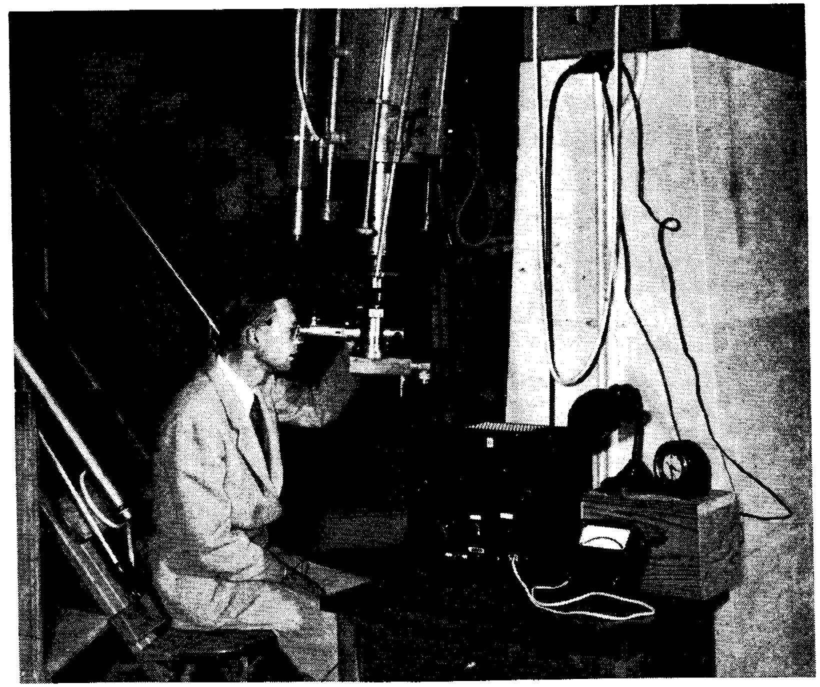
When Kron was asked just what general sort of work is done with the photometer, when coupled with amplifier described in the preceding chapter, and what it would be like, he gave informal replies from which the following notes have been made up.

"The photometer is like a glorified exposure meter; it is capable of making extremely accurate measurements of light as faint as starlight. The receiver could be attached to a telescope as small as a 6-inch reflector, and the operator can do photometric work on stars as faint as 7th magnitude with an accuracy rivaling the best that could be done before by anybody on stars of this brightness. With such an instrument there are no problems of photometry or color measurement that cannot be tackled, within the range of the instrument and telescope. An amateur owner would find it a tool for studying the variations of any type of variable star with utmost accuracy. The procedure consists of pointing the telescope at a variable star, allowing light to fall upon the receiver, and recording the resulting galvanometer deflection. Next, the light from a nearby constant comparison star is recorded in similar fashion, and the ratio of these two readings, converted to star magnitude difference, may be regarded as one observation. As this procedure is continued through the night, the observations are plotted on graph paper and a light-curve of the object (if of short period) being studied slowly grows before the observer's eye. In the hands of amateurs, the instrument has particular value to astronomy when events such as the outburst of novae come along or rare interesting phenomena such as an eclipse of Zeta Aurigae. There are other types of problem that might interest amateurs. The bright satellites of Jupiter rotate and their surface is spotted. Photometric observations may determine rotation periods and even tell something about the nature of the spots. Observations in two colors, done with glass or gelatin filters, might tell something about the color of the spots. Possibly the rotation period of Venus could be determined by the same method. I could go on and on in this vein.

"The photometer described in Circular 451 is different from previous designs in that any intelligent person could build one. It is no longer a laboratory instrument to be built and operated only by a person having highly specialized knowledge. On the other hand, it is not a toy; it is an expensive, complicated instrument and I would not advise anyone except a serious worker to attempt the construction and use of one. But I am sure that anyone capable of building one of the better amateurs' telescopes could build one of these photometers. Though creditable work can be done with a 6-inch reflector, I believe that ownership of a 12-inch telescope would more nearly justify the

cost of this instrument. I think that a photometer could be built for about $200 (1953) by anyone capable of making all but the 1P21, the galvanometer, and the batteries. If the same person should build an amplifier instead of using a galvanometer, he might save another $10 at least.

"The accompanying illustration shows the guiding eyepiece in profile (likewise the author.—*Ed.*) and a good side view of the light receiver containing



the 1P21 multiplier, attached to a 12-inch refractor. On the desk is an electric clock, used for determining the time of an observation, also for timing the individual exposures to the light, ten seconds each. The unfinished wooden box contains the batteries for furnishing the multiplier voltages. The large black box is an elaborate amplifier which can be used either with the multiplier photometer or, at much higher amplification, with a photocell type of photometer not shown. An amplifier designed for the multiplier alone would be smaller and simpler than the one shown. Readings of star brightness are made on the meter just below the desk lamp. One operator sits at the telescope as shown, and operates the photometer. A second operator sits at the desk and records the meter deflections and the time of each observation."

Gremlins that made war on one photoelectric photometer were discussed by John J. Ruiz, Dannemora, N. Y., in *Sky and Telescope* (Cambridge, Mass.) 1951, Dec., pp. 43–45. The gremlins are: less than high telescope rigidity; moisture and dew; dirt; extraneous light such as moonlight, auroras, and local sources. The American Association of Variable Star Observers has a program for the photoelectric observation of variables with electronic equipment and there is need for more observers. Those interested should address the AAVSO, in care of Harvard College Observatory, Cambridge, Mass., which will put them in touch with members who have had experience in this field.

An article on "Amateur Photometry," by William Baum of the Mt. Wilson and Palomar Observatories, in *The Griffith Observer* (Griffith Observatory, Los Angeles 27, Calif.) 1950, Nov., contains practical data on photoelectric photometry, also a bibliography.]

Notes on Lenses for Astronomical Photography

By Henry E. Paul

Since some amateurs in astronomical photography will obtain a stock model lens for their work, rather than make one, a few hints on the selection of a lens and plate size may save considerable wasted effort. It is, of course, to be understood that star photographs may be taken with almost any lens. However, a little discrimination and selection will make the difference between good and poor work. A good drive and guiding system are taken for granted and these subjects will not be a part of this discussion.

Focal Length: For general stellar photography focal lengths shorter than 5 inches do not give satisfactory star separation. The negatives are rather small for enlargement without grain or resolving power troubles. Focal lengths of from 6 to 12 inches serve splendidly. A lens of 10-inch focal length is a good choice for beginner and advanced worker alike. Special work will vary the above figures.

Clear Front Aperture: A clear front aperture of at least 1 inch should be chosen. The faintest point object, such as a star, that a lens will record is dependent on the linear diameter of the lens opening and not on the focal length. There are, of course, some practical limitations to the above statement. If the focal length of the lens is too long for the aperture (above $f/22$) diffraction will begin to cause trouble. If too short, ordinary lens aberrations will interfere. However, on extended objects such as nebulae, of greater than point size, the f-number, or ratio of focal length to aperture, is a factor of prime importance.[1] For ordinary lenses the front diameter is often accepted as a rough measure of effective clear aperture. To get the exact clear aperture, place a bright point-source of light, such as a flashlight bulb without the reflector, at the determined focus of the lens. Set the diaphram wide open. Shield off most of the light, excepting that going through the lens. Now place a piece of thin tissue paper over the front of the lens. The diameter of the illuminated disk on this tissue is the *effective clear aperture* of the lens. It is generally somewhat smaller than the distance across the front lens and, on extreme wide-angle lenses, may be only a fraction of the front lens diameter.

Speed, or f *Ratio:* Lenses slower than $f/8$ have small place in general work, while lenses faster than $f/3.5$ seldom give the definition required at the edges of a plate covering reasonable angles (ranging from 20° to 40°). An $f/4.5$ lens is an all-around compromise if it is used at its greatest aperture, as is most commonly the case. At the cost of longer exposure, stopping an $f/4.5$ lens to $f/5.6$ will considerably increase the definition and the illumination at the edge of the plate compared to the center. Some of the higher aperture lenses ($f/2.8$ to $f/3.5$), if stopped to $f/4.5$, will outperform the regular $f/4.5$ lenses in edge-of-plate definition and illumination. However, the increased

1 A most useful table of limiting magnitudes for various apertures and f-values appears in Dimitroff and Baker, "Telescopes and Accessories."

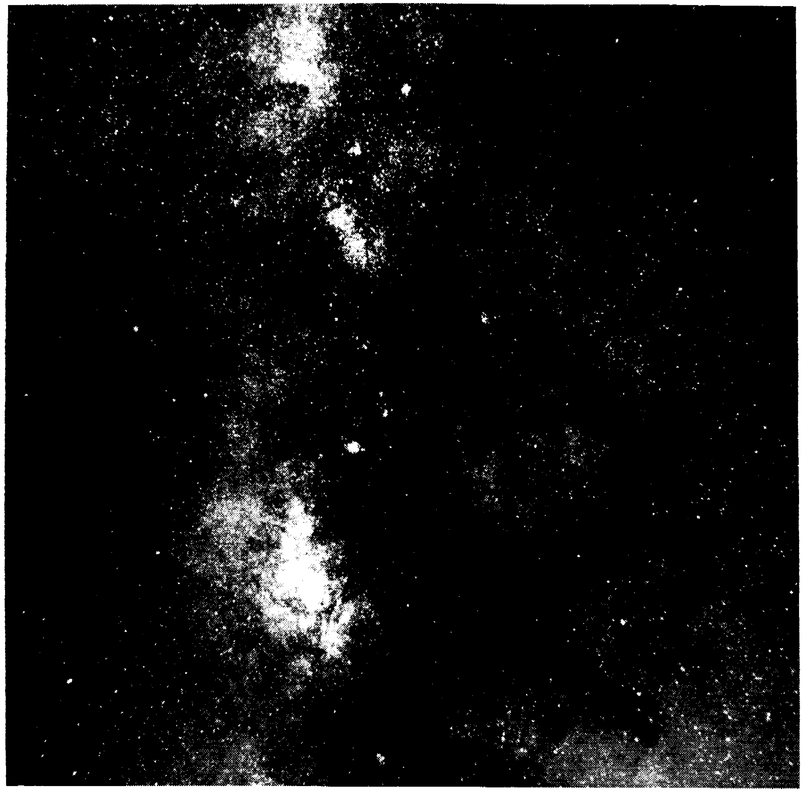


FIGURE 1

A Milky Way area about 25° square, centering on approximately R.A. 17^h 55^m, south declination 22°, photographed 1946, July 2, 12:45 A.M., using the camera shown in Figure 2 with 7-inch focus Eastman aerial Ektar f/2.5 lens stopped to f/4. Eastman 103aC spectrographic plate, no filter, 40-minute exposure. Developed 6 minutes at 68° with D-19 developer, printed on F-4 Kodabrome paper, developed with paper developer D-72, 1 part to 1½ parts water, enlarged from 3⅛-inch square to 7¾-inch square and reduced to present 4⅛-inch width for 120-screen half tone.

cost is a factor to consider here. I use an *f*/2.5 coated Eastman Aero Ektar 7-inch lens stopped to *f*/4.0 to cover a 25° square (approximately 3⅛ inches square on standard 3¼ by 4¼ plate). The definition is such that 3× enlargements are excellent. One of these, reduced and reproduced in half-tone with the inevitable loss in detail, is shown in Figure 1.

Size of Plate: While film may be used, plates are more satisfactory since they may be held rigidly in the focal plane. However, certain aerial cameras may work well since provision is made in them to hold films flat. Ordinary lenses *will not* give satisfactory astronomical definition over as large an angle as used in the cameras for which they were designed, hence one should buy lenses alone and build a simple box with plateholder. Such a fixed box is far better than most cameras because relative position between lens and plate, once adjusted, can be maintained. Such a camera is shown in Figure 2. A

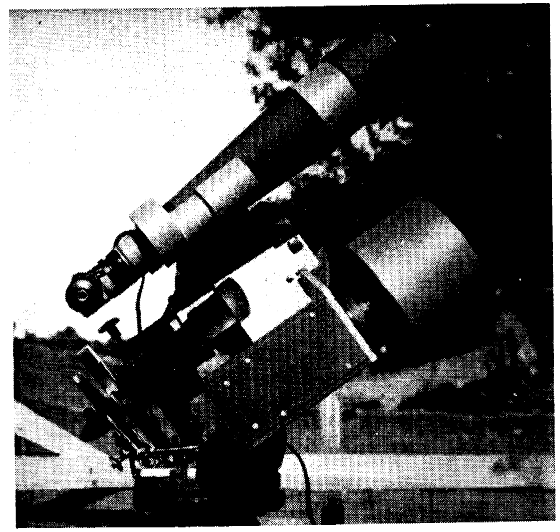


FIGURE 2

Astrographic camera, guide telescope, and drive which have proved very satisfactory for areas as 625 square degrees. Camera box is of Bakelite with aluminum right-angle corners. Solid ⅜-inch aluminum front serves as lens board and extends to form camera support. Lens screws into front for focusing and may be locked in position. The 6-inch diameter lens board at the front contains two 1-watt, 12,000-ohm, 110-volt radio resistors as an anti-dew unit. Two ⅛-inch thick flat bars ½-inch inside the rear on the narrow sides of the 3¼ by 4¼-inch opening support the plate. Before being fastened permanently these were adjusted as follows. The camera, without lens, was placed face down on a flat surface (probably plate glass would be suitable) and with the photographic plate in place a surface gage was used easily to bring all four corners equidistant from the reference or lens hood surface. Since the lens hood opening was threaded while the board was running true in a lathe, the lens axis was necessarily at right angles to the board and, after above adjustment was made, the plate was also at right angles to the lens axis. Only simple focusing by screwing the lens in or out along the axis now remained before perfect performance was obtained on stars. Fussing with tilting the plate holder about, to get uniform corner focus, was avoided. A spring system from a used film pack served inside the hinged back to hold the plate against its supports. The guide telescope and drive are described in the chapter on the Schmidt.

good size of plate to use with a lens may be safely assumed to be approximately one half that normally used. This would call for about $3\frac{1}{4}$ by $4\frac{1}{4}$ for 7 to 9-inch lenses and 4 by 5 for 10-inch or longer focal lengths. Unless special lenses are used it will not pay to go to larger than 4 by 5 plate size since the absolute lens corrections usually decrease with longer focal lengths, and even 20-inch lenses often fail to cover a 4 by 5 plate. A $2\frac{1}{4}$ by $3\frac{1}{4}$ plate with a 6-inch lens would be as small as one should conveniently go. This statement is made regardless of miniature camera fan opposition. I have taken many photographs with my 35 mm Contax $f/2.0$ stopped to $f/2.8$ and still prefer the larger cameras.

Lens Types: It is often said that the true way to know whether a lens will work well in astrophotography is to try it out. This is correct. The

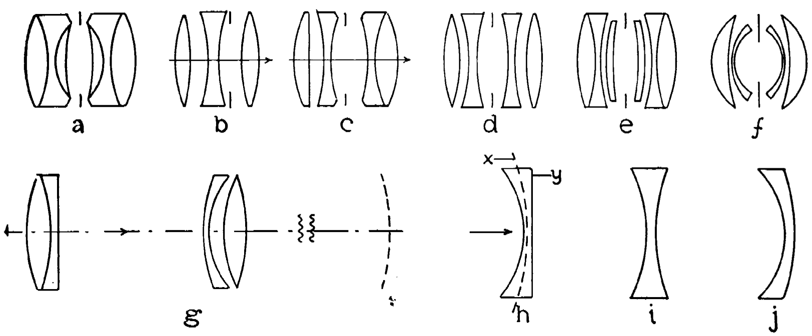


FIGURE 3

following suggestions are offered as an aid in first selection, particularly of used lenses. We will consider lens types *only* with respect to their suitability for astronomical photography. A high priced, high-quality lens of great aperture may prove unsuitable. Some of the most highly corrected lenses are too slow. Another fixed criterion is that we wish to cover a reasonably wide angle of view—say 10° to 20° each side of the axis—with the lens *wide open.* This requirement eliminates the ordinary $f/15$ refractor with its restricted angular field, discussions of which are easy to find elsewhere. In all lens diagrams presented light passes from the object on the left to the plate on the right. Classification is made according to the number of airspaced components or units in a lens. A component may consist of a single lens element or of two or more elements cemented together; that is, we may have a cemented doublet, triplet, quadruplet, or quintuplet compound component. For example, in Figure 3-c, we have a three-component lens, the first two components being single elements and the last component a cemented doublet. I have started with this three-component lens because it is from this type or class that specific lenses will be recommended for astronomical photography. This diagram represents the Tessar construction, which may be particularly well corrected

for parallel incoming light from astronomical objects. Specific lenses recommended are those of about $f/4.5$ aperture by Zeiss (Tessar), Eastman (Ektar) Schneider (Zenar), Bausch & Lomb (Tessar) and Ross-London (Express). The rear component of the last named lens is a cemented triplet. I am particularly partial to the Zeiss (Tessar) and Eastman (Ektar) lenses. Undoubtedly other good Tessar type lens are manufactured. New glasses and improved designs will bring new lenses to the market from time to time and these should be checked for possible improved performance. Used lenses may be damaged and therefore should be tested by you or the maker prior to purchase. A distant bright pinhole or star and a $\frac{1}{2}$ or $\frac{3}{4}$-inch good eyepiece properly used can give valuable initial information on a lens. A rough lens bench and ground glass test screen will furnish still more data.

So-called "triplets" (Cooke and others) consisting of three *single* elements airspaced, Figure 3-b, are in general not recommended except for smaller angles where high-speed or long-focus types may be used. Two common three-component lenses in which both the front and rear components are cemented doublets are the Voigtlanders Heliar and the Dallmayer Pentac. The former is of interest because it may be commonly found in the large sizes (up to 24-inch focus at $f/4.5$) and will cover a moderate angle. The latter may well be tried where a large-sized, high-speed lens ($f/2.9$ up to 12-inch focus, 4-inch front aperture) of medium angular coverage is desired.

Although of restricted use to the amateur astronomer, the two-component lenses should be considered. Only the symmetrical type, where the front and rear components are identical or very similar, will be discussed. A two-component lens commonly found in used camera shops is the rapid rectilinear, its front and back components being cemented doublets. It was manufactured most frequently at $f/8$ aperture and is of little interest, because of its slow speed and poor angular coverage. However, in focal lengths of 20 inches or more and clear front apertures above 3 inches these lenses may profitably be tried for small angle star photography alone—doubles, clusters, variables—where large clear aperture is desirable, for the sole reason that they may often be obtained for one tenth the cost of a corresponding anastigmat and may serve equally well for covering small (5° to 10°) total angles.

If we now consider the two-component lens where both components are cemented triplets, Figure 3-a, we arrive at the Goerz Dagor and related Voigtlander collinear types of construction. The Dagor is widely and justly accepted as a sharp lens for ordinary photography. At unit focus (1:1 copy work) oblique color error vanishes. At small stops very wide fields may be covered. However, for restricted astro use such two-component lenses recommended should be considered first. Cemented quadruplet two-component lenses, Zeiss Protar for example, and cemented quintuplet two-component lenses, Turner Reich for example, are somewhat slow and of small aperture. The commercial photographer nevertheless greatly values the 4- and 5-cemented lens components since each component may be used singly or in combination with another component of different focus. A set of three components may thus be used singly or in combination to give six different focal lengths!

In the four-component group, as shown in Figure 3-d, we have such lenses as the Cooke Aviar which was originally designed for aerial work. It might well be tried as the best of this type. The Goerz Dogmar is of similar construction. Incidentally, the famous Ross astrographic lenses made in aperture up to 20 inches and focal lengths up to 144 inches are of this type but undoubtedly special zonal corrections are made.

Where it is desirable to cover very wide angles (up to 90°) at moderate aperture and medium definition, as in meteor work, such lenses as Bausch & Lomb's Metrogon, Figure 3-f, working at $f/6.3$, and the slightly more complex (rear element replaced by two meniscus lenses) Ross $f/5.6$ wide-angle survey lens should be used. In using the Metrogon the writer has found that closing the diaphram only ½ stop (from $f/6.3$ to $f/8.0$) *very markedly* improved the star images at the edges of the wide field. Where the resulting light loss can be tolerated this procedure is recommended as giving more even exposure over the entire plate. Because of their deep curves these lenses are expensive to manufacture. For moderate angles (up to 70°) the Ross wide angle Xpress, Figure 3-e, working at $f/4.0$, should be tried. Bausch & Lomb aero lenses $f/4$ to $f/5$, Zeiss Orthometer $f/4.5$, and Hugo Meyer Double-Plasmat (made in large sizes) are of this similar rather well accepted design for moderate wide-angle work.

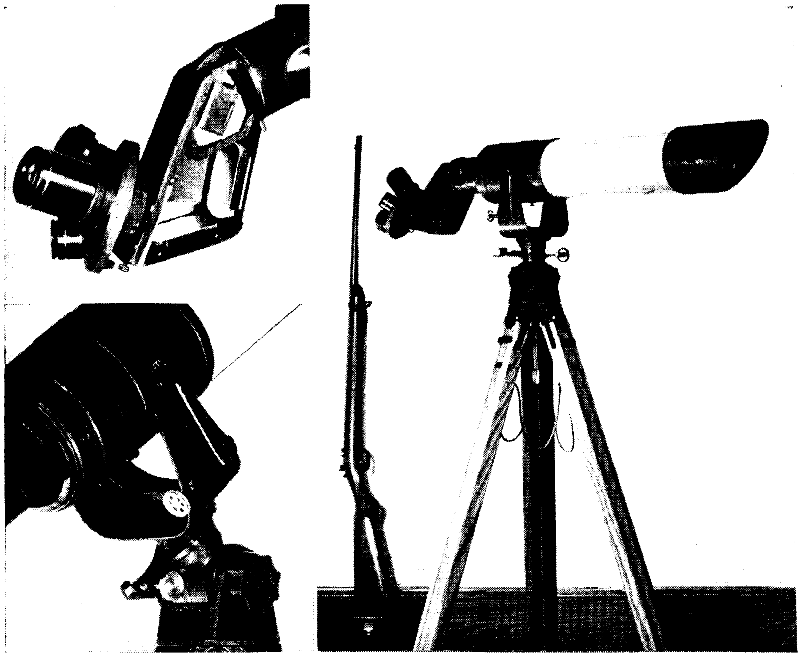
Lenses designed for aerial work present a group likely to be adaptable to our use since requirements are similar in some respects to those for astrographic lenses. Avoid those manufactured before 1918. Small amounts of residual aberrations in the fast ($f/2.5$) aerial lenses may necessitate some stopping down for adequate definition. Since many of these aerial lenses are designed for use with a yellow filter it would be best for greatest definition to use at least a light yellow filter, such as Eastman's Aero 1 or K1 with ordinary films or plates. Where blue light is not desired at all, as in avoiding stray moonlight, the Eastman Minus Blue (No. 12) filter should be used with a red-sensitive plate such as Eastman's 103aE Spectrographic Plate. Remember that a poor filter will wreck lens quality. I would recommend the use of the plain inexpensive gelatin film filters mounted permanently behind the lens out of harm's way. Little or no loss of definition would occur in the size of lens we are considering if the thin gelatin filter were mounted between the elements near the diaphram. Do not touch the gelatin filters while mounting.

No lens, regardless of design, will be good unless it is manufactured with the utmost care with regard to glass, surfaces, centering, mounting, etc. It is for this reason that the best lenses of reputable manufacturers are somewhat more expensive than many that are elsewhere offered, and yet these are the ones to be most seriously considered. However, price alone is no guarantee to be substituted for inadequate testing, especially in the case of used lenses. Certain other low-cost used lenses have proved by test to be of value in astronomy, particularly the large, old-style rapid portrait lenses of the type that gave sharp central focus. Beware of "soft focus" lenses.

Field Flatteners: The information that follows is not readily available or widely known, hence more than ordinary detail will be given. There exist in the used lens market many large obsolete lenses known as Petzval type portrait lenses which may be purchased for a song. These were manufactured by many firms and vary in speed from $f/3$ to $f/6$ and focal length from 10 to 40 inches. Such portrait lenses of 6-, 8-, and even 10-inch clear front aperture are known to exist. To an amateur desiring a large, fast, long-focus (about 20 inches is recommended) lens the very low *comparative* cost makes these a great temptation. A 20-inch $f/4.5$ Zeiss Tessar costs several hundred dollars. A device known as a field flattener may easily be made which, when combined with a true Petzval design lens, will yield a very good astrographic lens covering a field far greater than that of the original lens, which is very small—a 1-inch circle for a 20-inch lens. The field flattener idea is not new, having been suggested as early as 1866 by Piazzi-Smyth, according to R. Kingslake of Eastman Kodak. It has been used to increase the field of view of reflectors and in high speed astro lenses. The definition of the Petzval type of lens is excellent on the axis but falls off rapidly at a short distance away from the axis, mainly as a result of curvature of field. The Petzval design and curved field are shown in Figure 3-g. The very large separation between the front and back lens units is characteristic of the Petzval. This separation may sometimes be readjusted to the advantage of the off-axis definition and occasionally to avoid internal-reflexion ghost images. Be sure, however, that the lens you get actually is of the Petzval design, since Dallmeyer and others sometimes reversed the rear lens or modified the form to give larger fields *at the expense of sharp central definition.*

To give an idea of the extreme curvature of field in these lenses a ground glass was placed behind a 20-inch Petzval of 4-inch front aperture and a distant star (a distant street lamp would suffice) was focused as a point on the axis in the center of a 4 by 4-inch ground glass square placed at right angles to the axis. The lens was now swung until the star image moved on the ground glass to a location 2 inches from the center, or axis. Under a 1-inch magnifier the star image now appeared as a large circular spot of considerable diameter. If the ground glass was now moved forward—in the case just described a full tenth of an inch—the original fine definition was almost totally regained; showing that there was great curvature of field toward the lens. A trace of astigmatism remained. This curvature may be measured, after sharp axial focus has been obtained, merely by measuring the distance one must move the ground glass forward to obtain a good image at a measured distance away from the axis—say 2 inches off axis if a 4-inch circle on a 4 by 4 plate is planned. Experience tells us we can assume this curve to be a section of a sphere over small angles of 10° to 20°.

Let us make a field flattener for the case above, where at 2 inches off axis the distance the ground glass plate must be moved forward to obtain sharpest possible focus is 0.1 inch. A field flattener using a glass of index 1.5 would appear in cross-section as in Figure 3-h. It would be 4 inches in diameter and have a flat back. The edge thickness would be 0.3 inch *plus* the allowed center thickness. The difference between center and edge thickness (0.3 inch in this case) is fairly critical. The center thickness need not be exact but



A terrestrial and astronomical refractor that performs well under varied conditions from rifle spotting to solar observation. The 4½-inch airspaced astronomical quality achromat of 31½-inch focus is used with three eyepieces: a 1.25-inch six-element coated Erfle wide field (25×) which covers a 3° field; a 0.9-inch orthoscopic (35×); and a 0.5-inch orthoscopic (63×). An Amici roof prism of 1.375-inch clear aperture is placed 9 inches inside focus (shown directly behind the focusing knob, top left-hand illustration) turns the light downward 90° and the image from right to left. The roof angle must be good, 90° ± 1 second, otherwise doubling will occur at high powers. The 1.5 by 2.5-inch, ⅛ wave aluminized flats then receive the light at an angle of 33.75° to their surfaces (56.25° to their normals) to complete erection of the image. The light enters the eyepiece at an angle of 45° to the axis of the telescope. This erecting system has three advantages: the 45° tilt of the eyepiece is ideal for ease on the neck in both terrestrial and astronomical use; it affords convenient sighting along the top of the tube from a point near the eyepiece; and it permits replacement of the flat under the prism with a solar wedge in a mounting open at the bottom to allow 90 percent of the light, and heat, of the sun to escape downward.

The triple eyepiece turret (designed by Clayton Howe, Decatur, Mich.—Sci. Am., *1940, Nov.) adds much to the pure pleasure of use. It may be swung about on its base to accommodate either eye. A filter holder slides under the turret.*

The tube is of Synthane (Micarta, etc.) and major parts are of 24ST aluminum. The yoke is fabricated of ⅛-inch stock with a ¼-inch band-sawed web inserted with screws. This short yoke, chosen for sturdiness, as used in the alt-azimith position, is shown in the large photograph. It affords a 45° tilt above and below the horizon, the latter important for terrestial use. The entire vertical axis unit may be tilted back against a latitude stop (lower, left-hand illustration) to become the polar axis of an equatorial mounting operating to N.45°. For angles farther north in the sky the entire unit may be swung around on the tripod head and used on sky areas in altazimuth fashion.

At full aperture, views are excellent on nebulae, star clouds, and on rifle targets on dull days. Aperture stops f/11 to f/16 on the objective aid in reducing excess light from the moon and sun and in reducing residual secondary spectrum common to short focal ratio achromats.

Optics for this instrument were "collected," not made; in fact, nothing was built that could be adapted without loss of performance. Nevertheless the instrument had to be designed and a major portion constructed. It is believed that in producing similar instruments other amateurs will find true pleasure through following their own ideas of design, materials and execution.—Henry Paul.

would best be from 0.05 to 0.15 inch for a corrector of this size. Not having to work for exact thickness eases the work a bit. The dotted curve x represents the curved field of the Petzval lens before the plate was introduced. With the plate in place the focus moves to y, where it is now practically flat and fits a photographic plate placed there. This lens might to great advantage receive non-reflecting coatings, as well as all other lenses in the Petzval system. Ghost image trouble will thus be avoided. For a glass of about 1.5 index (ordinary crown) the edge thickness is thus about three times the measured correction desired at this point, plus whatever extra is allowed for central thickness. A corrector made after no more calculations than this will remarkably improve the field. To obtain more exact edge thickness the measured correction desired at this point should be multiplied by $n/(n-1)$ and the center thickness be added. One could also calculate the radius of curvature of the Petzval lens field from test data and divide this by $n/(n-1)$ to get the radius of the corrector curve, assuming a flat back. The value obtained for the corrector radius should be a little more than one third the field curvature radius, for ordinary crown glass.

Assuming the same edge and center thickness, other corrector shapes could be used. I have used the form shown in Figure 3-i, with two thirds of the curve on the front and one third on the back as perhaps giving a little better overall correction. Form j has been used on wide field lenses of extreme aperture.

To obtain the best corrections the field flatteners described should be placed as close to the plate as possible. If a stock crown glass plano-concave lens is tried, first choose one with a radius one third (or a focus two thirds) of the focal length of the Petzval lens. If the focal length is not indicated on the Petzval lens, place an object in front of the lens along the axis at such a distance that the image formed is identical with the object in size. The distance between the object and image, divided by 4, gives the focal length of the lens. It is difficult to estimate or guesstimate the focal length of these lenses because of the wide central separation.

My 20-inch $f/5$ Petzval tests very well over a 4-inch circle with the corrector in place. Previously, only the central 1-inch circle was usable. Thus there is a gain in usable area of about 16 times. My initial investment of $10 and a little work produced an astrographic lens that performs better than ordinary photographic lenses of similar size and selling up to $500.

Mr. R. Bourne, of Hartford, Connecticut, has also constructed a field flattener for use in conjunction with a Petzval lens, and I was permitted to see some fine nebular and star-cloud photographs he had taken with this unit. The excellent definition attested to a good lens system—and to good guiding.

For those who wish more detail from books I would recommend pages 10 to 67 of Henney and Dudley, "Handbook of Photography," as being excellent in showing types of lenses and in naming makers with the lists of lenses they make. Two books of merit are Allen R. Greenleaf, "Photographic Optics" (The Macmillan Co., New York) and St. Clair, "Photographic Lenses and Shutters" (Crown Publishers, New York). Very good review papers by Prof. R. Kingslake appeared in *Journal of the Optical Society of America* (Lancaster, Pa.) Volume 32, pages 129–134 (1942, March), in Volume 36, pages 251–255 (1946, May), and in Volume 37, pages 1–9 (1947, Jan.). On wide-angle lens design, see a paper in *Journal of Applied Physics* (Lancaster, Pa.) Volume 11, pages 56–59 (1940, Jan.). Of exceptional merit for broad coverage in a compact and readable article is "The Assessment of Lenses," by A. Cox and H. Martin which appeared in *The Journal of Scientific Instruments,* London, Volume 22, pages 5–12 (1945, Jan.). Merte-Richter-von Rohr, "Das Photographische Objectiv," is in German but the lens data near the back of the book are the same as in English. See also Arthur Cox, "Optics, the Technique of Definition," (Focal Press, Locust Valley, N. Y.) Rudolf Kingslake, "Lenses in Photography," (Garden City Books, Garden City, N. Y.), E. W. H. Selwyn, "Photography in Astronomy" (Eastman Kodak Company, Rochester, N. Y.).

Plates and Films for Astronomical Photography

By Henry E. Paul

Since astronomical photography is a highly specialized branch of photography it is logical that the selection of proper photosensitive emulsions will lead to superior photographs as well as a considerable saving of time and labor.

Among the important properties of emulsions on plates or films are the following which are of particular interest to the astronomer.

(a) Sensitivity to light, or "speed" of the film or plate *at the light intensity at which it will be used.*

(b) Inherent contrast of the film or plate.

(c) Graininess and resolving power.

(d) Color sensitivity.

(e) Miscellaneous properties.

For those who are not interested in theory, to be discussed, a specific list of recommended films is included at the end of this chapter. From these a selection may be made and, if desired, work started at once. For more complete information it is strongly recommended that the reader address the Research Laboratories of the Eastman Kodak Company at Rochester, N. Y., and request the free booklet "Photographic Plates for Scientific and Technical Uses."

Speed or Sensitivity of Emulsion: Most of us know that films or plates vary greatly in speed, or sensitivity to light. For snapshots in dim light we choose a "high speed Pan" film while, in copying a line drawing where we are not in a hurry, we use a slow-speed copy film which has better properties for this work.

The astronomical photographer is intensely interested in the speed of his plates or films because this regulates the time—often in hours—during which he must patiently guide his telescope. If normally a two-hour exposure is required with his telescope and ordinary plate to catch a dim object, he may be sure that a special plate of four times this speed, which will cut his guiding time to 30 minutes, will be more than welcome. A poor selection of plates or films may lead to much greater differences than this. In ordinary photography the speed of films is measured by standard systems of rating, Weston speed being the most common. It therefore will be used here even though new systems are in the making. For ordinary photographic use a film of Weston rating 100 is twice as fast as one of 50 and four times as fast as one of 25; etc.

We astronomers, of course, have to be different and often work at low light intensities where the Weston or typical ratings, while of broad general value, are not a reliable index of speed. This is caused primarily by failure of the Reciprocity Law at low light intensities. We are all familiar with this law under the statement, "for half the light, give twice the exposure." This law may also be stated in a different manner. The density or completeness of exposure of our films is dependent on two factors—intensity of light and time of exposure. Hence if we have half as much light we give twice the exposure time and get the same density, or completeness, of image. This law holds for ordinary photographic light intensities with exposures as long as one full second. For *considerably* longer exposures, as used in astronomical photography, this is not, however, the case. As the light falling on the plate becomes dimmer and dimmer the exposures become disproportionately longer; and so, where we calculate that a ten-minute exposure will suffice, we may find that an hour's exposure is required. This phenomenon of slow response of films to fainter and fainter light comes under the heading of "Reciprocity Law Failure." A very important fact for the beginner to remember is that, while all films and plates are subject to this handicap, some are far more affected than others, and that general speed ratings, such as Weston, are not a reliable index of this failure. The properties of films responsible for this failure are not known. Trial alone will answer this question and tell you the effectiveness of films or plates on long exposures (one minute or more)—either your trial or someone else's. A comforting thought to those working on cold winter nights is the uncommon fact that lowering of temperature can increase film speed to light of low intensity.

To illustrate the importance of this factor I will use a concrete example. I found that Eastman Super XX sheet film (Weston 100) and Eastman Super Panchro Press Sports type sheet film (Weston 250), when subjected to a low light intensity requiring 30 minutes for a faint but usable image, gave results far different from the Weston ratings indicated. The Super XX actually produced an image twice as dense as the other film and was *twice as fast* at this light intensity and exposure as a film that rated 2½ times its own speed by the systems regularly used for ordinary photography. In fact, it is sometimes possible, when photographing by blue light of stars over periods of *many hours,* for a relatively slow contrast process film (such as Eastman Contrast Process Pan film—Weston approx. 16) to be comparatively faster than the highest Weston-rated panchromatic films. Further, the Super XX film mentioned has much finer grain and will stand better enlargements than the fast "press" film.

No published data on films commonly sold are available to the average amateur but from the above he should see that a few types may profitably be tried before he makes many long exposures. I suggest trying films in the Weston rating range of 50 to 100 (so-called "Daylight Rating"), as the best group from which to choose, and a specific preference is given later.

Graininess and Resolving Power: Resolving power may be regarded merely as the ability of a film to catch fine detail. It is usually expressed as the ability of film to resolve or record a certain number of fine lines per millimeter ($1/25$ inch) under fixed conditions. Most film will resolve about 40 to 60 lines per millimeter, or at least 1000 lines per inch. This figure is worth remembering. Since at viewing distance (10 inches) a picture having a fineness of detail of about 250 lines per inch appears good and sharp, we now see that four or five times enlargement is about our limit if we expect sharp prints. Those of us who like sharp 8 by 10 glossy prints of our star photographs should build instruments to produce *at least* 2 by 2 negatives—or work from film sections no smaller than this.

Resolving power depends on choice of film, development, and exposure. Unfortunately, fine-grain films are often too slow for astro use. Fine-grain developers also greatly reduce film speed, and on exposure we usually want all the speed we can get. As usual, a compromise is best.

We have just noted that medium-speed films (by Weston rating) may often be the fastest for astro use. These also have good resolving power—about 60 lines per millimeter. They should be developed with a normal rapid developer. I have found the D-19 developer recommended by Eastman Kodak to be best for their plates, as well as excellent for films. It is fast, gives good emulsion speed, and produces good contrast. Almost equally good results may be obtained by using the more common D-72 developer diluted by one part water to one part developer (as used by news photographers). About 7 minutes at 70°F is a good average time for development.

There are, of course, useful exceptions to the above. For example, in lunar photography at focus (plenty of light there) I prefer Eastman "Micro-File" 35 mm film (resolving power 135 lines per millimeter) and development with D-76 for 10 minutes at 70°F (or twice that recommended for this developer with this film to obtain proper contrast). The resultant negatives have just the right contrast for printing on an F-3 glossy Kodabrome paper. Thus a 16-inch diameter lunar photograph (frontispiece), crisply sharp for wall hanging, has been made from an approximately 0.8-inch image taken directly at the

focus of a 10 inch reflector of 90-inch focal length. Exposure times run in the range of ⅕ second for first quarter moon. Thus no drive was required.

Planetary photographs may also be made in this manner. Mars, however, may well be excluded. On one occasion when Mars was near the earth and formed an image on the film about $1/100$ inch in diameter (Micro-File film will resolve 30 lines over this width) a photograph was taken at a focal length of 90 inches, showing the polar cap—but it took a high-power magnifier to see it on the film. On another occasion, when photographing a very distant bright nebula with a 10-inch $f/2.0$ Schmidt camera, resolving power and fineness of grain proved all-important. The usual exposure of 10 minutes (before film

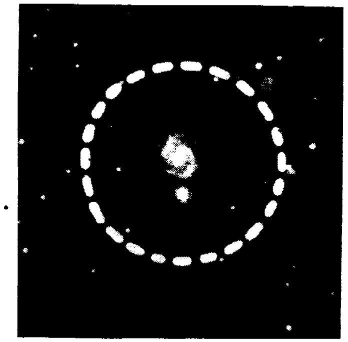


FIGURE 1

fogging sets in at this great lens aperture) was tripled and the extremely fine-grain developer Edwal-20 was used on the special 103aE Eastman spectrographic emulsion. The resultant photograph of M51—the Whirlpool Nebula—is reproduced (Figure 1) though the half-tone process does it no good. The dotted circle encloses an area having the diameter of the head of a pin on the negative, enlarged 16 diameters. This distant galaxy is usually considered out of range of the average amateur's camera but here it is. Later work established that *ordinary* E. K. Contrast Process Pan sheet film, developed in D-19, under identical conditions of long exposure, gave even better definition on this object.

The above examples serve to show special cases and applications.

Color Sensitivity: Films vary in sensitivity to different colors. For example, panchromatic film is sensitive to red (plus all other colors), while non-panchromatic and orthochromatic film will not record red. With ordinary lenses ranging up to 10-inch focal length the question of color sensitivity is not too important as far as image definition is concerned. Almost any film may be used. In photographing at the focus of a reflector, film of any color sensitivity may be used. We must, however, be more careful with the conventional $f/15$ refractor. The refractor brings green light and some yellow light to a sharp focus but does not bring blue or deep red light to the same focus. These colors therefore must be eliminated. Extremely red-sensitive films or plates should be avoided and a yellow filter used to cut out the blue light. We may now expect sharp pictures with our regular refractor. Specific recommendations will be given later. The color sensitivity of a film may be used for picking out stars of similar colors. A red-sensitive film (usually used with a yellow filter to cut out blue light to which all films are sensitive) can be used to make the red stars stand out among their neighbors. Conversely, a film which is most sensitive to blue light alone may be used to photograph objects of blue color. The best all-around film is an ordinary medium speed "pan" film (used with a yellow filter on refractors).

Miscellaneous Properties: All plates used must have antihalation backing. Orders for special plates from Eastman must be so marked. Practically all films are backed when received. Some light always gets through the emulsion on a film or plate and, unless stopped by a special (antihalation) backing on the emulsion glass or film base, it will return to the rear of the sensitive emulsion, forming an undesirable ring. This is positively so in stellar photography in the case of bright stars.

Films may lose speed and fog (turn grey in developing) on prolonged storage. Keep all films as cool as possible and dry. Do not store in a damp basement—better at room temperature, but dry, than cool but wet. An electric refrigerator, if kept properly defrosted and free from uncovered liquids, is ideal. Film may, however, be stored in sealed tin containers if there is doubt about the dryness of the refrigerator. This is particularly important when storing the so-called "a" emulsion Eastman plates which are very sensitive to light of low intensities. These will soon fog in warm storage.

In most astro work at low light intensity development may profitably be carried on 50 percent longer than is commonly recommended for a particular film and developer, since a clearer image and better contrast are obtained in this manner. Fine-grain developers always reduce film speed, particularly in underexposed films, and have no place in astronomy except for special use. D-76 may, however, be considered a normal developer; it does not lose speed but produces low contrast on normal films.

Do not prolong fixing time, since faint objects may be lost by action of the fixer, particularly if the fixer is not fresh.

Don't enlarge more than four or five times and expect pinpoint images with the enlargement held at the end of the nose unless slow, fine-grained, high resolving power films are used with *long* exposures.

Unless special devices are used to hold film flat (as in the Schmidt camera and aerial cameras) it should not be used, as not all parts of the film will be at the focal plane. In this respect film packs are very poor. An exception is the case of the small 35 mm precision film cameras which, by a pressure plate, do hold film precisely flat. For larger work plates are by far the best. A lens fastened by three push-pull screw arrangements at 120° about the flange to a home-made box fitted to take a plate in a fixed position is ideal.

You can compare the speeds of film for use in your star camera by using your photographic dark room. Just put a standard 7½-watt bulb, about 1 inch in diameter, in your enlarger and a piece of fogged film or paper of medium thickness in the negative holder. If after five minutes of dark adaptation you can barely read your watch on the enlarging base board, you have a starting point for making film speed comparison. A little trial and error will enable you to adjust the light by means of lens stops, etc., so that after about 30 minutes or one hour exposure (which is about the mean of photo times many amateurs will use) you will get a medium or low fogging on the exposed portion of a film on the base board. Now you can compare the sensitivity of a whole series at one test—marking them by clipping corners or by other means. I use a home-made density wedge to supply a little more information on contrast of film, since this too is important. The final test is still on the object you plan to photograph.

Specific Recommendations: The views expressed below are not meant to be dogmatic. They are given to help the beginner. No claim is made that film manufacturers other than those named may not have equally good films. However, many films were tested in order to supply these data.

For general work with reflectors on nebulae, galaxies, or faint stars, Eastman spectrographic *antihalation backed* plate 103aE is recommended. For use with lenses up to 10 or 20-inch focal length antihalation backed 103aC spectroscope plates are recommended. For long focus refractors, antihalation backed spectrographic 103aB plates with Wratten "minus blue" filter No. 12 are recommended for all work. The above plates should be developed about 7 minutes at 70°F in D-19 (or one part D-72 solution plus one part water).

If the above emulsions were obtainable on backed films they would be ideal. Unfortunately, this is not the case unless the user is willing to pay several hundred dollars for a large manufacturing run. Recommendations are as follows:

For dim objects such as nebulae, galaxies and faint stars, where fastest possible film is desired for medium length exposures with ordinary lenses, Eastman Super XX cut film performs well. Eastman Plus X roll film or 35 mm film are good in the roll and 35 mm film classes.

For general star work alone, where good contrast is particularly desirable, perhaps at slight speed loss on dim stars, Super Pancro-Press Type B cut film seems best. EK Contrast Process Pan sheet film can be used to an advantage in contrast and definition with very long exposures or with large aperture (at least $f/2.0$) lenses. The same development as for plates is recommended. Alternatively, the manufacturers' recommendations may be followed, with about 50 percent excess development time. Emulsions often vary from one lot to another. These variations are not, however, as great as among different emulsions. It is well to remember that for long exposures different films having the same rating, whether from the same or different manufacturers, vary greatly in speed for astro use—hence the specific listings given.

For lunar work Eastman Micro-File 35 mm film is recommended for photographs taken directly at focus. Were I to try cut film I should first try Eastman Contrast Process Panchromatic films, develop with D-76 for about 10 minutes at 70°F.

Order special plates from your E. K. dealer and give him the specific requirements. These require from a week to 30 days or more for delivery. I have been given to understand that this specific service is operated as a convenience and at a loss, so patience is suggested.

Schmidt Camera Notes

By Henry E. Paul

The purpose of this chapter is to present information gained from the construction and use of a Schmidt camera. A reasonable attempt will be made to confine comment to points not seen covered in readily accessible literature or else to enlarge upon details of material treated elsewhere.

A first and important consideration often overlooked in discussions is the question of size. A common procedure is to make a Schmidt camera and then wish you had chosen different specifications with regard to aperture, *f*-value, mirror diameter, correcting plate diameter, film holder size, focal length, etc. Many of these factors vary with the specialized use to which the camera may be put. I would like to recommend specifications of a Schmidt camera for *general* use and then suggest in which directions one should move for special uses.

Focal Length: Since focal length alone in general fixes the image size and separation of the objects being photographed (exception: size of star images) let us consider the question of selection of focal length. The Schmidt camera is not a true wide-angle (60° or more) camera, most commonly being limited to 20° or less of total angle, with 10° to 15° even more frequent. Therefore, since we cannot expect to photograph an entire segment of the Milky Way at one time, we shall be interested in detail in small sections of it—special objects such as the Andromeda Nebula, Orion Nebula, the Trifid, Lagoon, etc. To obtain detail on these objects of small angular width we must choose a focal length long enough to achieve resolution on the film used. My experience suggests that, after considering all factors involved, such as grain size, the desire to make practical sized enlargements, etc., a focal length of at least 10 inches should be chosen. For very high speed (*f*/1.0), wide angle (20° +) Schmidts used in meteor work, search work, etc., focal lengths of 5 to 10 inches are useful. For general use focal lengths of 10 to 20 inches are useful. For general use, focal lengths of 10 to 20 inches are needed in order to give fine detail on the many interesting objects within reach of the amateur's instruments.

Nothing in the above should be taken as a recommendation to build a huge "white elephant." It would be better to make a *good* moderate sized instrument. One soon tires of moving a heavy instrument around, and this mental or physical handicap soon condemns it to collecting dust. This is why the range of 10 to 20 inches in focal length is recommended.

The f-Number, or Speed: On objects that cover angles considerably greater than single stars, such as the nebulae or distant galaxies, the ratio of the focal length to lens diameter, *f* number, or *f* value, is important in governing exposure time. Sometimes the first thought of the would-be Schmidt maker is to build the fastest camera possible, hence he reads about *f*/0.6 and *f*/1 instruments with great anticipation. He cannot understand how the old "hardheads" can even consider an *f*/3 slow-speed instrument (as this is written I am designing an *f*/4 camera of 8-inch aperture and 32-inch focus). While these fast cameras cover wide angles, the definition at the edge of the field may fall below that required for the enlargement to 3 to 6 times usually desired. The steep curve of the film holder may also cause trouble in obtaining film conformation. For the minimum focal length of 10 inches recommended one must make a big, clumsy instrument. It is true that exposures with such cameras may be exquisitely short but, with modern emulsions, exposures are short enough on an $f/2$ instrument. If the old-timers could expose plates five to ten hours the younger generations should find enough patience for the maximum of 10 to 30 minutes required by an $f/2$. It is probably a bit unkind to remind the $f/1$ worshipper that, if he wishes a 10-inch focal length in order to obtain satisfactory sized images of nebulae and galaxies, he will have to make a 10-inch clear-aperture correcting plate and, theoretically, about a 16-inch mirror —in several respects a rather inconvenient size.

The most important factor of all with regard to the f value is the rapid increase of film fogging due to stray light, particularly near large cities, in the faster instruments. Sooner or later we shall be interested in catching faint single stars. The dimmest stars (limiting magnitude) that we can photograph because of this night sky light will vary with the f value of the instrument. Dimitroff and Baker, in "Telescopes and Accessories," state that an $f/2$ camera will catch stars more than one magnitude fainter than an $f/1$, and that an $f/5$ will reach stars about three magnitudes fainter than an $f/1$.

In general, then, $f/2$ *is a good compromise for general use* and has proved so by trial. Certainly $f/1.5$ to $f/2.8$ is a good range within which to work.[1]

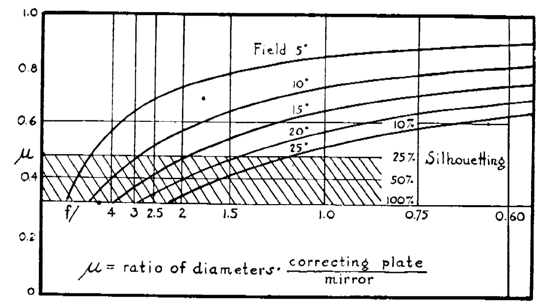
Vignetting: This term generally is used to designate a loss of light at some part of the photographic film, usually at the edge, due to design factors. In the Schmidt camera, to avoid loss of light at the edge of the field, the mirror diameter should be equal to the clear diameter of the correcting plate plus twice the diameter of the film holder. This subject was well covered in an article by Professor Charles H. Smiley, in *Popular Astronomy*, 1940, April, from which the following is quoted by kind permission of publisher and author.

"Persons sometimes wish to prepare specifications for a Schmidt camera to serve a particular purpose, or even to construct such a camera, without studying in great detail the mathematical theory. For the convenience of such persons, the graphical relations between nominal focal ratio, the ratio of diameters—correcting plate to mirror—and the diameter of uniformly illuminated field has been prepared in the accompanying figure. No great originality is claimed here; all the relations exhibited were included in Strömgren's article (Strömgren, B. "Das Schmidtsche Spiegeltelescop." *Viert. d. Astron. Gesellschaft,* 70, 65–86, 1935) in the form of mathematical equations. The abscissa is the nominal focal ratio, that is, the ratio of the diameter of the

1 [EDITOR'S NOTE: William A. Mason, a Lorain, Ohio amateur, writes as follows: "I built two 5-inch $f/1.1$ Schmidts but if building more Schmidts I would certainly *not* make them $f/1.1$. They are too fast. Around $f/2.5$ to $f/3$ is fast enough. Using slow film (Process) with the $f/1.1$ I get all the sky fog I want with 2½–3 minutes' exposure. With Panatomic-X (Weston 50) film 30 seconds gives plenty of fog. All this on clear moonless nights. Incidentally, collimation, which took nearly six months to perfect, was the most difficult part of the job."]

correcting plate to the focal length of the camera. The ordinate is μ, the ratio of diameters, correcting plate to mirror. On this set of axes, five curves are drawn, corresponding to fields 5°, 10°, 15°, 20° and 25° in diameter. Here the fields are such that all parts are evenly illuminated with the exception that cameras with constants placing them in the cross-ruled area have fields which diminish in illumination near the center, or in other words, the field of uniform illumination for cameras in the cross-ruled area is annular and of the diameter indicated. The percentages of silhouetting indicated for certain values of μ are those calculated for the center of the field.

"In the accompanying figure," Professor Smiley continues, "it is seen that, as the correcting plate is made larger and larger in comparison with the mirror,



the uniformly illuminated field becomes smaller and smaller, until the point is reached at which the correcting plate is the same size as the mirror ($\mu = 1$) and the field of uniform illumination vanishes.

"As an example of the use of the chart, suppose one wishes to use a correcting plate of 24-inch aperture with a mirror of 33-inch diameter to make a Schmidt camera of focal ratio $f/3.5$. μ will then be approximately 0.73 and it is seen that the field of uniform illumination will be about 3° – 4° in diameter while less than 10 percent of the incident light will be lost due to silhouetting.

"It can be seen at once that in a camera of focal ratio $f/1$, designed to cover 20°, the silhouetting must necessarily be greater than 10 percent. Likewise one notes that a field of uniform illumination of 20° is not possible with an $f/1.5$ camera."

A point not covered by Professor Smiley is the following. In most classes of scientific astronomical Schmidt camera photography no loss of light at the edge of the field can be tolerated, hence the large mirror required in relation to size of correcting lens. However, in amateur work, which is most often directed to obtaining interesting pictorial photographs, considerable loss of light can be tolerated at the edge of the field—even up to 30 percent. In the ordinary photographic camera—your own, for example—covering a 50° angle, there is a 30-percent light loss in the corners of the picture, because the round aperture is projected as an ellipse at the corners of the field. Loss of this proportion of light at the edge of the field is not particularly disturbing. Therefore we may make our film holders a little larger than the maximum of one third of the correcting plate's diameter often advocated, and our mirrors may be somewhat smaller than called for. We may thus cover a larger field at a greater aperture for a fixed tube and mirror size and have larger instrument performance at little apparent loss in our resultant photographs.

What would be the optimum specifications of a Schmidt for general use? I would choose an $f/2$ instrument with correcting plate of 7-inch clear aperture (worked down from an 8-inch plate), using a 10-inch mirror and a 2.5-inch diameter film holder covering 10°. Good quality films from such an instrument will enlarge five times, to 8 by 10 inches (or to a 12½-inch circle) with sharp detail. The 14-inch focal length will give excellent image size and star separation. The instrument is of a size convenient to shift about. To grind the 10-inch mirror is a big enough job; 12 inches is a bit heavy to provide much fun. The 8-inch correcting plate disk may be worked on a handy size standard 8-inch Pyrex flat to be described later.

Construction: The following notes are based on a 5-inch aperture $f/2$ Schmidt camera I designed and built. While somewhat smaller than the optimum size recommended, it is highly portable and its 1.75-inch diameter films fit my precision miniature enlarger using a Contax lens for enlarging. I deliberately chose to build the highest possible precision into this relatively small instrument and enlarge the negatives from it. The inherent grain size of usable films limits such a reduction in instrument size. The slightly larger instrument recommended above gives a little more leeway on constructional tolerances. The notes given are intended only to supplement data already available and to offer suggestions on methods as a result of experience.

Mirror: This is an 8-inch of Pyrex, hogged out with full sized tool and vertical spindle pin-bar type of machine running at about 100 rpm. This machine was described in *Scientific American,* 1945, December. Household gelatin or drugstore "Metamucil" was used to thicken the 80 Carbo grinding mix as an aid in keeping it on the work. Mirrors used on $f/1.5$ or faster cameras, where much glass must be removed, may be ground more rapidly if a cast-iron convex tool or a ring-shaped tool is substituted for glass as tool material, but a well powered machine works fairly fast with a full sized glass tool used with generous overhang at the start. One then does not have to fuss later in making special glass fining tools, since iron tools tend to scratch in fine grinding. Plenty of 80 Carbo (perhaps ten pounds) should be at hand and should be used freely. The unused parts may be reclaimed from the pan by washing, a simple operation. With the power-driven spindle referred to only Carbo 80,220,600 and a fine emery are required, since grinding takes place rapidly.

Polishing is done in the usual manner. Figuring was done on the vertical spindle with varied sizes of small tools, including the thumb.

Foucault testing of deep spheres presents two difficulties. The line of sight must be on the same axis as the test light and the test light must spread its illumination at a wide angle so that the mirror will be *fully* illuminated. We are, of course, making a sphere and we therefore test for uniform greying of

surface before cut-off. Those who have made paraboloids will find the sphere a welcome simplification in figuring.

I have used the following testing method and found it very convenient, even though it required as accessories a microscope objective (easily obtained 16 mm objective) and a thin microscope slide cover glass. The microscope must emit a cone of light having wide enough angle to cover the entire mirror. An ordinary 16 mm N.A. 0.25 objective will emit a 29° cone of light and will accommodate mirrors of $f/2.0$ cameras and slower speeds. For mirrors of

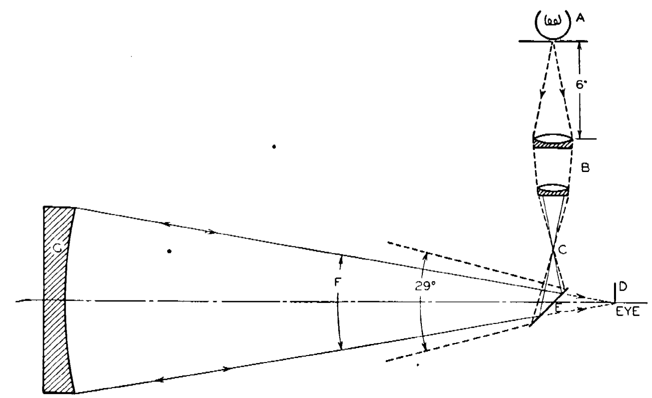


FIGURE 1

Set-up for testing deep spheres. A: Small lamp bulb and ground glass with 0.01 to 0.02-inch hole. B: 16 mm 0.25 microscope objective. C: 0.001 to 0.0002-inch aerial image of pinhole. D: Knife-edge and eye. E: Flat, thin microscope cover glass section. F: For 16 mm objective this angle must be less than 29°. G: Spherical mirror.

$f/1.0$ to $f/2.0$ an 8 mm N.A. 0.50 objective emitting a 60° cone of light should be used.

The microscope cover glass should be checked for flatness and should be within a wave or thereabout of flat on the side that reflects the light to the mirror, and *must* be held in some manner to avoid flexure. The objective should be mounted (Figure 1) at right angles facing the axis of the mirror near the center of curvature. A 0.01 to 0.02-inch hole in black paper or tinfoil in front of a ground spot on a flashlight type of bulb serves as a light source and is placed 6 inches behind the objective. This hole is projected as an image of only 0.001 to 0.002-inch diameter at a short distance in front of the objective. To locate this image use ground glass or tissue paper.

Now mount the approximately ¼-inch square section of cover glass on a support taped to the underside of the objective. Use a small (to avoid bending) speck of Duco or similar cement in the center of the bottom edge of the glass to mount it at a 45° angle in front of the objective so that it reflects the light to the mirror. An optically flat ground square or a circle with a central opening made into a half-silvered pellicule mirror (Strong, 1938, p. 75), would be even better than a microscope cover glass. The returning cone of light passes through the cover glass and comes to a focus. Here a knife-edge is used. A little trial and error will solve the remaining details.

Correcting Plate: This should be of optical glass quality and 0.2 to 0.3 inch thick. Thinner material is difficult to work, while thicker material introduces undesirable aberrations [See Selby, "Eyepieces," appendix.—*Ed.*]. In a way of speaking, I made my own "optical glass" by buying a half dozen 12-inch squares of Crystallex (Pittsburgh Plate Glass Company, Grant Building, Pittsburgh, Pa.) and selecting a portion 6 inches in diameter, as follows. An ordinary telescope mirror of medium quality was roughly set up as for the knife-edge test. The Crystallex plate was placed in front of the mirror, where all striae could easily be seen. A 6-inch circle was cut from a section of it free from striae. A small 2-inch square of the discarded portion was checked edgewise with Polaroid and found to be well annealed (no colors). A thin strip cut from microscope slides stuck on opposing rough-cut edges of the square with Canada balsam permits looking through an edgewise section without interference from the edge variations if the rough cut is a good one.

I now had a 6-inch circle of ¼-inch high-quality optical glass (by definite test) obtained at low cost, without a long period of waiting, and in a more workable form than regular optical glass. The plate should be made ½ to 1 inch greater in diameter than the clear aperture desired.

One side was found to be within a few waves of flat, and was figured to one wave without regrinding. The other side was now ground so that the edge thickness was the same all the way around, within 0.001 inch. It is easy to check this with an ordinary micrometer—even a cheap one—as we are working for "no difference" and not for exact thickness. Any lack of parallelism will give ghost images of bright stars from internal reflections. The parallelism is not maintained this close to avoid "prism effect," as is thought by some, since this defect alone would permit greater leeway.

The sponge rubber method of correcting plate support often advocated proved to be only a headache to me. I later found it better to support all Schmidt plates by using olive oil between the correcting plate and a solid, flat supporting surface (such as an optical flat). Three "fingers," concaved to fit the edge of the correcting plate and covered with cork, keep the plate from sliding off the optical flat. These fingers are fastened to the base plate on which the optical flat is cemented. One finger must be removable. Slight edge pressure on these holds the plate from rotating. Each of these fingers should be about 2 to 3 inches wide for a 6-inch correcting plate. While metal fingers lined with cork would be best, I turned a 6¼-inch hole in a 1 by 8-inch piece of oak, soaked it in hot paraffin, cut out three 3-inch segments, and lined these with ⅛-inch cork. The olive oil film acts as a cushion, prevents scratches, and is easily washed off with soap.

Do not let the optical flat requirement scare you. Obtain three plate glass disks 1 inch thick, preferably slightly less than the correcting plate in diameter. These will be fairly flat anyway and, if one side of one of them chances to be within a wave or two, use it as is. Grind successively on each other with fine Carbo or emery as described in ATM and ATMA. Proper use of a good Starret straightedge will bring the disks as flat as desired, and they may be used unpolished—what could be easier? The vertical spindle and small 1- to 3-inch circular grinders were used. Round wooden disks paraffin soaked on all sides except the bottom, where a layer of about 1/16-inch rubber (thicker sponge rubber would be required for an $f/1.0$ or $f/1.5$) followed by a layer of ⅛-inch cork to which ½-inch squares of microscope slide glass were cemented, worked excellently. A very small and very handy tool had only two ⅜-inch squares.

My most important discovery in Schmidt correcting plate grinding consisted of using a thin circular microscope slide cover glass under the finger in the final stages of fine grinding. These cover glasses are flexible enough for this use. A full box should be obtained, since they naturally wear through rapidly. In this manner figuring may be done mainly in fine grinding, which greatly simplifies final polishing and figuring. Only the finest emery should be used.

A caution to the beginner is to remember that the deepest part of the curve of the plate of an $f/2.0$ camera of the size described is only about 2 thousandths of an inch, hence he must not start with too coarse a grinding abrasive. On a speedy spindle 600 Carbo will cut very fast. Fine emery such as American Optical Company's 305½, is good for the fine figuring. Curves and calculations for Schmidt correctors are available elsewhere but, with a correct testing arrangement such as the one to be described, no calculations of any kind are required in order to make correct Schmidt plate surfaces, particularly for $f/2.0$ or slower cameras.

Testing: The mirror and correcting plate were mounted in the instrument. A 3/32-inch silvered glass bead was mounted on the axis at the focal point (Figure 2). This should be adjustable along the axis. A parallel beam of light, as from a flashlight, was directed on the bead from one side of the mirror. This places an artificial star at the focus. Preferably, a refractor of aperture equal to the clear aperture of the plate should be placed in front of and looking into the Schmidt. A knife-edge should be placed at the infinity focus of the objective or testing telescope. Thus it is possible to study the figure of the correcting surface of the plate.

It is obvious that, if the artificial star is at the true focal point and if the correcting plate has the correct curve, parallel light will be emitted from the Schmidt. Collecting this light with a telescope and testing with a knife-edge at the telescope's infinity focus will result in the field greying over uniformly as in a perfectly corrected paraboloid at focus of a sphere at radius of curvature. If we now insert an ordinary flat glass plate in place of the corrector the shadows will reveal the apparent high and low circular zones. Since the deepest point in the surface of the correcting plate should be 0.7 of the distance from the center to the edge of the corrector, for smallest glass removal, we slightly adjust the glass bead light source in or out on the axis until the apparent hump (or depression, depending on location of knife-edge) centers at the 0.7 distance. Now we merely grind and polish until the surface we are working looks flat and the field greys over uniformly. The job is then finished, no calculations having been needed. Only by trial and error can the worker know how to grind in order to affect apparent bumps and hollows. A ruler, notched at each ¼ inch, with big notches at each inch, is a valuable aid if held or taped against the corrector to locate zones. A similar ruler aids in locating zones to grind out on the spindle. The bead system fails and must be replaced

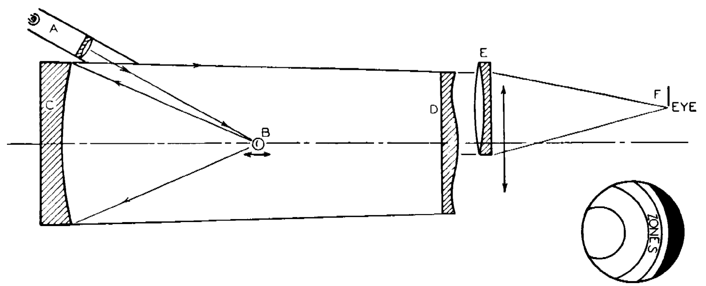


FIGURE 2

Plan drawing of set-up for testing correcting plate. A: The light source and collimator. B: The silvered glass bead. C: Spherical mirror. D: The correcting plate under test. E: Refractor (f/10 to f/15, or a reflector) of full diameter or down to a little more than half the diameter of the plate. F: Knife-edge at infinity focus. Insert: Right side of corrector as seen by the eye.

with an 8 mm microscope objective system similar to Figure 1, *A* and *B*, on faster cameras such as *f*/1 to *f*/1.5.

To make a fine-ground surface transparent I use ordinary kerosene evenly rubbed on it. If testing takes too long this must be renewed. In the early crude grinding stages mineral oil might be used, with a switch to kerosene later. More elegant fluids have been recommended but, used with care, the kerosene technic is satisfactory. It is better to use too little kerosene at first and rub it well in until surface deviations caused by the kerosene itself are learned. If shadows are being studied on right and left sides of the center, the kerosene should be rubbed from right to left so that the ridges thus formed will be at right angles to those under study on the glass.

To adjust the testing telescope at infinity, mount the knife-edge in position and set up on a star or *very distant* street lamp. Otherwise a flat must be placed temporarily in front of the telescope, with a light source at the focus. A reflector probably could be used, with some complications, however.

Refractors, down to a little above one half Schmidt aperture, could be used since, once the system is set up, it is necessary to see only one side of the correcting plate. I used a 3½-inch refractor on my 5-inch clear plate opening

and moved it from side to side to scan the entire surface. Since plates are, or should be, symmetrical there is no need to see the top and bottom. Once the alinement is reached the right side alone is viewed and the corrector brought to apparent flatness. For *faster* cameras (*f*/1.0 or *f*/1.5) the DeVany test offers many advantages and might well be tried in the early stages of grinding as simpler than the above, which I prefer on *f*/2.0 or slower cameras.

It has been said that the adjustment of a Schmidt is a slow and tedious outdoor job. My Schmidt was in perfect adjustment on leaving the shop. The method used consisted of placing an artificial star at the infinity focus of the refractor used in testing, and feeding the parallel light into the camera. A disk of undeveloped film, as chosen for later use in the Schmidt, is placed in the film holder and the image of the artificial star falling on its surface is examined with a low-power microscope, about 30×, placed at a 45° angle from the holder. The entire camera is tilted about in front of the telescope objective so that three points 120° from each other around the *edge* of the film holder may be examined. If the curvature of the holder is correct, sharp images at these edge points will insure that the entire field is in perfect focus.

You are now ready to go out, put in film and take perfect pictures—provided your improvised parallel light was really parallel, as is starlight.

When lining up an instrument some of the adjustments prove to be far more critical than others. Critical adjustments are: (1) The distance of the film surface from the mirror along the axis (i.e., focusing). (2) The axis of the mirror must coincide with the axis of the film holder and pass through the optical center of the correcting plate. If the correcting plate was kept centered on a vertical spindle while grinding, the optical center will be the physical center. Less critical adjustments are: (1) Having the correcting plate at right angles to the axis; a little tilt will do no harm. (2) Flexure in the correcting plate due to edge supports or clamps, or sag of thin correctors as a result of their own weight. (3) The physical centers of the mirror or holder need only be near the axis—it is any tilt of either with respect to the other that is critical. (4) Distance from the corrector to the film holder may be placed closely enough by ordinary measurement.

Cross threads accurately centered by measurement on the correcting plate in the completed instrument will allow alinement of the mirror axis with the center of the correcting plate merely by viewing from the front and making the reflection of the cross threads coincide with the threads.

In connection with design and adjustment Professor C. H. Smiley, in a letter, presented me with two helpful *fundamental principles* of the Schmidt: 1) The spherical surface of the film holder is concentric with the mirror surface. 2) The position of the vertex of the film holder is determined by the "focus" of the zone of the spherical mirror for which the rays are not deflected by the correcting plate.

The Mounting: A satisfactory mounting, drive, and guide telescope are shown in Figure 3. The small prismatic finder shown covers the field (10°) of the Schmidt at 3.5×, gives an erect image, and has high light-gathering power. The larger 40-power guide telescope has a 3-inch aperture and 20-inch focal length. A ½-inch three-lens Hastings magnifier (American Optical Company) serves as an excellent 20× eyepiece with a conveniently high eye point. White single silk fiber cross-hairs are illuminated by a small 1/25-watt, 110-v glow lamp (General Electric NE-2) in series with a 200,000-ohm, ½-watt resistor. The right-angle feature, which permits the guide telescope eyepiece to swing around, adds a great deal to the ease of guiding and avoiding cramped positions. Two pins in the ball and socket joint (not very satisfactory—a heavy

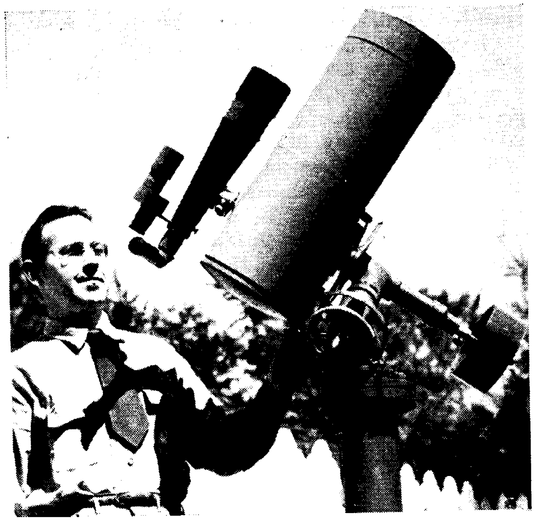


FIGURE 3
The Schmidt camera described in the text

commercial "pan-tilt" tripod head proved better) allow the guide train to be alined on the axis so that the declination "slip drum" may be set on a known star.

Dew may be kept off the guiding telescope lenses by using a 1-watt, 12,000-ohm resistor inside the lens hood, provided 110-volt current is available. Three or four 1-watt resistors in series, with a total resistance of about 12,000 ohms, distributed inside the Schmidt lens hood, will work well in preventing dewing.

Before starting construction, one should sketch a scale design of the camera mounting. Such a scale drawing, also the completed instrument, is shown in Figure 4. Blueprints or more detailed drawings than these are not available but, while no scale is shown, a scale of a kind is given by the fact that the distance from the mirror surface to the axis of the film holder is 10 inches.

For good performance, so elaborate a mounting as this is not necessary. For illustration, the complex shutters, while excellent in performance, may be

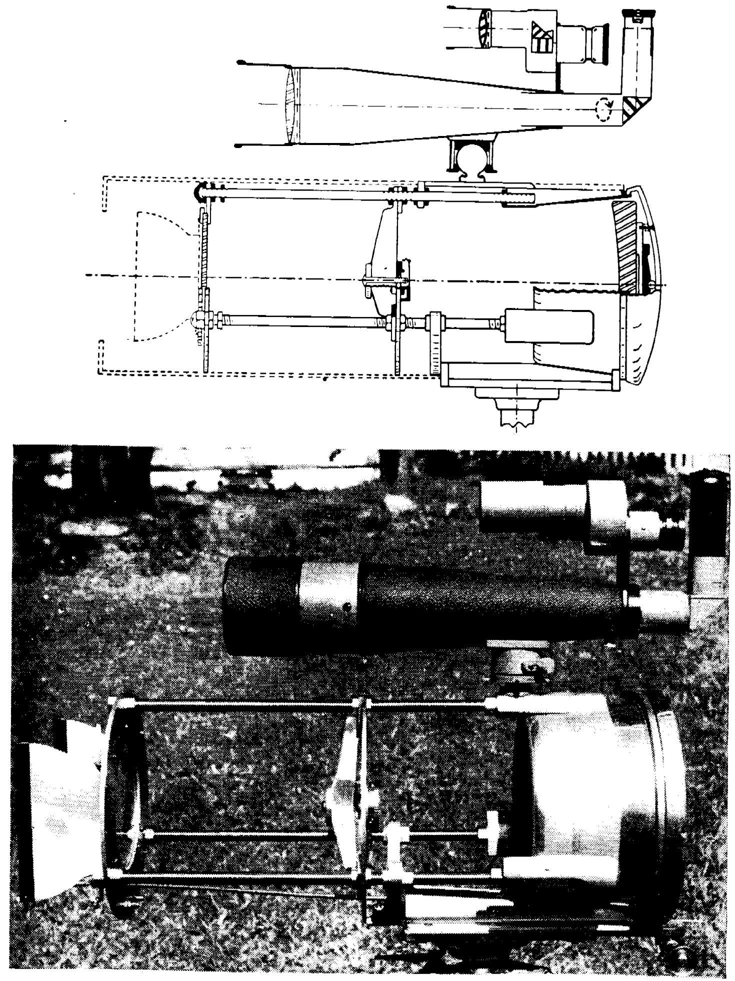


FIGURE 4
Drawing and photograph of the 8-inch Schmidt described in the text.

replaced very neatly by hanging your hat, if free from holes large or small, over the end of the camera. On smaller cameras I use this method in preference to all others.

I made three identical film holders (Figure 5) of 1.75-inch diameter with light-proof caps. These are of bayonet-type construction and each holder screws into place on a central stud. For simplicity, it is recommended that the holder be permanently fixed on the spider and a screw-ring system used to load films right in the camera through an opening in the side.

The drive for this camera has the usual slow motions in R.A. and declination. Both the main polar axis and the first worm turn in SKF ball bearings. The motor used is actually a small 2-watt synchronous unit from an ordinary

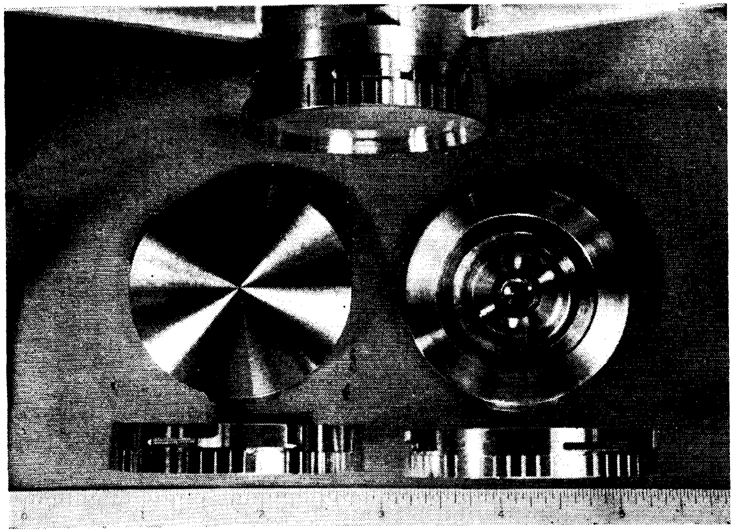


FIGURE 5

Above: Film holder in place on spider in camera. Middle: Front and back of film holder. Bottom: Bayonet lock rings with slots to fit ears on above holders. Three complete assemblies (minus light-tight case) appear in this photograph. Inch scale shows at bottom.

house clock. The shaft from a common sealed unit of this kind rotates at 3.6 rpm and the two worm reductions, of 1:22 and 1:235, net one revolution in 1436.068 minutes. Since guiding must be done for other errors anyway, this is close enough. The 235 teeth are on the main worm wheel. Although the clock can drive the camera, if the telescope is counterbalanced carefully, it actually does not do so. The weight is adjusted so that the clock merely regulates the rate of fall. A ten or more watt motor should be used if forced drive is desired. At the time of building, none was obtainable. The motor should be mounted at least 2 inches, preferably more, from iron, else synchronization will suffer. For warming it in cold weather a 12,000-ohm 1-watt resistor (110-volt) should be enclosed with it. Otherwise, use a stronger motor, particularly if the main axis is not fitted with ball bearings.

Portability: Since stray sky light will handicap the performance of even a perfect Schmidt camera it is well to consider a portable instrument, or at least one that can be rendered portable during vacation trips. Even in the country an occasional night may be spoiled by excessive sky light resulting from auroral activity. This is not an adverse criticism of the Schmidt since

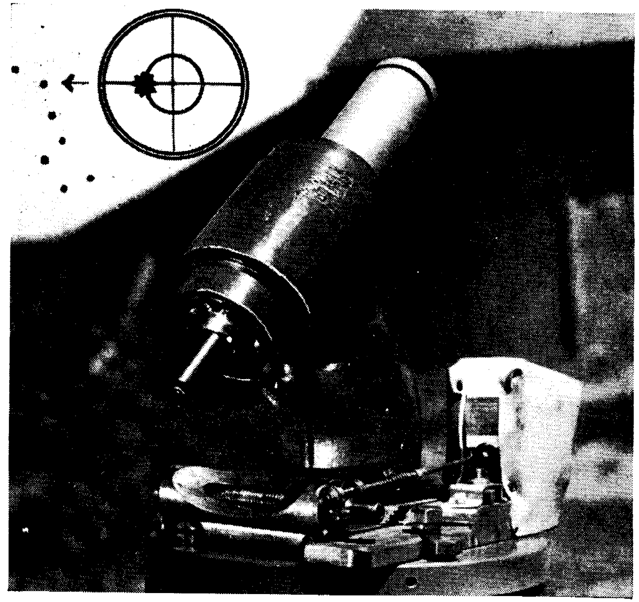


FIGURE 6

the same remarks apply to any type of astro-photography, particularly where dim objects are photographed with high aperture fast lenses.

The major problem in setting up a portable camera is in alining the polar axis within a reasonable degree of accuracy and period of time. The "long-winded" photographic or other methods often described leave little remaining time for the real fun of actual operation. The method to be described, while not new, is particularly suitable for the average portable Schmidt, and is speedy.

My Schmidt drive is so constructed that the polar axis may easily be slid out and a small astronomical telescope (Figure 6) fitted in its place. The telescope rotates freely in the bearings and is carefully machined to the same dimensions as the polar axis. The inserted circle illustrates the field of view, which should be about 4° angular diameter. An achromat of 7 to 10-inch focal length and about 1-inch aperture will work splendidly with a ¾ to 1-inch Ramsden eyepiece. On a glass or plastic blank, to be inserted at the eyepiece focus as a reticule, is inscribed a circle of angular diameter exactly equal to *twice* the angular distance of Polaris from the celestial pole. Hence the circle was inscribed to include 2° of angle, but the more precise worker must ascertain the distance of Polaris from the true pole in the current year, though the yearly change is small (see "World Almanac").

With the telescope in place in the polar axis, Polaris is brought into the field of view by rough adjustment of the mounting or tripod, and the fine-adjusting device provided is manipulated to bring it to the edge of the 2° circle facing the second star (Zeta) from the end of the dipper handle (insert). The cross mark, which can rotate with the telescope in the axis, serves as an aid in placing the Dipper or star in Cassiopeia, Polaris, and the marked optical center of the telescope in line. It *must* be remembered that we are using an inverting telescope, Polaris being actually 1° on the opposite side of the true pole from the Dipper star named. In case the Dipper is not above the horizon, place Polaris on the circle at the point, as seen in the inverting telescope, farthest from Delta Cassiopeiae (ATM, 44, Figure 39). A flashlight properly used near the objective serves to illuminate the circle in the reticule, yet still to permit seeing Polaris. Of course, the Dipper and Cassiopeia stars are not visible in the field of view of the small sighting telescope and must be alined by alternately sighting with the unaided eye or by using both eyes, one sighting through the telescope and one unaided; the latter method requires a little practice. The total time required to set up my portable mounting in close enough adjustment for accurate exposures up to one hour ranges from 5 to 10 minutes.

I use a telescope having 1-inch aperture, 7.15-inch focal length and ¾-inch diameter. A circle subtending a 2° angle at 7.15 inches is exactly 0.25 inch in diameter. This diameter would be proportionately larger or smaller for longer or shorter focal lengths. The reticule is mounted in a lathe and the circle marked with a diamond point, after considerable practice on disks of scrap. A pair of good scribers would do as well on a plastic disk.

The device described has changed a job of drudgery into a pleasant one and removed one of the worst handicaps of portable photographic mountings.

Films for use with the Schmidt camera are discussed elsewhere. Pictures taken with the instrument shown in Figure 3 won several prizes for fine star detail on enlargements ranging from 4 to 16 times. A 7/4 reduction (with loss of detail) from an 8 times enlargement from a 15-minute exposure film of the North America Nebula is shown in Figure 7. Fine definition is shown in the 16× enlargement of the Whirlpool Nebula shown in the chapter on films.

For those who wish to build a fast Schmidt of focal ratio in the range of $f/1$ for special use—comets, meteors, and nebulae—the 5-inch aperture, 4-inch focal length, $f/0.8$ camera shown in Figure 8 may be of interest.

Spider diffraction caused by the usual film holder supports has been elimi-

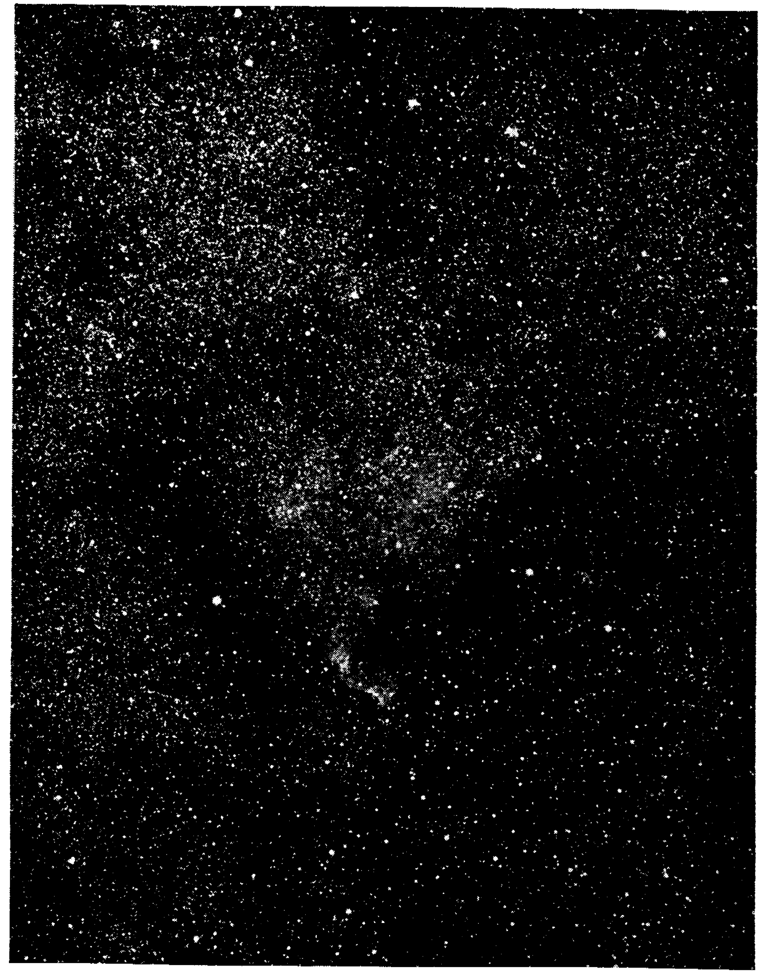
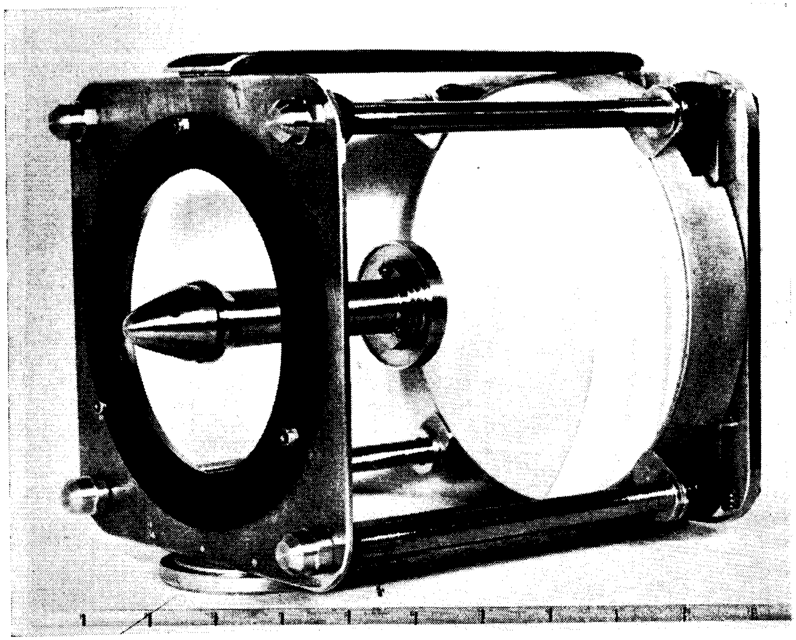


FIGURE 7

nated by fastening the film holder directly to the center of the correcting plate with a hollow light-weight stalk. This stalk is made of magnesium having about double the coefficient of expansion of the four main supporting bars (½-inch stainless steel), hence the camera automatically compensates for tem-



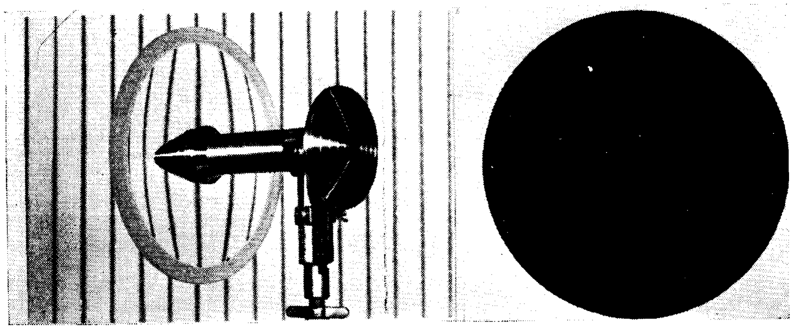


FIGURE 8

perature effect on focal length, distance from film to mirror, which thus remains practically constant. This system is the one long used on compensating clock pendulums and works well. Thus expensive Invar or 36 percent nickel steel main bars are not necessary. The system shown worked perfectly at 20° below

and 80° above zero F. Aluminum 24ST was used for the remainder of the metal parts except that the nuts which are of brass. Grooving of the film holder face allows escape of trapped air from behind the film, but if the film retaining ring is turned slowly when run on this it is not necessary.

One half of the total calculated depth of curve was placed on either side of the correcting plate to avoid ghost images from the flat surface usually employed on one side. Aberrations may also be thus reduced but the extreme difficulty of maintaining lateral symmetry of one side with regard to the other (one can't center by edging!) is such that the alternative of placing the full curvature on one side and giving the flat side or both sides a non-reflecting coating is definitely recommended.

An important detail not visible in the photograph is the three push-pull screws at 120° points about the correcting plate to allow precise lateral adjustment. This adjustment is very critical, as is the movement of the entire correcting unit, including film holder, along the main bars for final focusing. As shown, when the correcting plate is tilted and held in front of a pattern of parallel straight lines one may observe the smooth pattern formed by the convex or positive magnifying effect of the center coupled with the concave or negative diminishing effect of the edge. The supporting ½-inch edge of this plate has been ground flat.

This $f/0.8$ Schmidt is more than six times as fast as the $f/2$ recommended for general use. Exposures are limited to *about four minutes* using Eastman Contrast Process Pan sheet film, which works well with fast cameras. By both calculation and trial only 20° of the 28° diameter field covered on the 2-inch diameter film are of top quality for star work but the whole field has been useful in searching. A two-minute exposure of the Dipper indicates the large field of 600 square degrees useful for comet search.

An $f/1$ camera covering 20° would be superior to the above and may be taken as a reasonable limit for this regular form of Schmidt. An $f/1$ of 7 inches clear aperture and equal focal length is a convenient size for a first Schmidt—or of larger sized (not faster) cameras are desired these measurements may be proportionately increased.

Those who are interested in specialized Schmidts such as these should by all means read A. Bouwers, "Achievements in Optics" (Elsevier Pub. Co., New York, N. Y., 1946).

The following is a short, selected, and annotated bibliography limited to actual construction of Schmidts:

Journal of Scientific Instruments (London) Volume 15, pages 339—40 (Oct. 1938). "Note on Figuring Schmidt Correcting Lenses," by R. L. Waland. Describes method used in testing correcting lens—a slit at focus of the mirror and a Ronchi grating at the focus of the checking telescope.

Journal of the British Astronomical Association (London) Volume 48, No. 8. "The Construction of a Schmidt Camera," by H. W. and L. A. Cox. A straightforward account of the construction of an $f/1.5$ Schmidt, well worth reading before starting work. Same journal, Volume 50, No. 2, pages 61–68 (December 1939), "Further Notes on Schmidt Cameras," same authors. De-

scribes construction of a second Schmidt camera. Includes description of DeVany test.

Popular Astronomy April 1939, pages 197–200. "A Rapid Method of Making a Schmidt Correcting Lens," by Arthur DeVany. Describes DeVany test.

Scientific American (New York), August 1939, pages 118–123. "Some Applications of the Schmidt Principle of Optical Design," by D. O. Hendryx and Wm. H. Christie.

Scientific American, Nov. 1939, pages 314–317. Comment by James G. Baker on article cited above.

The Sky and Telescope (Cambridge, Mass.) July, Aug., Sept., Oct. 1940, Mar., May, 1943. Describe actual construction, except Oct. 1940, which, however, is of great value in determining relationship between field, plate and mirror sizes.

U. S. Patent 2430637, Dec. 8, 1944, Roger Hayward, patentee, describes clearly a test using ball bearings and a flat plate of glass to make directly visible the curvature, regular or irregular, of Schmidt correcting plates during figuring. Probably best applied to Schmidts faster than $f/1.5$ of focal lengths not more than 10–20 inches where deviations of 0.001 inch can be tested, particularly in rough stages.

[Editor's Note: Theoretically the articles cited in the preceding selected bibliography are available to everybody. You just drop in at a large public library and read them to your heart's content. Actually, this would be so difficult for most of the owners of this book that the articles might almost as well not exist. Even if you knew of a library that had them all you'd probably have to travel some distance, hurriedly snatch at the articles and couldn't take them home with you. What you want is something that's yours, at home, parked beside your fat old reading chair where you can pick it up, pore over it whenever you feel like it, unhurried, maybe undressed, mark it, soak it up gradually, and then have it afterward to refer to. You may now do that, for most of the articles—those that are hardest to get hold of—follow in reprinted form, with some others thrown in for good measure. It is even possible that the lack of instructions for building the Schmidt, not in periodicals but frozen in a book where they can't run away, largely explains a 15-year lag in its adoption by amateurs.]

Note on Figuring Schmidt Correcting Plates

By R. L. Waland

From the *Journal of Scientific Instruments* (London) 15,339–40 (1938), by permission

The successful method used in figuring the correcting lens for a $5\frac{1}{2}$-inch aperture $f/2$ Schmidt camera for astro-photography may interest readers.

The usual method is to follow each spell of fine grinding by an hour or so of polishing in order to apply the optical tests. As this involves a great deal of time, the idea was tried of very lightly smearing the finely ground surface with paraffin applied with a piece of absorbent cotton, which renders the lens

semi-transparent. The test was carried out with an illuminated slit at the focus of the spherical mirror, an object glass being placed in front of the correcting lens under test, with a 120-line wire grating for the Ronchi test placed a little inside the focus of the objective and parallel to the slit. Figure 1 shows the path of the light from the slit to the eye. L is a small bulb, G a piece of ground glass in front of which is placed a narrow slit S about $\frac{3}{8}$ inch long.

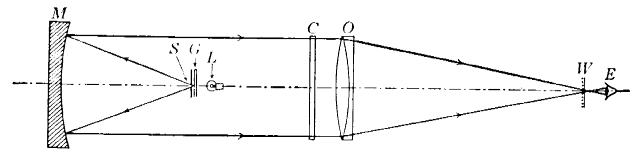


Figure 1

Optical system for Ronchi test.

From here the light rays diverge and are reflected from the spherical mirror M in a nearly parallel beam. The correcting lens C, if correctly figured, makes these rays parallel; the lens is shown as a plane disk, the departure being very small. The corrected rays pass through the object glass O and converge to a focus a little beyond a 120-line wire grating W and are seen by the eye at E. If the test is made with the correcting lens in position, the appearance on placing the eye at E with the grating a little inside the focus is shown in

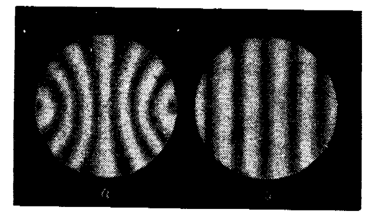


Figure 2

Appearance of Ronchi patterns.

Figure 2a, and indicates that spherical aberration is present. If the grating is placed outside the focus the lines curve the opposite way to that shown in Figure 2a, while if placed exactly at the focus the test is similar to Foucault's. The correcting lens must be figured till these lines appear straight as indicated in Figure 2b. Foucault's shadow test can be applied in a similar way by replacing the slit by a pinhole and placing a knife-edge exactly at the focus of the objective to replace the grating. Although perfectly satisfactory for testing a polished correcting lens, it is unsuitable for testing through a paraffin-smeared surface.

The object glass was used for testing the camera only, the camera having but two optical components. In use, the photographic film (which must be sprung to conform to the curved field) is placed in the position occupied by the slit during the test, this being the infinity focus of the mirror. The bulb must be enclosed to prevent light reaching the eye direct.

This method, of course, cannot be expected to give such a clear impression of the figure as would be obtained by polishing, for irregularities can be seen, generally in the form of vertical ridges, caused by the liquid running to the lower edge of the disk. This is unavoidable no matter how sparingly the paraffin is applied. However, it was found that this was not sufficient to render the test useless, because after a little experience it was possible to distinguish errors caused by the paraffin from zonal errors. It was gratifying to find that after an hour of polishing the figure seen on test was substantially the same as that interpreted by the "paraffin test."

As this was the only correcting plate so far figured, a little further experimenting with various liquids may prove to be of value. Obviously a liquid with a higher refractive index would render the glass more transparent, but whether it would prove a success in other ways remains to be seen.

The choice of abrasive for figuring is rather important. It must leave a surface fine enough to polish in a reasonable time, yet be fast enough to grind to the required depth. I found Messrs. Bausch & Lomb's 906 Corundum very satisfactory in this respect. With practice the figuring of a 5½-inch $f/2$ correcting plate, so far as the grinding is concerned, could probably be accomplished in about one hour. Such an abrasive would also handle the deeper curve of an $f/1$ camera and no further grinding should be required before polishing.

Points to note are: (1) the grating must be parallel to the slit, otherwise lines will not be seen at all; (2) a fairly brightly illuminated slit should be used, e.g. a 12-w car headlamp bulb; (3) the paraffin must be applied very sparingly. [Paraffin, anglice kerosene.—*Ed.*]

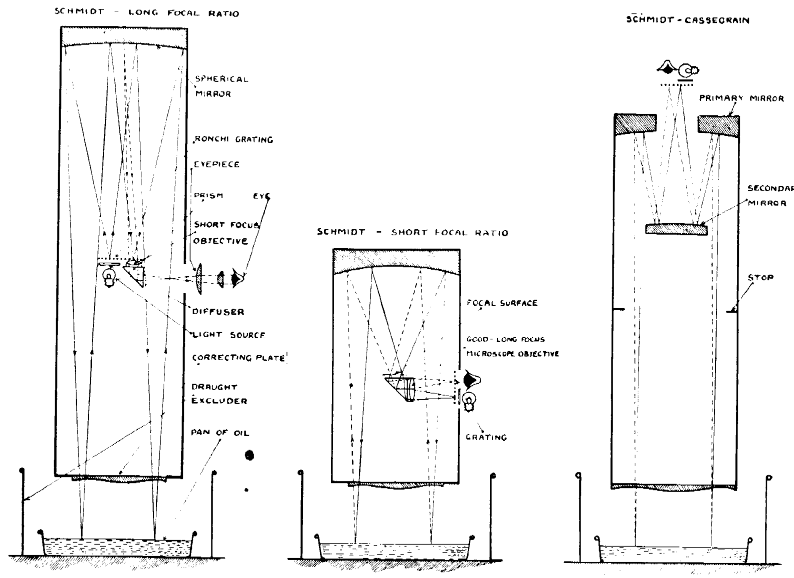
The curve with the least chromatic aberration was chosen, convex at center changing to concave at the edge, the other side being an optical flat. Great care was taken to see that the edge thickness was uniform, as this cannot be corrected by subsequent edging as is possible with an ordinary lens having spherical surface. As the two surfaces are nearly parallel, this measurement was conveniently made by a vernier micrometer reading to 0.0001 inch.

[The author of the preceding paper is optician at St. Andrews University, Scotland, where he built a 30–36-inch Schmidt-Cassegrainian. He has kindly offered us the following supplementary note.—*Ed.*]

Autocollimation Test for Schmidt Cameras: The following is an alternative test to the method described in the *J.S.I.* Schematic layout is shown in drawing, left, and is, in effect, an autocollimation test. A vessel of oil is used to produce the necessary optical flat.

The source of illumination is placed near the infinity focus, as shown. After passing through one half of the Ronchi grating, the divergent pencil of light is reflected and made nearly parallel by the spherical mirror. These rays, after

passing the correcting plate, are, if the plate is correctly figured, refracted back by the oil flat along its own path to the focal surface again. Since, however, this position is inaccessible to the eye, a right angled prism is placed adjacent to the other half of the Ronchi grating. A telescope of about unit magnification, and focused on the sphere, transfers the viewpoint to a position outside the tube as shown. The telescope must have a sufficiently wide field to bring the whole of the sphere into view. It should be focused on the



surface being figured, which in this case is the correcting plate. In practice the difference is unimportant.

The drawing is not to scale, the source of illumination and viewpoint being shown relatively too far apart, for the sake of clarity. This distance should be reduced to an absolute minimum in order to reduce astigmatism. Since the telescope has about unit magnification the objective need not be more than about 0.5 inch in diameter. The grating should be at right angles to the position shown in the drawing in order to avoid parallax effects (see Strong, "Modern Physical Laboratory Practice," pages 75 and 77. [Title of British edition, same otherwise as American edition entitled "Procedures in Experimental Physics."—*Ed.*]

The test described above is suitable only for relatively long focal ratio Schmidts, the limiting factor being radial astigmatism.

In both tests the sphere should be silvered (or aluminized), otherwise the total reflexion would be too weak. The test is used for figuring the correcting plate. The advantages claimed are: (a) twice as sensitive as objective test (b) independent of the perfection of any auxiliary test optics, since the oil flat can be relied upon *if suitable precautions are taken.* These precautions are: (1) The oil should be clean and free from dust on the surface. (2) The container should be at least 2 inches greater in diameter than the aperture to avoid capillary effects at the edge. (3) A draught excluder should be placed around the container. (4) Leave a clear 3 or 4 inches above the oil to reduce convection current effects and their disturbance of the surface. (5) Leave test apparatus for an hour in order to avoid temperature differences when such exist. (6) The oil should be placed, preferably, on a rigid concrete foundation, rather than on a wooden floor. (7) Choose a calm day for the test, as windy conditions disturb the surface. (8) Avoid human disturbances, such as slamming doors, people walking about, etc. (9) Finally, *do not use mercury.* The reflexion is better, admittedly, but it registers every tremor. Using mercury, I was able to see the Irish Boat Train register itself 15 miles away! (The first test of this nature was performed when I lived in Dumfries, Scotland.) My advice is, use oil. Medium engine oil is quite good. If dust particles disturb the surface, matters may be improved by trailing a strip of metal (a clean cabinetmaker's scraper is ideal) over the surface. This draws the dust particles to the side, out of harm's way. In any case, if a few persist no harm will result, as the worker can easily recognize and ignore them.

I have figured several telescopic doublets (3½, 6¼, 10-inch aperture) using the autocollimation test with the oil flat and in no case were any difficulties attributed to the oil encountered when the necessary precautions were taken, and the 3½- and 6¼-inch proved to be good to $\lambda/8$. The standard was much less in the case of the 10-inch, due to poor quality of the disks. The schematic layout is shown in a sketch. [Omitted because simple and obvious. It is the same as Ellison's drawing of autocollimation test, ATM 121, if turned up on end above an oil flat and upper end, eye, etc., arranged as in present drawing, right. Objective supported on annular wooden ring with three equally spaced leveling screws.—*Ed.*] The test can also be applied to the Newtonian telescope, as shown in another drawing. [Omitted but again simple: Invert tube, mirror at top, secondary flat in place, same as Porter's drawing of test at focus, ATM 15, except eye end as in present drawing, right.—*Ed.*] This enables the test to be carried out at the infinity focus instead of at the center of curvature. One will immediately appreciate the advantage of not having to zonal test. The secondary can, of course, mar the test but since it is an integral part of the Newtonian it would spoil the final performance in any case.

Since the test is used to figure the main mirror, the latter cannot be silvered. This means two unsilvered surfaces, if the oil flat is used. If a very powerful illuminant is used, such as a 35-w car headlamp bulb, the test should be workable. The bulb should be carefully shielded so that no direct light reaches the eye. The same applies to all the other tests.

Drawing, right, shows how the test could be applied to a Schmidt-Cassegrainian system and is self-explanatory. Both mirrors should be silvered in this case.

Finally, I do not recommend using the oil flat indiscriminately. It is perfectly satisfactory in all cases up to 10 inches or so aperture, with the exception of objectives, where larger sizes may be tested. The objective is supported only at the edge, and it makes little difference if it is inverted. With large mirrors it is another matter; they must be carefully supported on the back, and if placed face down would have to be supported at the edge only. This would lead to distortion and render the test useless. In such cases a good optical flat is indispensable. All the tests can be performed equally well with a good silvered flat.

Having recommended the oil flat I am, nevertheless, not averse to a good optical flat. They are, in my opinion, a priceless asset in any optical shop. But, having made three myself, I speak with feeling when I say, if there is any other way out, without the final product suffering, then I am all for it!

The Construction of a Schmidt Camera

By H. W. and L. A Cox

From *The Journal of the British Astronomical Association*, Volume 48 (308–313) 1938, June, by permission

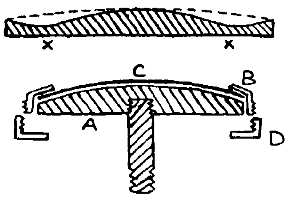
As a reflecting telescope with parabolic mirror only produces a good image when the incident light strikes it squarely, we find that the images around the edge of the photograph suffer from coma when a fairly large area of the sky is being photographed. Schmidt overcame this trouble by using a spherical mirror and so obtained freedom from coma. The spherical mirror, however, suffers from spherical aberration, but in the Schmidt camera this is corrected by a very thin lens placed at a point which is nearly at the center of curvature of the mirror. This thin lens can be figured to one of several curves, but the best curve to give minimum chromatic aberration is one that is weakly convergent in the center and weakly divergent toward the edge. The face toward the mirror is flat and that on the remote side is convex in the center and concave on the outside. The maximum departure from flatness on the curved side is very small and in our case amounts to only 0.00039 inch. It is the figuring of this lens which is the difficult part of the construction of this type of camera, and so far no cut-and-dried method has been devised for doing this work.

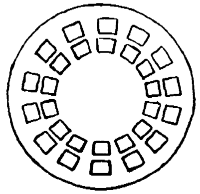
The resulting field of the Schmidt is not flat, but follows a curve convex to the mirror and equal in radius to the focal length of the mirror. Owing to the curvature of field, rigid plates cannot be used for the photographs, and film has to be sprung in a holder to follow the curve.

In the camera about to be described we have the following values. The mirror *A* is of 9-inch aperture, and has a focal length of 9.65 inches. The correcting lens is of 7-inch aperture, stopped down to 6½ inches and is $\frac{3}{16}$ inch thick. The film holder ensures that the film follows a curve of 9.65 inches radius. In giving the constructional details of our own camera, we will pay most attention to the correcting lens, but among other things the spherical mirror has some interesting points.

Firstly, this $f/1$ mirror has a concave surface 0.53 inch deep in the center, and this required 66 hours' coarse grinding with 16 pounds of 80 Carborundum. This grinding, with that of the correcting lens, was done entirely by machine. There were several minor patches of trouble in the construction of this mirror which were all due to the very steep curve, but as they were overcome by well-established methods, there is no need to dwell on them here.

The testing of a short-focus sphere of this type introduced difficulties. We found it impossible to obtain even illumination over the whole mirror with the knife-edge test, and we therefore discarded it in favor of the Ronchi test.





Another difficulty with a short-focus mirror results from the light source and grating not being sufficiently close together. If the grating and light slit are not both on the optical axis of the mirror the test appears to show a badly warped mirror. We overcame this by setting up the apparatus as shown in Figure 2. [Not reproduced, but clearly described in next sentence.—*Ed., ATM3.*] The light from the slit is turned at right angles by an unsilvered flat, and on returning from the mirror passes through the flat and is inspected with the Ronchi grating just behind.

The making of the correcting lens was possibly the most interesting part of the construction, as normal lens procedure would not work here, and flexible laps had to be used in order to follow the complex curve. Two lenses were made by us, as the first lens suffered from an unsymmetrical figure and we considered that our technic had in this case been poor. The second one, made by a revised method, was quite successful, and this only will be described.

The plane side of the lens was ground against two other 7-inch diameter glass disks and polished with an ordinary 4-inch diameter pitch on glass lap. The surface after polishing was flat to within about 0.00005 inch and anything more accurate than this does not seem to be necessary.

The reason why the first correcting lens was unsatisfactory was that the use of a very small tool for local grinding work, plus the use of fairly coarse abrasive of 300-mesh in the early stages, produced a surface that was not a figure of revolution. Therefore, in this second lens we used nothing coarser than 500-mesh Carborundum, and obtained a true figure in the following way.

The sketch shows the curve of the lens, the depths of curve at various radii being:

Radius in inches	0	0.5	1	1.5	2	2.5	2.75	3	3.25
Depth in mils	0	0.25	0.95	1.79	3	3.78	3.9	3.74	3.26

If we superimpose a convex as shown by the dotted line, we find that at point x, which is equivalent to 2.75 inches radius, there is only approximately 0.001 inch to be removed instead of nearly 0.004 inch as when working from a flat surface. It is obvious that if the convex curve can be obtained with a true figure, then the removal of 0.001 inch of glass will cause less trouble than the removal of 0.004 inch. We therefore convexed the lens by grinding it against another 7-inch diameter disk, using firstly 500 and then 600 abrasive. This, of course, is ordinary mirror-grinding practice, and needs no elaborating. This curve and the true Schmidt curve were measured for accuracy with a spherometer of conventional type and with a reading accuracy of 0.0001 inch.

Having convexed the surface, we then had to concave it around the point marked x. For this a special flexible ring lap was made up as follows: a disk of sponge rubber 7-inches diameter by 3/4 inch thick was cemented with gold size to a 7-inches diameter glass disk. Then two concentric rings of 3/8-inch-square lead facets were in turn cemented with gold size to the sponge rubber. These lead facets were about 1/16-inch thick and spaced about 1/16 inch apart. The diameter of the rings was such that the space between the inner and outer rings coincided with point x. Grinding strokes of suitable length gave very nearly the desired curve with this one lap after three hours' grinding with 600 abrasive. The spherometer showed that generally the curve was satisfactory, but there were raised zones of about 0.0002 inch at 1¼-inch radius and 2¾-inch radius. Two more flexible ring laps were made, but this time with only single rings of facets. One lap had its ring arranged to reduce the 1¼-inch zone and the other to reduce the 2¾-inch zone. About four hours' grinding with all three laps used alternately was sufficient to smooth out the curve to an accuracy within the reading limit of the spherometer.

During the grinding and polishing stage the lens was held in a Keramot ring screwed to the turntable, and was lifted out when being tested with the spherometer.

Besides a flexible grinding tool, we had also to have a flexible polishing lap, and several types were tried before we finally found one that worked really well. The most successful was one consisting of a rubber disk of 4 inches diameter by 3/16 inch thick cemented to a metal back with gold size. On top of the rubber we cemented a cork disk (table mat) of 4 inches diameter by 1/8 inch. The cork provides a flexible, yet fairly firm, backing to the coating that has to be applied. Some workers have used rubber only under the pitch or resin surface, but we found that arrangement very slow in polishing, as the rubber gave way too much under the polishing pressure. Our cork disk was covered with a mixture of resin and beeswax, and the final lap behaved very satisfactorily indeed.

Ten minutes' polishing was sufficient to enable the first optical tests to be applied. Owing to the very short focal length, the Schmidt camera cannot be tested at the focus, and so we used a method which has been used with success by several workers in America. Instead of supplying the mirror with parallel light and then inspecting the image at focus, we reversed the procedure and placed a slit of light at focus and observed how nearly parallel the light was as it came backward out of the camera. If the slit is made about ⅜ inch in length it is possible, by standing some 20 feet away, to see the image of it extending from top to bottom of the mirror. Then, if without any correcting lens in position, the head is moved from side to side, the extended bright line will move in a similar fashion. However, instead of remaining straight, it will begin to curve and become convex toward the center of the lens. If the correcting lens is then placed in position, the line should keep perfectly straight as it passes out on each side.

On testing our lens by the above method we found a good figure with a slightly raised zone at 1¼-inch radius, and a rather rough effect at 2¾-inch radius. As the errors only appeared to be slight, we decided to go ahead with the polishing in the hope that these zones would disappear in the process. Another nine hours were sufficient to polish out the glass, and we found that the zones had then disappeared as we had hoped.

The next part of the camera to be made was the holder for the film. The sketch shows the design.

A is made from Bakelite and is fitted with a threaded metal rod projecting from the back, so that it can be fixed to the spider in the camera cell by means of a wing nut. *B* is a thin brass ring threaded on the outside so that the brass ring *D*, which has an internal thread, can pull the ring *B* down on to the film *C*. A small slot is cut in the ring *B*, and a pin in the Bakelite engages in this slot and prevents the ring from turning. If the ring turned, the film would probably turn with it, and, rubbing on the surface of the Bakelite, would be severely marked. So far we have found this arrangement to work perfectly, and the film smoothly to follow the contour of the holder without any wrinkles appearing around the edge.

A Schmidt camera of $f/1.5$ ratio is sensitive to changes in focus of only 0.003 inch, and so it will be realized that not only must the curve of the film be very accurate, but also its distance from the mirror. At the same time, the film holder must be squared on very accurately. We ensured rigidity in alinement by making the camera cell of sheet iron, bolted around cast aluminum rings of angular section. All fixings for the optical parts were made on the heavy side so that flexure would be reduced to a minimum.

Mr. H. Lower, who has made a $f/1$ camera, informed us that his cell, made in the form of a wooden box, is suspected of flexing under the weight of the heavy mirror. Also, as his camera is sensitive to out-of-focus errors of 0.001 inch, film which varies in thickness by this amount will cause appreciable faults to appear on the negative.

The final alining of the camera had to be done by taking a series of star photographs, inspecting the negatives and making adjustments until no further improvements could be made. In all, this alining entailed the taking of some 20 photographs before we were satisfied with the results.

Photographs taken show that coma is satisfactorily corrected and that star images over the entire negative are quite small. A small amount of astigmatism sometimes appears and this is believed to be due to uneven film, inferior following, and possibly small distortion in the mountings for the various parts.

Further Notes on Schmidt Cameras

By H. W. Cox and L. A. Cox

From *The Journal of the British Astronomical Association*, Volume 50 (61–68) 1939, December, by permission

In a previous number of the *Journal* (1) methods that were employed in constructing the aplanetizing lens for a $f/1.5$ Schmidt camera were described. Since the writing of that article another camera of similar speed, but covering a 20° field, has been constructed for Mr. Prentice. An article on the figuring and testing of the aplanetizing lens for this camera was written for and appeared in the *Journal of Scientific Instruments* (2). The methods employed on this camera and also on the now completed correcting lens for a duplicate camera for Mr. Prentice will now be discussed.

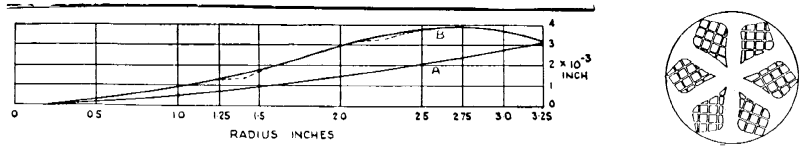


Figure 1

As in the first lens (1), the surface of the glass disk to be figured was first convexed to the lower curve shown in Figure 1, left. This was done in order to give a surface with a true figure of revolution as a point for the commencement of figuring, and in order to reduce the amount of glass to be removed in this process. Curve *A* shows the spherical curve and curve *B* shows the final curve aimed at in the figuring. The multiple ring lap, used in the first lens and previously described (1), did not produce a smooth curve in one figuring operation but left hard zones at the points indicated by the dotted lines. These zones, which were produced because the facets were arranged in unbroken rings and tended to produce zones about their own range of movement rather than as a blended figuring, had to be worked out afterward by other ring laps.

In the case of the two other lenses, the figuring was done in a single operation by using the special type of lap shown in Figure 1, right. Lead facets arranged in the shape of petals were cemented with gold size on to a ⅜-inch thick sponge rubber. The shape of the petals was calculated to ensure that the amount of lead passing over any given zone per stroke was proportional to the amount of glass to be removed. This is similar to the method employed by Linfoot when figuring the correcting lens for a Schmidt type microscope (3).

It will be seen that the individual facets are also arranged diagonally in order to reduce possibilities of zones and also that alternate petals are of different length, again in order to assist in the production of a smooth surface.

Before figuring started, the lead facets were ground with 600 Crystolon against a piece of flat glass in order to remove irregularities in the surface. The lap was then concaved against another 7-inch glass disk, which had been previously convexed to the spherical curve *A* in Figure 1. Six hours' grinding with this lap, using 600 Crystolon, was sufficient to figure the lens so that it completely satisfied the spherometer test. The limitation of measurement with the spherometer was ±0.00005 inch. No local figuring was found necessary. Using the same lap and levigated alumina as the abrasive, the lens was then fine ground in six hours. Very light pressure on the lap was used for this purpose. On inspection, the lens again passed the spherometer test, showing that very little glass is removed in this stage.

Polishing of the lens, which took 5 hours, was done with a lap slightly different from that described in the previous article (1). A 3/8-inch thick by 4-inch diameter sponge rubber disk was cemented with gold size on to a suitable backing plate. On the rubber was cemented a 4-inch diameter by 1/8-inch thick cork disk (table mat), and this was covered with 1/16 inch of three-second pitch. Channels, spaced 1/2 inch apart, were cut in the pitch in order to assist flow. In the case of the third lens the lap was modified slightly from this.

The modification was as follows:

The pitch surface was heated and contacted against a piece of glass covered with string netting. After pressing, the netting was stripped off the lap, leaving the surface covered with small facets about 1/4 inch square. To prevent the netting from sticking to the pitch, it was first well soaked in a mixture of soap and glycerine. This lap was so successful and made such good contact that the same procedure was adopted in making the lap for the 12-inch spherical mirror. This worked extremely well, and it was so easy to secure contact that it has been decided to use this type of lap on all future mirrors. No claim for originality is made, as this type of polisher has been used with success by other workers. However, it is mentioned here as it is not generally used.

The figuring and polishing of both these new lenses took less than 20 hours each, excluding the time taken in preparation of the laps. It is interesting to note that these laps wear out fairly slowly and can be used for three or four lenses before they become too bad to use.

To test each lens, the mirror was placed in its cell with its axis horizontal, and the mounts for the film holder and the lens were erected in front of it in their correct positions. In the mount for the film holder was supported a straight vertical slit, 5/16 inch long and 0.001 inch wide, and this was adjusted to the true focus of the camera. It is sufficient to make this adjustment to 0.01 inch. The slit was illuminated by a straight filament lamp placed immediately behind with a piece of frosted glass interposed between them. This is similar to the test equipment used in the testing of the first lens (1), but a more detailed description of the actual testing will now be given.

If the camera is inspected from a point on the axis 40 feet away, the extended image of the slit can be seen stretching right across the correcting lens. The criterion of the quality of the camera is the straightness of the image as the head is moved to one side. If a straightedge is placed immediately in front of the lens it is possible, by watching the occultation of the image by the straightedge, to detect errors of straightness of 0.05 inch. Narrow zones are best seen at a distance of 6 feet, when the straightedge will reveal errors of 0.01 inch. The lens is rotated and tested in each meridian in order to have a complete test of its quality.

Both the figures given above for the accuracy of measurement are outside the theoretical Dawes limit for angular measure, but the effect of the occultation of the line by the straightedge is to increase the sensitivity of the measurement. Both the lenses passed this test, having no zones greater than those quoted above, and photographs subsequently taken showed that the stellar images were satisfactory.

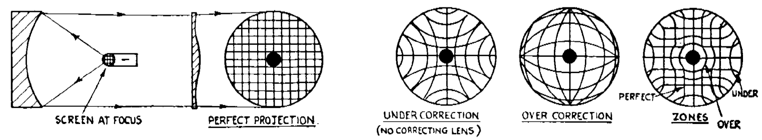


FIGURE 2

While on the subject of testing Schmidt correcting lenses, we should like to mention an improved method invented by DeVany in America. This was communicated to us by letter, and an article subsequently appeared in *Popular Astronomy* (4). Figure 2, which shows the method, is really self-explanatory. In place of the slit of light at the camera focus, a wire screen of about 200 mesh is used. Instead of seeing a single line, needing piecemeal analysis of the lens, we can study the whole aperture at once.

A short description of the first of the two 20° meteor Schmidt cameras may be of interest to members. Figure 3, left, shows the construction of the camera. The mirror, of 12-inch aperture, is ground to a focal length of 9.65 inches, to obtain which it was necessary to concave the surface to a depth of 1 inch. After polishing, the mirror was aluminized, as it was considered that in view of the difficulties of alinement of the optical system, it would be unwise to have to remove the mirror for silvering at fairly frequent intervals.

The construction of the camera is as follows:

The cell (1), made of sheet iron, is bolted and soldered to the rings (2), these being angle section gunmetal castings. Mirror (3) and heavy brass cell (4) are mounted on the mirror support (5). Squaring on of the mirror is done by adjusting the three legs of the support on the screws. Similarly the film-holder spider (6) is squared on by adjustment of the screws (7). The film holder (8) and focusing system are shown in greater detail in Figure 3, right.

Although the correcting lens (9) does not require a high order of accuracy in squaring on, it is provided with a cell (10) with adjusting feet (11). Part (12) in the drawing is a combined top cover plate and hood, with the latter provided with a felt lining (13) and heater coil (14) to prevent dewing on the lens. Two doors (15) are provided in the cell so that the initial focusing and subsequent insertion of the loaded film holders can be performed. The bottom cover plate (16), and the saddle (17) for fixing the camera on the mounting, complete the main description of the camera. The top and bottom cover plates, together with the doors, clamp down on rubber linings to make the joints reasonably airtight. This reduces to a large extent the effect of corrosion and humidity. With an aluminized mirror the quality of the rubber is not so im-

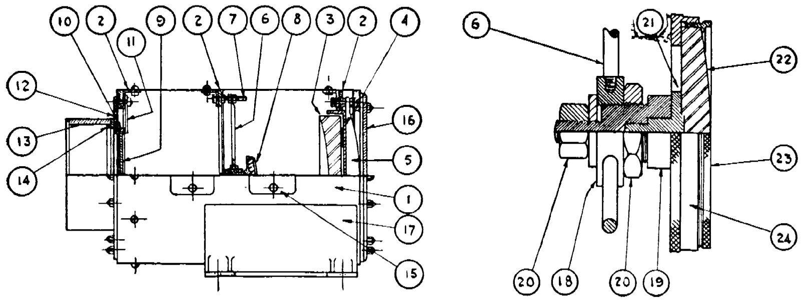


FIGURE 3

portant, but if a silvered mirror is used it is important to use pure rubber, free from sulfur content, or the mirror will quickly tarnish. The whole of the interior of the cell is painted dead black to prevent internal reflections.

The film holders, shown in Figure 3, right, of which six were supplied with the camera, were designed so that they could be quickly inserted with one hand into the camera. The central support (18) is located and squared on by means of the spider (6). An adjustable seating (19) for the film holders can be moved along the optical axis and locked in any position by means of locking nuts (20). Adjustment of this seating permits focusing of the film holders independent of squaring on. The film holders themselves are similar to those described in the previous article (1), but special brass screws (21) are provided on the backs so that they can be screwed into the seating (19). Push-on covers lined with black felt cover the films when being fitted into the camera. The curved surfaces of the Bakelite backs (22) were ground to an accuracy of ±0.0005 inch, and the height of the center of these surfaces above the back of the flange on the screws (21) was in each case adjusted to within ±0.0005 inch. This ensured that all film holders were accurately in focus. The curved surfaces were ground to curve with the Bakelite disk screwed on to their associated screws, and with the screws running true in a lathe. This ensured that the film holders were also all square with the optical axis of the camera.

Photographs taken at Mitcham showed that the stellar images were rather better than those obtained with the first camera, and that there was no noticeable difference between any of the six film holders. Photographing coincided with a period of full moon so that no long exposures were attempted. The test exposures were only for a few seconds, but sufficient stars were photographed to reveal the actual quality of the images.

When the camera was tested at the observatory of Mr. Prentice at Battisford, it was found that a 45-second exposure on the North Polar Sequence reached magnitude 13 when Ilford Hyperchromatic film was used. This film is not panchromatic, and normal red sensitive film would not give any greater sensitivity on other than red stars. Kodak now make a very fast red sensitive film known as Super Panchro Press, and this, like its Agfa equivalent, is three or four times as sensitive as ordinary panchromatic film. Using this film it should be possible to reach magnitude 15 with one-minute exposure on a good night. In meteor work as high a speed as possible is desirable, but unfortunately if the extra fast film is used the total length of exposure must be reduced or meteors will be lost in a background of sky fog. Again, when used on regions of star clouds, the fast film will quickly produce a white background of stars against which the fainter meteor trails will be lost. This means that films will have to be changed at short intervals unless a less sensitive film is used.

The methods used in lining up the optical system of ordinary Schmidt cameras may be worth some little discussion. The mirror, correcting lens and film-holder support are placed in position and adjusted to relative distance and squareness as near as possible by ordinary mechanical means. Two strings are stretched across the correcting lens at right angles to each other and arranged so that they cross at the center of this lens. If we look into the camera in a bright light, say sunlight, we see three main things:

(*a*) The reflected image of the film-holder support (this will be somewhat magnified).
(*b*) The crossed strings.
(*c*) The reflected image of the crossed strings situated apparently a little behind the strings themselves.

The mirror is now adjusted until the image of the crossed strings falls immediately behind the strings themselves and can no longer be seen. If the film-holder support has been mounted truly on the optical axis, the central part of it should fall behind and directly in line with the crossed strings. If this is not so, then the support or correcting lens should be moved until this point is satisfied. In the latter case the mirror may then have to be readjusted.

The rest of the lining up and focusing is done photographically by trial and error and by constant inspection of the images. At this stage squaring on and focusing of the film holder is done. It may be necessary to make a final adjustment to the squaring on of the correcting lens, but this will probably not be necessary if the previous adjustments have been well performed. It will not be at all necessary to make any readjustment of the correcting lens along the optical axis. For the final lining up by means of photographs, reference is made to the article by Smiley on "Flare in Schmidt Cameras" (5).

Before concluding this paper we may refer to the many other applications of the Schmidt principle to astronomical apparatus. There are many variations of this, taking the form of such things as cameras for stellar spectrographs, solar spectrographs, off-axis cameras and solid Schmidts (in which figuring of the correcting surface is done on the front of a piece of glass, with the background convex and back silvered). There are many other variations, and members interested in this work are advised to read the article by Hendrix (6) covering this subject.

In conclusion, we should like to thank Mr. V. Orloff for making the drawings included in this paper, and also to thank the Editor of the *Journal of Scientific Instruments* for permission to reproduce the first two drawings from a previous article in that paper.

References

(1) *Journal British Astronomical Association* 48, 308 (June 1938).
(2) *Journal Scientific Instr.*, 16, No. 8, p. 257 (Aug. 1939).
(3) *Journal Scientific instr.*, 15, 405 (Dec. 1938).
(4) *Popular Astronomy*, 26, 953 (1938).
(5) *Journal Opt. Soc. America*, 28, 130 (April 1938).
(6) *Scientific American* (Aug. 1939).

Bibliography

Burch and Cox, *Journal B.A.A.*, 49, 52 (Dec. 1938).
Lower, "Amateur Telescope Making—Advanced," p. 410.
Smiley, *Popular Astronomy*, p. 418 (Oct. 1936).
Smiley, *Journal B.A.A.*, 49, 34 (Nov. 1938).
Waland, *Journal Scientific Instr.*, 15, 339 (Oct. 1938).
Wright, "Amateur Telescope Making—Advanced," p. 401.
Wright, *Publ. Astr. Soc. Pacific*, 47, 300 (1935).

Some Applications of the Schmidt Principle in Optical Design

By D. O. Hendrix and William H. Christie *
From *Scientific American* 1939, August, by permission

One of the most outstanding inventions in optics in modern times is to be credited to Bernard Schmidt, late optician of the Hamburg Observatory in Bergdorf. The first Schmidt camera saw the light of day in 1930. Using the camera as a telescope, Schmidt and a friend amused themselves by reading the epitaphs on the tombstones of a nearby cemetery, and by looking at various

* Respectively, Assistant Optician, Mt. Wilson Observatory Optical Shop and Astronomer, Mt. Wilson Observatory.—*Ed.*

buildings in the distance. In Figure 1 the reader will see the reproduction of a windmill about 2 miles away, made by Schmidt early in 1931 with the first Schmidt camera. This photograph was made on a *moonless* night with an exposure of two hours. On the original print one can actually count the twigs on some of the distant trees.

As in most great inventions, Schmidt's method of eliminating coma and aberrations from reflecting telescopes is simplicity itself and, as one looks back, it seems incredible that no one appears to have thought of this simple solution long ago.

Several articles have been written about the Schmidt camera since the inventor set forth its principles in 1931, but little that is new has been included

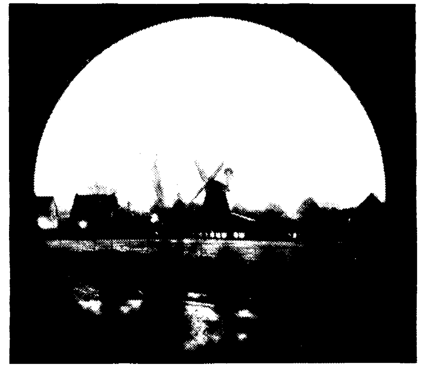


Figure 1

in these discussions. Since there are many ramifications of the Schmidt principle it has seemed worth while to discuss this remarkable camera and its applications fairly completely, for it will be found that there are but few fields in optics where this invention cannot be applied to some advantage.

The outstanding defects in the images formed by lenses and mirrors are spherical aberration, coma, astigmatism, curvature of the field, distortion, and for lenses we have, in addition, chromatism. *Of these defects, only one is distributed uniformly over the whole field;* this defect is spherical aberration; all other defects are proportional to their distances from the axis.

Now *a spherical mirror has no axis* and, furthermore, a mirror is perfectly achromatic, so, could we but find a method of eliminating spherical aberration from the images produced by a spherical concave mirror, such a system should prove ideal.

Spherical aberration is caused by rays from various zones failing to come to the same focus; the more distant the zone is from the central ray the closer its focal plane is to the mirror. This defect, for spherical concave mirrors, is shown diagrammatically in Figure 2, at *A*. Suppose, now, we place a very small aperture in a screen at the center of curvature of a spherical concave mirror, as shown at *B*; this aperture will limit the size of the incident beam so that the center and outer zones will come practically to the same focus, for it can be shown that, for small apertures, and focal ratios less than $f/10$, the Rayleigh limit of $\lambda/4$ is not exceeded. If the incident beam be swung about the point *o*, all parts of the mirror will be illuminated in turn, and the focus will trace out the spherical curve, *ff*, which has its center at *o*. It will be seen that each point source of light toward which such an optical arrangement might be turned would form its image on the focal curve *ff*.

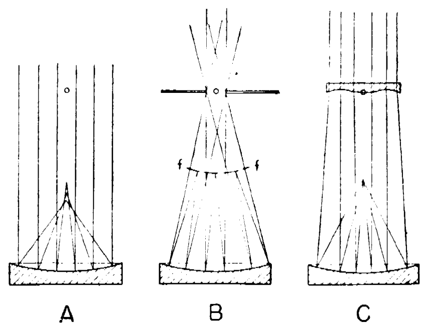


FIGURE 2

On increasing the size of the aperture the focus is no longer sharp; spherical aberration is now appreciable, but we can eliminate this defect by introducing equal and opposite aberrations into the incident beam, as shown in *C*. These opposite correcting spherical aberrations may be produced by a suitably shaped lens, or mirror, placed anywhere in the parallel beam *for one particular point source* of light, but when we are dealing with more than one source it becomes imperative to place the correcting plate in a position common to all rays; that is, with the optical center at the center of curvature of the mirror. For many purposes a large field is not required and it becomes more convenient to move the correcting plate away from this position and perhaps incorporate it with some other optical surface, such, for example, as the face of a prism or the collimator of a spectrograph. The corrections, of course, are not identical for all positions of the correcting plate.

On introducing the correcting plate into the incident beam of light we also introduce chromatic aberrations. For moderate apertures this defect is negligible, but when we attempt to make a camera with an aperture greater than its focal length we run into difficulties; how these may be partially surmounted will be discussed later. Of course it is possible to design an achromatic correcting plate by using two plates of different indices of refraction. It is also possible—and practical—to distribute the required corrections between several surfaces when it is desirable to avoid deep or steep curvatures.

The curvature of the field may be removed (approximately) by means of a simple plano-convex lens placed immediately in front of, or in contact with, the photographic plate, the plane side facing the emulsion. The radius of this lens is $f/3$ for glass with an index of refraction of 1.50. This is satisfactory for cameras having an *f* ratio of $f/5$ or less.

Applications of the Schmidt Principle: In the accompanying diagrams, Figure 3, we have portrayed some of the numerous adaptations which may be made of the Schmidt principle. Unfortunately, Schmidt left no account of the various ramifications of his camera of which he must have thought, and we do not know, in most cases, who originated the various arrangements we present; most of them have been devised here, but we do not claim priority. In a few cases, where the originator is known, we have appended his name to the diagram, although it is probable that others interested in fast cameras may have independently thought of them.

In the central column of the diagrams we have arranged illustrations of the fundamental types of Schmidt cameras and, to the right and left, some adaptations of these types, most of which need no explanation. No. VI, which shows the diaphram replaced by a correcting mirror, is shown, as are most of these diagrams, in an exaggerated form; in practice it is necessary to reduce the angle between the incident and reflected beams to a minimum in order to reduce the foreshortening effect. A perfect correcting mirror should be figured in an elliptical form but, since such a figure is very difficult to produce, we must be satisfied with an approximation in the form of a circular correcting mirror. If the aperture ratio of a camera using a correcting mirror is small, the foreshortening will be negligible, and here we have a perfectly achromatic arrangement which should be exceedingly useful in working at the extreme limits of the spectrum.

When a Schmidt camera is constructed with an aperture greater than its focal length, the curves in the correcting plate become steep enough to introduce appreciable chromatic aberration. If, however, we use a thick mirror, R/2 in thickness, silvered on the back surface, as shown at IX, we increase the speed of a Schmidt camera by a factor of $2\frac{1}{2}$ to 3 times, depending upon the kind of glass used, because, on passing from one medium to another, the energy-density of a cone of rays is changed by a factor equal to the square of the inverse ratio of the indices of refraction of the two media. To put this in other words: since the rays, after passing through the surface of the mirror, are refracted toward the normal, they appear, *as seen from the surface of the mirror,* to emanate from a point closer to the axis; hence the angle subtended by an object is reduced, and the image formed by the mirror is correspondingly diminished in size. The geometrical focal length, however, has been changed but little, and thus we can obtain the speed of an $f/0.66$ camera with a field and correction-plate curvature of an $f/1.0$ camera. This is shown clearly in Figure 4, where an ordinary Schmidt camera is compared with one of the thick mirror type.

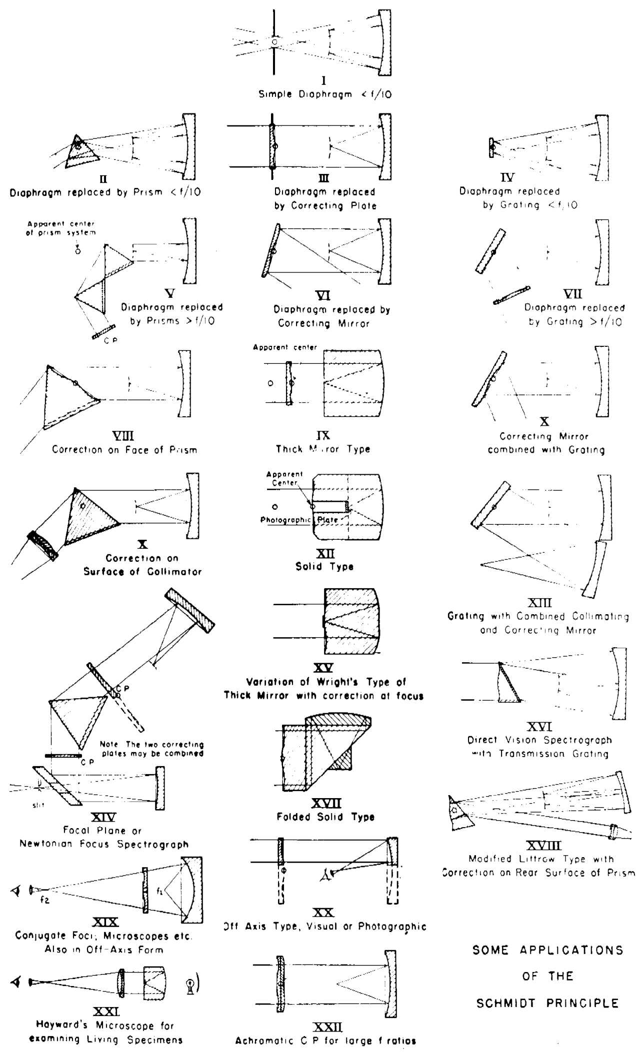


FIGURE 3

In such a camera the correcting plate is placed at a distance of $R/2n$ from the front surface of the mirror, where R is the radius of the mirror and n the index of refraction of the glass. This position is the *apparent* center of curvature of the mirror as seen from the mirror surface. (In all cases where the focal curve lies at the surface of the glass the photographic emulsion should have a film of oil between it and the glass, in order to make optical contact. Coal-oil will be found quite suitable for this purpose.)

In XII, Figure 3, we have the extreme form of solid type—one in which there is no medium other than glass between the correcting surface and the focus. This was first suggested to us by the late Sinclair Smith. We do not

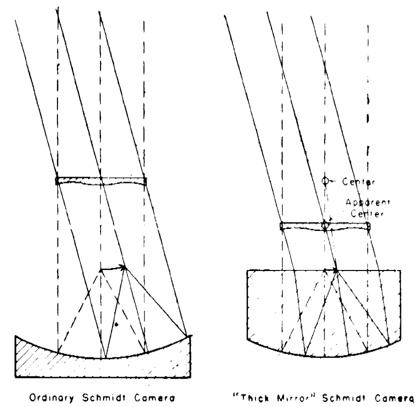


FIGURE 4

know of such a camera having been made and there are some practical optical difficulties to be surmounted in constructing a solid Schmidt; furthermore, the increased absorption of the thick glass becomes important, and, since it must be sufficiently homogeneous for its purpose, such large blocks are very expensive. The two parts, separated by the dotted line in the diagram, should be figured separately, but when cemented together they must be accurately coaxial. The photographic plate could be introduced into the focal curve through a hole in the half containing the correcting surface, either from the side or along the axis as shown.

The difficulties of the extreme thick mirror types may be overcome by a variation of Wright's ("Amateur Telescope Making—Advanced") system; that is, by placing the correcting surface at the focus as shown in XV; but here we are confronted with two non-spherical surfaces, extremely difficult to figure in conjunction with each other. An experimental camera of this type, with an aperture ratio of $f/1$, was constructed here, but it was not a success because the higher order aberrations rendered the images unsatisfactory. It is possible that a camera, geometrically $f/4$, or with an equivalent focal ratio of $f/3$, would be entirely satisfactory.

One of the neatest of all solid types is that shown in XVII—the folded solid Schmidt, designed by Hendrix. Here we have few practical optical difficulties, although there are four components. Of the seven plane surfaces only the hypotenuse of the large prism must be worked to a high degree of precision; the cemented surfaces are sufficiently accurate if worked to a wave, because the cement, which should have an index of refraction equal to that of the glass, fills in the irregularities between the surfaces. Small errors in the thickness of the components may be rectified when adjusting the small prism during the final assembly.

The "off-axis" type, illustrated in XX, is exceedingly useful in practice because, with this arrangement, the photographic plate or film may be placed outside the light beam. This system also is adaptable for visual observations. Making a single off-axis correcting plate of large dimensions is, unfortunately, somewhat wasteful of time and material, because it is necessary to figure a correcting plate of more than twice the required diameter. If more than one camera of the same focal length is required, the waste is reduced, because several off-axis plates can be cut from the original one. This type seems to be the only practical one for mass production.

In XIX the Schmidt principle is used in the form of a microscope. Such an arrangement might prove useful for low power work where a large field is desired, such as in microphotometry; but perhaps the most ingenious arrangement is that of Hayward, XXI, in which he suggests a thick mirror with the focal curve ground out of the mirror face, and serving as a reservoir for small living organisms. An unsilvered portion of the spherical mirror serves to admit light for dark field illumination.

The Design and Construction of Correcting Plates: The deviation, Δ, of the surface of a correcting plate from a plane is given by the biquadratic parabola formula

$$\Delta = \frac{x^4 - kr^2x^2}{4(n-1)R^3} \qquad (1)$$

where x is the radius of the zone; k, a constant; r, the radius of the correcting plate; R, the radius of curvature of the spherical mirror; and n, the index of refraction of the glass.

Now, let $4(n-1)R^3 = 1/K$ then (1) becomes

$$\Delta = x^2(x^2 - kr^2)K \qquad (2)$$

which is in a convenient form for computation. Giving k various values from -1.0 to $+3.0$, we obtain the series of curves shown in Figure 5. When $k = 0$ we have a lens with a sharply turned up edge and flat in the center. This form is one of the most difficult to figure, yet the writers have seen it recommended for amateurs! As k is increased the center rises and the edge is depressed until, when k is unity, edge and center are equally high, and the depressed zone lies $0.707r$ from the center. In this form the amount of glass to be abraded from the lens surface is a minimum and it is this figure which we have found most satisfactory for general purposes; it is also the easiest to construct. When $k = 1.5$ we have a correcting plate in which the effect of chromatic aberration is at a minimum. This is the type of correcting plate which we have used for our "thick-mirror Schmidt" cameras; several of which

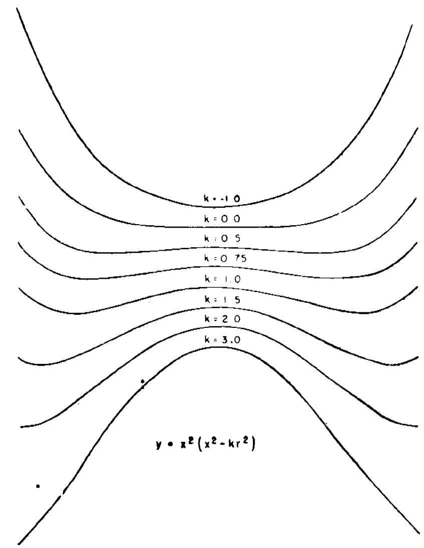


FIGURE 5

have been constructed here. When $k = 2$ the neutral zone is at the edge of the plate and the figure becomes difficult to achieve in practice. In all plates the edge gives some trouble while figuring, because of the flexible nature of the tools used in this work, hence it is best to make the plates at least 1 inch larger than the required diameter; the troublesome edge can then be masked out when the camera is assembled. It is estimated that the cost of labor in making a correcting plate is reduced at least 50 percent by making a generous allowance for the edge.

Differentiating (2) and equating to zero, we have

$$x^2 = \frac{kr^2}{2} \qquad (3)$$

This gives the distance of the neutral zone from the center, and, by substituting this value for x, in (2), we obtain

$$\Delta = \frac{k^2 r^4}{4} K \qquad (4)$$

the depth of the curve at this zone. With these two dimensions, (3) and (4), at our disposal the correcting plate may be rapidly roughed out to shape, the depth of the zone being measured with a suitable micrometer.

The angular field, θ, of a Schmidt camera is given by the equation

$$\sin\frac{\theta}{2} = \frac{d'}{2f} \qquad (5)$$

where d' is the diameter of the plate holder and f is the focal length of the mirror, and, in order to utilize all the light, the diameter, D, of the mirror must be

$$D = d + 2d' \qquad (6)$$

where d is the diameter of the correcting plate. For ordinary purposes d' should not greatly exceed $d/3$.

The correcting plate is made from plane-parallel glass plates free from striae. It is very important that the plates be plane-parallel, especially for telescopes used for stellar photography. If the plates are not plane-parallel, ghost images, caused by the internal reflections in the lens, will be formed to one side of the brighter stars. (It has been suggested to us that these ghost images might prove useful in stellar photometry.) When the plates are plane-parallel these spurious images fall on the image of the star causing them. For ordinary work a high-grade plate glass, such as Crystallex, may be used, but when high ultraviolet transmission is desired, glass such as Schott's U.B.K.5 or Vitaglass must be used. A satisfactory thickness for the correcting plate is of the order of 1/40 to 1/50 of its diameter.

The plates are best supported, during grinding and polishing, on a circular felt pad which should be shrunk before use; the pad should be a little smaller than the lens. For small lenses the glass is held in position by a metal ring slightly larger in diameter than the disk and projecting above the level of the turntable by an amount sufficient to hold it in place, but not high enough to interfere with the motions of the tool. During grinding and polishing the plate should be rotated frequently upon the felt base. In the case of large lenses the plate is best retained on the table by means of sets of vertical spring bronze "fingers" attached to the turntable; at least six such sets should be used.

It will be noted that a certain polishing action is going on, on the rear surface of the plate, during the polishing stage, due to the motion of the plate upon its supporting pad which is difficult to keep free from rouge at this stage. The effect of this is eliminated, after the required figure has been approximated on the front surface, by making the final corrections on the back. During grinding no abrasive should reach the back surface of the correcting plate because of the protective gap between the felt and the edge of the lens. (This is the reason for cutting the felt disk smaller than the plate.)

The best form of tool we have found for grinding out the zones is constructed as follows. Three triants (120-degree sectors of circles) are cut from moderately stiff spring-bronze sheet in such a manner that the grain of the metal—that is, the direction in which the sheet was rolled—is the same in each. These sectors are then cut into radial "fingers," to the underside of the extremities of which are cemented the grinding facets. These facets are cut from unglazed ceramic tile, such as the small size used for bathroom floors. The sectors are then attached to a suitable hub and, if necessary, the fingers may be bent downward and outward, keeping the outer ends parallel to the surface of the plate.

Polishing is done with facets of moderately soft pitch attached to a sponge-rubber base about ¼ inch thick, the rubber permitting the tool to conform to the zonal curvature of the correcting plate. Polishing tools with a sponge-rubber base will be found excellent for working on all optical surfaces where zonal curvature exists.

It will be realized, we think, that all but the smallest tools are of the ring form. For smoothing out irregularities in the curvature of the zones a small common tool, one quarter, or less, of the diameter of the plate may be used. This should be given a long elliptical stroke in the direction of the zone.

Schmidt's method of polishing correcting plates was to place them concentrically on the lip of a shallow circular metal pan, the edge of which was ground so that an air-tight seal could be made between the glass and the metal. The air was then pumped out of the pan, causing the center of the plate to be depressed; then, by the use of a spherical tool of the correct curvature, the zones were automatically polished to shape. This method is not to be recommended, however, except for mass production, when it becomes ***the modus operandi.***

The figure of the plate may be examined during the grinding stage by dipping it into a solution of ethyl cinnimate and Xylol, mixed in a proportion of 4:1. This forms a smooth coating which has approximately the same index of refraction as the glass. After a little experience it is surprising how readily one can detect small irregularities in the curvature, or the displacement of a zone, by direct visual inspection of the form, using a good straightedge held in contact with the plate as a guide for the eye.

The Chinese mirror effect is sometimes useful in correcting local irregularities, and even in polishing and figuring plates with small curvature. The lens is here supported on suitably shaped pads of semi-cured rubber, such as that used for patching automobile inner tubes; the part of the lens thus supported is abraded more rapidly than the unsupported regions.

A number of methods have been worked out here for testing correcting plates, some of which will now be described. The figure of the correcting plate may be readily examined with a knife-edge if one has a telescope sufficiently large to take in the collimated beam from the assembled camera, as shown in Figure 6 at *A*. Using this method, a point source of light is placed at the focus of the camera, and the knife-edge at the focus of the telescope. The sensitivity of this test is proportional to the square of the ratio of the focal length of the telescope to that of the camera.

Where a large telescope is not available for testing we can make use of a small one, in conjunction with a pentaprism or an optical square, as shown at *B*. Here we have a small telescope rigidly set up at right angles to the axis of the camera. The optical square, consisting of two plane mirrors mounted at an angle of 45°, or a pentaprism, is set up in front of the telescope on a base which may be moved across the collimated beam of light. The image of the light source is focused on the intersection of a pair of cross-wires in the focal plane of the telescope. As the pentaprism is moved across the collimated beam the image should remain on the *vertical* wire; any *lateral* motion is due to the poor figure of the optical system; vertical motions may be due to irregularities in the motion of the pentaprism.

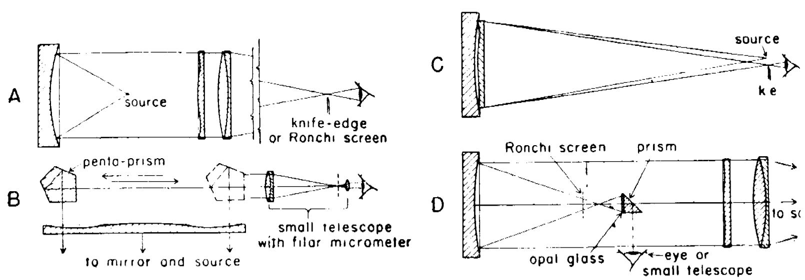


FIGURE 6

An excellent test for cameras having an aperture $f/5$, or less, is made by placing the correcting plate directly in contact with the mirror, as at *C*. The test is made on the axis of the lens, in a manner similar to that used for testing a parabolic mirror in the center of curvature; that is, by measuring the apparent radius of curvature of the various zones with a knife-edge at the focus. In this case the test is twice as sensitive as that for a parabolic mirror because the light passes twice through the lens. The formula now becomes $\Delta R = y^2/R$; this, *when both knife-edge and light source move together.*

A Ronchi screen placed inside the focus of a Schmidt camera will form a series of fringes on a screen placed at a suitable distance from the focal point, as shown at *D*. By using an opal or ground-glass screen these fringes may be examined readily. Each fringe should be straight with parallel boundaries, but the presence of zones in the correcting plate distorts these fringes which are interpreted in the usual manner. The familiar Ronchi screen method of testing is excellent, also, for lenses with large aperture ratios, or where the focus is too short for the eye to focus on the equivalent plane.

An illuminated, small, silvered glass bead serves as an excellent point source of light for testing purposes. The illuminating beam should be concentrated on the face of the bead facing the mirror or lens to be tested. Any stray light which passes the bead should be blocked off by a suitable diaphram placed behind it—a totally reflecting prism is excellent.

To test a correcting plate made to work in the extreme regions of the spectrum (infrared or ultraviolet) we can construct a testing mirror of radius R′ so that, in equation (1),

$$(n - 1)R^3 = (n' - 1)R'^3$$

and thus make the tests in visual light which gives an index of refraction of n'.

There are, of course, numerous other methods of testing correcting plates, but those given here are sufficient, we think, for the average reader. It must be remembered that the plates, to begin with, must be plane-parallel, and they must be free from striae. In selecting plate glass for correcting plates, sheets should be first tested with a micrometer for uniformity of thickness, and then tested for striae by holding the sheet between a small bright source of light, such as an arc, and a white screen. Shadowlike streaks on the screen show the presence of these defects, and their positions can then be marked on the glass with a wax pencil. Unless a large plate is required an area large enough for the purpose usually can be selected from relatively cheap glass.—*Pasadena, California, March, 1939.*

[EDITOR'S NOTE: Earlier publications by Strömgren, Lower, Smiley, Wright, Väisälä, DeVany, and others, together with knowledge and data to some extent existing "in the air" in the period concerned—the early 30s—may have contributed to a certain extent to some of the technics and thinking presented in the excellent article reprinted above.

Crystallex: Pittsburgh Plate Glass Co., Grant Bldg., Pittsburgh, Pa. Vitaglass: Mississippi Glass Co., 200 Fifth Ave., New York, N. Y.

Anyone planning to build the solid Schmidt (type IX) or the thick mirror variation of the Wright (type XV) should read further discussion of these types in *Scientific American,* 1939 Nov., 314–17.

The article that follows was originally published in an X-ray journal because its physician author, seeking fast cameras for photofluorography, or photographing the fluorescent X-ray screen, became interested in the Schmidt and then in Schmidt the man. The original article contained four photographs of Schmidt.]

BERNHARD SCHMIDT AND HIS REFLECTOR CAMERA

By PAUL C. HODGES, M.D.
Division of Roentgenology, The University of Chicago *

Bernhard Schmidt was born March 30, 1879, on the little island of Nargen in Estonia and died December 1, 1935, in Hamburg, Germany. The existing

* Extracted from *The American Journal of Roentgenology and Radium Therapy,* Volume 59, 1948, January, by permission.

European and American literature dealing with optics based on Schmidt's great idea contains almost nothing about the man himself. There is one paper by Schmidt,[1] and Mayall[2] has translated this together with Schorr's appreciation written shortly after Schmidt's death,[3] but it is to Professor Walter Baade of the Mount Wilson Observatory[4] that I am indebted for all the intimate glimpses into the life of this man who has influenced so profoundly the optics of astronomy. Baade was associated with Schmidt intimately at Bergedorf and on an eclipse expedition to the Philippines. He was an early convert to the Schmidt camera gospel and has preached that gospel faithfully since his arrival in the United States in 1931. It is probably true that the world owes the Schmidt camera largely to Schorr's insistence that Schmidt come to Bergedorf in 1926 but it is doubtful that the Schmidt principle would have had such prompt and wide acceptance in the United States without the constant urging of an astronomer of the standing of Baade. Professor Baade devoted a full day to me in Pasadena, during which we talked of the old days in Bergedorf and the Philippines, and since then he has loaned me photographs and sent copious answers to my written inquiries about various points in the Schmidt story.

Nargen is the Germanic name for an island known in the Estonian language as "The Island of the Women." It is only five miles long and about half as wide and lies in the Gulf of Finland, 12 miles off the coast from Tallinn, Estonia, and about 40 miles south of Helsingfors, Finland. A lighthouse at the northern tip, a light buoy at the southeast, a fringe of tiny villages, and in the center fields and woods: that is Nargen as it appears on Estonian maps of 1929 and presumably much as it was in the late eighties and early nineties of Schmidt's boyhood. On the island old customs and costumes prevailed and life centered upon the farms. The Lutheran Church dominated the religious picture and, though the grammar schools probably were better than many American rural schools of the same period, it is remarkable indeed that in this isolated environment a first-rate optical genius should have risen and developed.

Schmidt's Swedish mother and German father were deeply concerned with the religious training of their son in the Lutheran faith, but their influence seems to have been not uniformly successful because on a certain Sunday morning when he was about 11, young Bernhard, though dressed in his Sunday suit, was not in church but instead out in the fields trying out a batch of gunpowder of his own manufacture. He packed it into a piece of metal pipe to assure a good bang and the powder proved to be so good and the tamping so well done that when the explosion did occur it cost him his right hand and forearm. The boy was tough, however, and resourceful. He washed the

[1] Schmidt, Bernhard. Ein lichtstarkes Komafreies Spiegelsystem. *Mitteilungen der Hamburger Sternwarte in Bergedorf*, 1931–1932, No. 36, 7–15.

[2] Mayall, N. U. Bernhard Schmidt and His Coma-free Reflector. *Publications of the Astronomical Society of the Pacific*, 58, 282–290 (1946).

[3] Schorr, R. Bernard Schmidt. *Jahresbericht der Hamburger Sternwarte in Bergedorf*. 1935, 15–18.

[4] Personal communication.

stump in a brook, improvised a tourniquet and made it home unaided, apprehensive principally of anticipated parental wrath over a blood-drenched Sunday suit. Though this ended Bernhard's experiments in ballistics, it did not dampen his interest in mathematics and the physical sciences. From his friend the village druggist he obtained a few photographic plates and a description of a camera that the latter had once seen, and then using a cigar box and the bottom of a beer bottle that he had ground into a lens in a saucer of fine sand, built a camera and actually took pictures with it.

Toward the end of the century, Bernhard enrolled as an engineering student at the Institute of Technology at Gothenburg, Sweden, where he specialized in optics but, true to the tradition of his native land, scorned regimentation in any form. The library received most of his attention and here among other papers on optics he was particularly attracted by those of Dr. Karl Strehl, a physics teacher in a technological school in the little German town of Mittweida near Jena. That the Jena district was a veritable Mecca for those who were interested in optics in no small measure was due to the work and philanthropy of the great Ernst Abbe of the Zeiss optical works and the University of Jena. The son of a workman, Abbe was a devout believer in technical schools as instruments for the advancement of ambitious and intelligent workmen. After the death of Carl Zeiss in 1888, Abbe bought out Zeiss' son, Roderich, in order to convert the firm into a socialized enterprise and turned his own fortune over to the Carl Zeiss Foundation, retaining only an appointment as executive director of the Carl Zeiss Company at a fixed salary. The foundation subsidized technical schools in the district about Jena and presumably the school in Mittweida was included in this program.

As soon as Schmidt could finance the trip, he traveled to Mittweida, to seek out Dr. Strehl, only to find that the latter had moved away four years earlier. Apparently Schmidt liked the environment, however, because he stayed on in Mittweida for a quarter of a century, supporting himself by making mirrors and lenses, and soon established a reputation as an unusually excellent source of small parabolic mirrors for amateur astronomers. Presently orders came from the professionals as well, and eventually Schmidt came to be recognized as one of the ablest of the German astronomical opticians.

But years and fame could not alter his social peculiarities. He scorned regular employment, including offers from the great German optical houses, and accepted orders for mirrors and lenses only as the spirit moved him and always without guarantee as to delivery date. He was a bachelor and his wants were few. Simple lodgings, cognac, cigars, a little food and freedom from regimentation—these were all he asked; and even at the moderate prices he charged, a few jobs each year supplied his needs. But though he was satisfied to work in this sporadic fashion, German astronomy was not satisfied, wanted more and more of the precise work that he was so peculiarly able to perform.

In 1920 Schmidt had made several mirrors for the Hamburg Observatory in Bergedorf and in 1926 Schorr, the director of that observatory, finally induced him to move to Bergedorf and share the living quarters of the younger unmarried astronomers. The arrangement was informal and Schorr describes Schmidt as a "voluntary colleague," an arrangement that avoided his intense distaste for restrictions on his hours of coming and going, working and rusticating, and still gave the Hamburg astronomers first call on his work when, as, and if he felt inclined to work. Schorr deserves great credit for appreciating the importance of bringing Schmidt to Bergedorf and financing his stay there. To do this involved reckless breaking of rules with the risk at least of censure and perhaps even of punishment at the hands of government officials. To pay a stipend to an astronomer or a technician who worked regularly was one thing; but a stipend for a "voluntary colleague" who spent most of his time roaming the woods and talking to himself, that was something decidedly different. It might have cost Schorr his job and his reputation but instead it gave the world the Schmidt telescope.

From the first years of his residence in Bergedorf Schmidt's mind was at work on overcoming the limitations of the reflecting telescope. Usually the mirror was parabolized by grinding away glass from its periphery. This allowed use of the full aperture and provided good resolving power for axial objects, but the field was extremely limited. If a diaphram with a very small central opening was set up at the center of curvature and the mirror was made spherical rather than parabolic, the field angle would be wide and resolving power would be good, but the speed would be very low and the image would be focused on a spherical rather than a flat field. The spherical field was not too bad because it would probably be possible to warp the film to conform to the surface of a sphere but how to open up the stop in the diaphram, admitting more light and thus gaining speed without at the same time introducing spherical aberration? The answer to this question was Schmidt's great contribution to optics. Instead of a simple diaphram opening or stop he decided to use a thin glass plate with an extremely shallow toroidal curve ground into one of the surfaces. Light traversing the center of this plate would pass to the mirror undeviated while that passing through the intermediate and peripheral zones would be deviated just enough to assure that on reflection by the mirror it would be focused sharply onto the the spherically warped film. For practical purposes the results would be the same as though a very small central stop had been used except that the light-gathering power of the system would be enormously greater.

From March to June, 1929, Schmidt accompanied Baade on an eclipse expedition to the Philippines, and one evening when they were in the Indian Ocean told him that he had solved the problem of designing a coma-free reflector that would have good light-gathering power and wide field. He sketched the basic design and then the details of construction, possible forms of correcting plate, size of field, residual color, vignetting, etc., and it was evident that the whole thing had been thought out some time earlier—perhaps even before leaving Hamburg. Baade urged that Schmidt plan to build such a reflector as soon as possible after returning to Bergedorf but the reply was that Schmidt must first think up an "elegant" way to grind the aspherical surface of the plate or in the vernacular of optics to "figure" it. To do it

with small grinding tools Schmidt thought would be a sloppy job and would produce a plate that was full of zones.

After the expedition had returned to Hamburg, Schorr in his energetic fashion joined Baade in urging Schmidt to get on with the work but to no avail. Schmidt was unperturbed and continued as before on his seemingly aimless daily walks. Finally in the winter of 1929–1930 he remarked casually that he had at last devised an elegant solution for the figuring of the plate but for some of the details needed to consult a treatise on elasticity. Baade suggested the recently acquired "Handbuch der Physik" and after more than a week of library work Schmidt announced that he had found what he needed and was ready to assemble his grinding equipment.

There was a heavy metal pan of carefully calculated diameter and with its upper edge ground at a precise angle or bevel based on the coefficient of elasticity of the particular glass plate that was being used and on the minute dimensions of the toroidal curve he wished to produce. The glass plate (of greater diameter than the pan) was sealed to the ground edge of the pan and then, by means of a hand pump and manometer, air was exhausted until a particular negative pressure had been developed. This caused the glass plate to warp slightly, the center being low, the glass over the edge of the pan high. Holding the plate in this position by maintaining a constant negative pressure, Schmidt ground the upper surface until it was again plane, and then when the vacuum was released the plate sprang back until its bottom surface was plane, its upper surface slightly figured.

Baade remembers visiting the basement workroom one morning. Schmidt was napping briefly after 36 hours of uninterrupted work and on waking accepted cigars but declined coffee and sandwiches because, though the plate now had the desired curve, there was still the drudgery of obtaining the necessary polish. Twelve hours later the plate was finished and, as predicted, was free of zones.

The camera went into operation early in 1930 and many dozens of stellar photographs were made in the following weeks and months. The windmill photograph, which was quite incidental, was made on a very cold winter night early in 1931 when the Schmidt camera was about a year old.

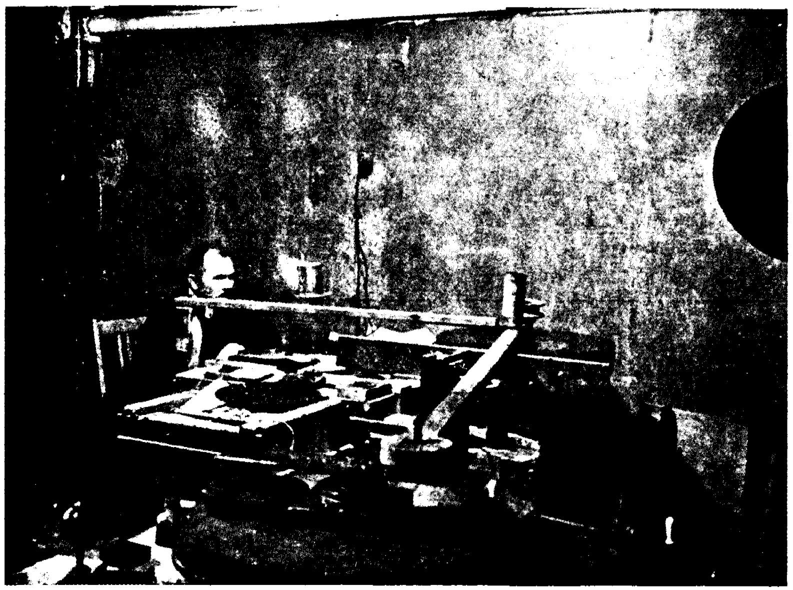
Schmidt's one and only publication appeared in 1932 and would not have appeared at all except for the loyal and diplomatic urging of his friends Schorr and Baade. Finally with the aid of the inevitable cognac, coffee, cakes and cigars he was induced to dictate the paper to Baade and after rewriting it for a last polish to give final approval to its publication.

In Schmidt's original camera the diameter of the correcting plate was 14.2 inches and that of the front surfaced mirror was 17.3 inches. The mirror had a radius of curvature of 49.2 inches, and the speed of the system was $f/1.7$.

[Editor's Note: Further facts about Schmidt have been supplied by Dr. Walter Baade of the Mount Wilson and Palomar Observatories, the astronomer who originally gave Schmidt's name to the camera Schmidt invented.

"An ardent pacifist, he saw the dark clouds of World War II gathering in his final years and the grim outlook made him despondent. Bitterly he complained that the military would sieze upon his invention and harness it to the chariot of Mars. As he feared, extensive use of the Schmidt principle was made by both sides during the war, but with the coming of peace it began to find the humane and beneficial employment that would have gladdened his heart.

"A highly unusual man, this Bernhard Schmidt. He always worked in the claw-hammer cutaway coat and striped trousers of formal attire. He rebelled



Hodges reprint

Bernhard Schmidt in his shop at Bergedorf testing photographic objectives for the 60-cm refractor.

at any regular working hours. Money meant nothing to him. He liked his schnaaps, and chain-smoked good cigars. Old German colleagues remember him pacing abstractedly about the Hamburg suburb of Bergedorf, a brown hat pulled low and his inevitable cigar tilted so high that they always feared he would set the brim of it on fire. His friends were few, for he was shy and retiring. His aloof manner encouraged little intimacy. He prized his independence above everything else.

"In 1926 Schmidt had proposed to me to correct the field of a reflector by putting in contact with the mirror a lens of the same size. He was very much in love with this idea but the astronomical trend was against this type of correction, because it would obviously have been impossible to provide lenses

of very large sizes. Apparently Schmidt became convinced himself of the drawback and quietly went on another tack. He told me his final solution during a shipboard conversation in the Indian Ocean. He had thoroughly worked out his new scheme and it only remained for him to figure such a system.

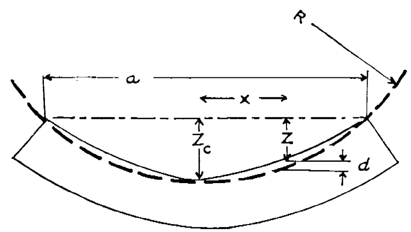
"By the summer of 1930 he had completed his first 14-inch. Schmidt called me one sultry Sunday afternoon to say it was ready. From an attic window of the observatory he trained it on a cemetery. 'Can you read the names on the tombstones?' he asked. 'Yes,' I replied, 'but I can see only one thing: the optics are absolutely marvelous.'

"Astronomers in Europe were skeptical and preferred to stick to the old types despite their aberrations. Even pictures made with the 14-inch Schmidt failed to persuade. At the price of $1100 the instrument went begging. But when I showed the stellar photographs made with the Schmidt to Hubble, Dunham and Sinclair Smith at Mount Wilson their enthusiasm was immediate. They asked how large a Schmidt was practical. On the Sunday afternoon of the first test Schmidt had set the size at 48 inches. Anything larger would encounter disminishing returns, and research at Mount Wilson and the California Institute of Technology bears out this forecast."

Elegant as it is, Schmidt's partial vacuum method of figuring correcting plates has not been used to any extent. Why? This question was submitted to Chief Optician Don O. Hendrix of the Mt. Wilson and Palomar Optical Shops, who figured the correcting plates for a number of Schmidts, culminating in the 48-inch "Big S" at Palomar Mountain. He replied:

"Schmidt's original vacuum bending method of generating the proper correcting curve was and is very successful. The only bugs are: (1) The plate will usually break if bent down enough to generate a curve for cameras $f/1.5$ or faster. (2) One can, by ordinary methods, make a correcting plate before he can compute the necessary curvatures and collect or make the necessary pumps and auxiliary apparatus. (3) For very fast cameras the curve obtained is not sufficiently exact and requires considerable hand correction. The reason for this is that as soon as one grinds for a while the deflection is *not* that for a parallel plate.

"If anyone wants to try the method for himself the deflection Z of a flat circular disk supported at the edge, not clamped, and uniformly loaded is (from 'Handbuch d. Physik')



$$Z = \frac{3}{16}\frac{(m^2+1)dP}{m^2EL^3}\left(\frac{5m+1}{m+1}r^2 - x^2\right)(r^2 - x^2)$$

where P = pressure per unit area, m = Poisson's ratio (3 for glass), E = elastic modulus (3500 tons per square inch for glass), r = radius of disk, L = thickness of disk, x = radius of zone.

When the above is shorn of constants it becomes

$$Z = \frac{Z_c}{\left(\frac{a}{2}\right)^4}\left[\left(\frac{a}{2}\right)^2 - \frac{1}{4}x^2\right]\left[\left(\frac{a}{2}\right)^2 - x^2\right] \quad (1)$$

and for the Schmidt corrector plate

$$d = \frac{1}{32(n-1)F^3}\left[k\left(\frac{a}{2}\right)^2 x^2 - x^4\right] \quad (2)$$

Combining (1) and (2) one gets the sphere (approximately)

$$Z + d = \frac{1}{2R}\left[\left(\frac{a}{2}\right)^2 - x^2\right]$$

and

$$R = \left(16(n-1)\left(\frac{F}{a}\right)^3\right]a \quad (\text{for } k = 1)$$

"Schmidt was a great believer in trade secrets and did not publish or otherwise divulge his method of correcting plates except to a few intimate friends, and thus almost lost priority for the method. Many others, including myself, independently worked out the same scheme of correcting Schmidt plates and it was not known until after Schmidt's death exactly how he made them."

In *Publications of the Astronomical Society of the Pacific* (675 Eighteenth Ave., San Francisco 21, Calif.) Vol. 58, pages 282–290 (1946, Aug.) Dr. N. U. Mayall of the Lick Observatory published a translation of a biographical sketch of Schmidt by R. Schorr, director of the Hamburg Observatory in Bergedorf, from which the following is abstracted by permission.

At Mittweide about 1900 Schmidt began the systematic manufacture of astronomical mirrors up to 7.9 inches in diameter, which were widely distributed in amateur circles and which created a mild sensation because of their perfection. In 1905 he made a 15.8-inch $f/2.26$ mirror which far surpassed in quality other existing mirrors at the time. His Cassegrainians usually were given spherical primaries, the secondaries being figured to match. He refigured the 19.7-inch objective lens of the Potsdam Astrophysical Observatory, the 23.6-inch photographic objective of the Hamburg Observatory in Bergedorf, also the 11.8-inch photographic objective of the Leipzig Observatory. He used the Foucault test and the interference test for mirrors. He worked with his left hand, his only hand. He always used relatively thin glass tools, never iron tools. He never used machines. He was eminently successful in other engineering and scientific fields, such as aerodynamics, gastrophotography, the manufacture of large micrometer screws of great precision, and the making of spectroheliosscopes.

In the same article Dr. Mayall translated Schmidt's own article from *Zentral Zeitung für Optik und Mechanik*, 52 Jahrgang, Heft 21; *Mitt. d. Hamb. Sternw. in Bergedorf*, 7, 15, 1931–32 (No. 36) as follows:

A Rapid Coma-free Mirror System *

By Bernhard Schmidt

If losses of light of a mirror and of a lens system are compared with each other, then for the same aperture ratio the mirror shows a smaller loss of light than the lens system. A freshly silvered mirror reflects at least 90 percent of the incident light, while a two-lens system transmits at most 80 percent, and a three-lens system at least 70 percent of the incident light. In the case of large lenses, the situation is still more unfavorable because of the stronger absorption of short wavelengths by the glass.

In large telescopes, the parabolic mirror thus would be more advantageous, in general, than a lens system, but unfortunately with large aperture ratios the usable field of view is very limited by coma. For an aperture ratio of 1 to 3, the spreading due to coma amounts to 37 seconds of arc for a field diameter of only 1 degree; moreover, the spreading due to astigmatism becomes 5 seconds of arc. Coma increases in direct proportion to the field diameter, astigmatism quadratically. As a result, astigmatism in the vicinity of the axis is negligibly small and almost pure coma is present, while at greater distances from the axis it is modified by astigmatism.

Nevertheless, a parabolic mirror of aperture ratio 1 to 8 or 1 to 10 surpasses the ordinary two-lens objective as regards image sharpness, which is due to the fact that chromatic aberration is entirely absent in the mirror. But it is a disadvantage that the light-distribution in the aberration disk of the mirror image is one-sided, for this condition can produce systematic radial displacements in measurements of such images.

But it will be shown below that even a purely spherical mirror of aperture ratio 1 to 8 or 1 to 10 is still quite usable. If the aperture stop were brought directly in front of the mirror, then there would be no advantage over the parabolic mirror, since the spherical mirror has exactly the same aberrations; besides, spherical aberration would be present, which increases the existing aberrations over the whole field of view. However, if the aperture stop is brought to the center of curvature, the spherical mirror no longer has any but longitudinal aberrations, for coma and astigmatism are zero. The image surface lies on a sphere whose radius is the focal length and which is concentric with the mirror surface, so that the image surface is turned with the convex side to the mirror.

The aberration of a spherical mirror of 1 to 8 or 1 to 10 ratio amounts to

* By permission of the Hamburg Observatory

12.5 or 6.4 seconds of arc at the paraxial image point, and the smallest possible aberrations are only one fourth of that, 3.1 or 1.6 seconds of arc.[1] In practice, even sharper images can be obtained if the focus is set between these two positions. Under normal conditions these aberrations are smaller than the spreading inherent in the photographic layer. Therefore, even with the use of flat plates, the image quality at the edge of the field is better than with a parabolic mirror of corresponding aperture ratio; the star images are round everywhere, with a symmetrical light-distribution.

Moreover, if a round, flat film is curved by pressing it with a ring over a spherical surface corresponding to the image surface, which is easily possible without wrinkling, then the confusion disks are the same size over the entire field. The same thing can be accomplished with a sharp-edged plano-convex condenser lens in front of a flat photographic plate (plane side of the lens toward the plate).

If the aperture ratio is greatly increased, however, then the spherical aberration becomes very large, since it increases with the third power of the aperture ratio. For 1 to 3, or 1 to 2, the aberrations at the paraxial image point are 240 or 800 seconds of arc. The smallest possible confusion disk has a diameter of 60 or 200 seconds of arc. With a focal length of 1 meter (39.4 inches), the paraxial rays then would be 1.2 or 4 mm (0.047 or 0.157 inches), or the smallest possible ones 0.3 or 1 mm (0.012 or 0.038 inches). In this case, therefore, the spherical mirror no longer would be useful.

I shall now show how completely sharp images can be obtained with a spherical mirror of large aperture ratio.

In order to produce a parabolic mirror from a spherical mirror, the latter's edge must be flattened, that is, be given a greater radius of curvature. However, a concentric curved glass plate (of the same thickness everywhere) can be placed on the spherical mirror, and one of its surfaces deformed. But now the curvatures must be reversed, and its edge must be more strongly curved than its center. Also, the amount of the deformation must be twice as great, because now the deviation results from refraction. In general, in order to obtain the same deviation by refraction as by reflection, about four times as great inclinations have to be given, but in this case, since the rays go through the glass surfaces twice, only twice as large deformations are necessary.

This plate can be optically sagged to such an extent that one side becomes plane again, while the other has a pure deformation curve. That is to say, a plane-parallel plate, instead of a zero-power meniscus, can be deformed just as well from the beginning. Almost the same effect is thus obtained optically with this correction plate as with a parabolic mirror.

A suitably shaped cover plate of this kind for a spherical mirror[2] also has the practical advantage that the silver coat of the mirror is well protected. It

[1] TRANSLATOR'S NOTE: The pair of larger figures refers to the size of the aberration disk at the focus for paraxial rays, the pair of smaller ones to the size of disk at the focus for rays from the outermost zone.

[2] TRANSLATOR'S NOTE: One form of this optical system is known as the Mangin mirror; it is described in Czapski-Eppenstein, "Grundzüge der Theorie der Optischen Instruments," 3d ed., pp. 110–11, 1924.

is a disadvantage in that, owing to the passage of light twice through the glass plate, the loss of light reaches about 20 percent.

The correcting plate can also be placed in another position in the optical path. If it is located beyond the focal surface, then the light goes through the plate only once. The plate then obviously must have twice as much deformation as in the first case. The loss of light is then only 10 percent.

If the correcting plate is now brought to the center of curvature of the mirror, then there result the same relationships as before in the case of the spherical mirror with aperture stop in the center of curvature, but with the difference that now the spherical aberration is abolished, even over the whole field. Thus it is possible to use aperture ratios of 1 to 3 or 1 to 2, and to obtain freedom from coma, astigmatism and spherical aberration.

If the inclination of the incident rays is very large, then the correcting plate is projected as an ellipse, and the deformation is not projected on the correct places of the mirror, so that the correction is variable and even introduces an overcorrection in the radial direction. However, large inclinations do not need to be considered at all, since the photographic plate soon would become greater than the clear aperture. In practice, photographic plates greater than one fourth to one third the aperture can hardly be used, the inclination aberrations then being negligibly small.

The case is somewhat different for the chromatic aberrations of the correcting plate. In order to keep these as small as possible, the correcting plate is so shaped that the central part acts like a weak condensing lens, and the outer parts have a divergent effect. If the neutral zone is placed at 0.866 of the diameter, then the chromatic aberration is a minimum. If the point of inflection of the curve is at 0.707, then the thickness of the edge is equal to the central thickness. The remaining difference in thickness between the thickest and thinnest parts of the plate is very small, only several hundredths of a millimeter, so that a disturbing color effect does not occur; in any case, the effect usually is much smaller than the secondary spectrum of a corresponding objective.

This chromatism is identical with the so-called "chromatic difference of the spherical aberration."

If the mirror has the same diameter as the correcting plate, then the incident cylinder of rays for outer images falls eccentrically on the mirror, and there is a part of it left out, so that the outer portions of the plate obtain somewhat less light. If this is to be avoided, the mirror must have a greater diameter than the clear aperture, and of course it must be greater by about twice the plate diameter. In a mirror of 50 cm (19.7 inches) clear aperture (diameter of the correcting plate) and of 1 m (39.4-inches) focal length, the photographic plate for a field of 6° has a diameter of 10.5 cm (4.1 inches), and accordingly the mirror must have a diameter of 71 cm (28 inches).

The rapid coma-free mirror system described here offers, according to the preceding considerations, great advantages in regard to the light-gathering power and aberration-free imagery. There is assumed, however, a technically complete understanding of the correcting plate.

Building a Birefringent Polarizing Monochromator for Solar Prominences

By Henry E. Paul
Norwich, N. Y.

Introduction: A touch of excitement tinged with awe usually accompanies the first viewing of an eruptive prominence surging upward from the sun at thousands of miles per minute to reach tremendous heights. These millions of tons of glowing gas often stream back in graceful arch to the sun as if drawn by a huge magnet.

Since the early days of man, the sun has always been a subject of study. With the advent of the telescope, total eclipses permitted an occasional glimpse of the flaming prominences as rosy cloudlike formations, constantly changing above the surface of the sun. However, these glimpses were all too few. The birth of the spectroscope, which isolates narrow regions of color or wavelengths of light, such as the red line of hydrogen abundant in the prominences, opened a new era. Observers such as Lockyer could now view these phenomena through the widened slit of a solar spectroscope in any clear sky. Soon vibrating slits and rotating prisms extended the field of view for Hale and others as the simple spectroscope was modified to become a spectrohelioscope.

Newer and effective narrow transmission band filters developed by Lyot and Evans became compact instruments for viewing and photographing prominences. Out of combinations of these with Lyot's coronagraph, a refined occulter of the sun's surface, there emerged new and powerful tools for research on both solar prominences and surface activity.

The viewing of the spectacular solar prominences by red hydrogen light requires the possession of an instrument capable of removing the entire visible light emission spectrum of the sun excepting a narrow pass band of red light coinciding with the hydrogen (Hα) absorption line (so-called C line) of the solar spectrum. The Hα line of these solar prominences is about 1 angstrom wide centered on wavelength 6562.8. For prominence work the effective transmission band width should be held within a range of 3 to 7 angstroms for best performance. Sun surface work requires filters having an effective pass band in the range of 1 angstrom.

Of the various types of instruments designed for solar study, only two seem suitable for construction by the average amateur, the spectrohelioscope and the quartz-Polaroid filter. Each has advantages and disadvantages for both amateur and professional.

The spectrohelioscope (see ATM) permits narrow band viewing of both surface and edge activity on the sun. It permits viewing the sun by any wavelength of light, for example those of the calcium, hydrogen, helium lines. It suffers from obvious defects of vibrating slits or rotating prisms and, above all, for the amateur, the necessity of obtaining a suitable grating at a cost within his means. The years have rolled by without the numerous promises of "cheap" high-quality replica gratings coming true.

The quartz-Polaroid filter permits beautiful wide-field viewing of the promi-

nences in sharp detail without vibrating slits or expensive parts, as may be noted in the photographs at the end of this chapter. It also has disadvantages. The temperature of the filter must be closely controlled. The simple fixed temperature form discussed here can be constructed for use at only one wavelength, for example Hα. Optical quartz is scarce and expensive and, in the past, directions for construction have been none too complete.

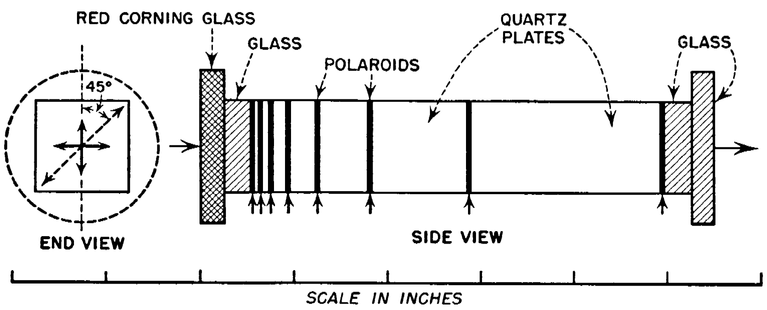
The present chapter is written primarily as an aid in the construction of a quartz-Polaroid filter. Emphasis will be placed on those factors omitted or not clear in the literature cited at the end of the chapter or which gave me excessive trouble. It will be unnecessary to give a detailed theoretical discussion, since extensive reviews of the theory of these filters have been written by competent men such as Lyot (3), Evans (5) and Pettit (2). The use of other birefringent materials is also discussed in these papers.

What spare time I have had for several years has been devoted to the construction of quartz-Polaroid filters. The excellent series of articles by Dunn (1), had they been available sooner, would have saved me much investigational work. All references listed are excellent articles and honest differences of opinion with them in this chapter are not to be regarded as criticisms. The major contributions to the birefringent filter itself have already been made by these and others, and thus it is the task of the present writer to help "clear up" some of the annoying details of *actual construction* which may confuse one making a filter for his own use.

To anyone who is building one of these filters, I cannot overstress the importance of obtaining the literature referred to at the end of the chapter, in order of usefulness, excepting perhaps the Lyot paper for those who do not care to translate French. The articles are not wholly different but the reading of essentially the same information expressed in a different manner often helps to clear up annoying details. For those unfamiliar with methods of obtaining literature, the simple expedient of turning to the head librarian in any modern city library is recommended. She can obtain almost any article on loan from the larger libraries as well as photostatic copies when desired. Some of the authors may still make reprints available to the serious if approached.

The Basic Filter: The simplest form, described here, consists of seven quartz plates having a Polaroid sheet between each plate and on each end. Each quartz plate is exactly twice, or half, as thick as an adjacent plate. The vibration planes of the eight Polaroid polarizers are all parallel to each other and at 45° to the optical axis of the quartz plates. The optical axis (c or z axis) of each quartz plate is parallel to its polished faces and two sides. Side and end views of such a square element filter are shown in Figure 1, with square glass end caps and circular retaining plates indicated (one of which may be a red glass filter). The optical axis (c or z axis) of the quartz plates runs from top to bottom, as indicated by the dashed line in the end view. However, any plate may be rotated 90° about the line of sight. The axis is a direction *only* and applies to any part of any plate. The diagonal double headed arrow indicates plane of vibration or polarization of *all* the Polaroids. These could also *all* vibrate at 90° to this direction.

Light entering this filter has its directions of vibration polarized by a Polaroid to vibrate at 45° to the quartz axial direction. Upon entering the birefringent quartz plate, this light is broken up into two parts, one vibrating vertically, the other horizontally, perpendicular or parallel to the axis of the quartz, as indicated by short arrows in the end view. These rays travel at different speeds, and upon emerging from the quartz plate are again both brought together into the 45° plane by a Polaroid, where they reinforce or interfere according to the wavelength of the light and thickness of the quartz plate. If a



OPTICAL ELEMENTS OF A BIREFRINGENT QUARTZ-POLAROID FILTER

CLEAR AREAS INDICATE QUARTZ PLATES ↑ARROWS INDICATE POLAROIDS

Drawings by J. F. Odenbach, after the author

FIGURE 1

Polaroid-quartz-Polaroid "sandwich," as described, is placed in parallel light in front of a suitable spectroscope, the varicolored spectrum observed will be alternately broken up into bright and dark sections. The spacing and location of the bright channel spectrum or pass bands (and alternate dark bands) depends on the thickness of the quartz plate. For a thin quartz plate, about 1/32″, these broad pass bands will be widely separated by about 500 angstroms. A plate exactly twice as thick would have pass bands of half the separation and band width of the thinner plate. If we keep doubling thickness from plate to plate, as in the case of the seven plate filter of Figure 1, the thickest plate (64 times the thinnest) of about 2″ will have pass bands separated by approximately 9 angstroms and an "effective" width or "half width" of *about* 4 angstroms. Figure 2 illustrates graphically the terms used. These rough illustrative values apply only to the region in the red near Hα (6562.8 A). Precise computations must be made to have a pass band fall upon Hα at a fixed temperature. Exact figures will be given in the section on construction and tolerances. Starting with the thickest plate the method by which each successive filter plate eliminates alternate pass bands is amply described by Pettit (2) and Evans (5,6)

and others. See also Figure 8. Suffice it to say that the thinnest plate governs the separation of final narrow transmission bands, and the red pre-filter to be used, while the thickest plate governs the width of the final narrow band passed, say 9 angstroms at Hα. While no extensive knowledge of the basic theory of these filters is required for construction (and hence its discussion is omitted), a little study of the recommended references may assist in their construction.

Before obtaining materials of construction certain problems will plague the

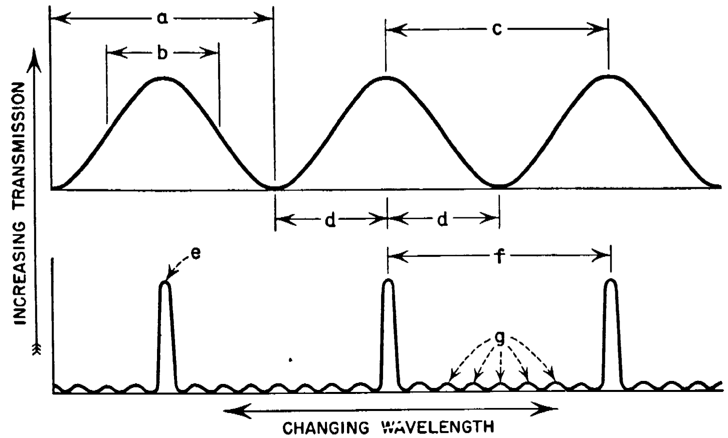


FIGURE 2

Transmission pattern of channel spectra plotted against wavelength. Upper figure: single plate plus Polaroids; a, full transmission pass band width, usually in angstroms, minimum to minimum; b, "half-width" transmission; c, peak to peak separation; d, maximum to minimum separation.

Lower figure: Multiple (4) plate filter; e, primary pass band; f, primary pass band separation; g, secondary or "leakage" bands.

beginner, such as filter size, and shape, best pass band width, number of plates, etc. For the amateur the square plate is recommended as easier to orient than the round. The square plate also may reduce vignetting in photographic setups. A 1″ square (or circular) aperture is ample for prominence work if used in a proper lens system. The cost of true *optical* quartz also suggests this size. However, if ample quartz is available the amateur might well select 1¼″ square as an optimum size. This slightly larger plate is actually easier to work. Other advantages of the 1¼″ size are listed in describing accessory optics. Should some of the corners of the squares fall short during the cutting of the crystal, or be chipped, a circular aperture may be used with the filter. Dunn (13) has made the observation that hexagonal or octagonal plates might well be used to save quartz in larger elements.

Some early filters of about 4 angstroms' effective band width were made with six plates, omitting the thinnest plate. Unless careful consideration is taken of several factors such a filter may not function at its best, since the pass bands are so closely spaced (about 250 angstroms) that even a well selected, sharp cutoff red filter may either transmit some of the adjacent band on the blue side, or reduce transmission at Hα, while the band on the red side of Hα still transmits considerable light to the eye. The thinnest seventh plate is recommended as solving all these problems although it is a bit difficult to make.

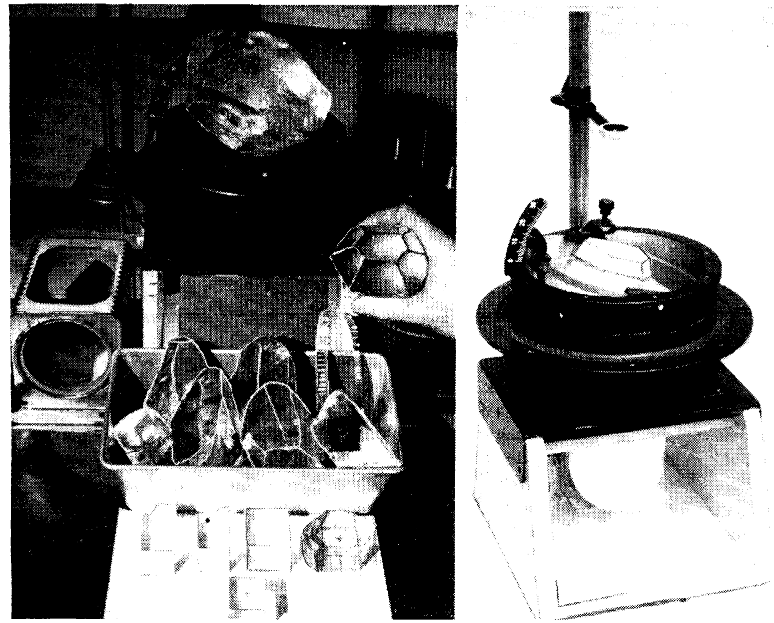
An effective pass band width ranging from 3 to 8 angstroms is recommended for prominence study. I have chosen about 4 angstroms as optimum and note that Evans (6) also states this effective band width to be nearly optimum for observation of solar prominences. The beginner may shy away from the 2″ quartz plate, or an equivalent one of calcite. If this is omitted the filter of 8 angstroms' effective width would still show the solar prominences in times of good seeing.

Optical Quartz: The problem of obtaining high quality quartz can be an annoying one. It may best be likened to the horse trading of earlier years, where the quality of the merchandise is most likely to be governed by the same "rules," much depending on the purchaser's ingenuity and luck but mostly on his knowledge and testing equipment. As always, the integrity of the supplier is important, but to my knowledge no dealer will or should be asked to guarantee raw quartz for a particular purpose. It is supplied with the hope that it will be suitable. Fortunately, most dealers will permit one to inspect and test the quartz with the understanding that unsatisfactory stones may be returned in "as received" form; i.e., uncut and unchanged. These arrangements should be made at the start. An offer to pay all shipping expense on unpurchased material may help interest the seller in your relatively small orders.

Sources of Quartz: The Diamond Drill Carbon Co., 53 Park Row, New York 38, N. Y.; Murray American Corp., 95 Summit Ave., Summit, N. J.; Martin E. Quitt, 855 Ave. of the Americas, New York 1, N. Y.; Karl Lambrecht, 4318 N. Lincoln Ave., Chicago 13, Ill.; Pan American Trading Co., Inc., 50 Broad St., New York 4, N. Y.; American Gem and Pearl Co., 6 West 48 St., New York 19, N. Y.

Optical quartz is sold only in certain crystal size ranges by weight in grams (453.6 grams/lb.). The price increases rapidly with weight. Three ranges will be of interest: 300–500 gms., 500–700 gms., and 700–1000 gms. While some 1″ squares can be squeezed from the first group, the 500–700 gm. range seems the best choice. For 1¼″ square plates and the 2″ long plates the 700–1000 gm. crystals will be best. Prices per pound vary greatly ($25–$50, 1952). Ask for Grade 1 *optical* quartz crystals (sometimes called stones) having a usable proportion of 60 to 100 percent. By usable portion is meant a single large area free from all defects detectable in an oil bath using both a moderately bright coverging light cone and polarized light. You will have to determine usableness yourself. See Figure 3, left, showing raw and semifinished quartz. In the lower left corner of the tray and on the orienter plate are small and large end

caps of river quartz, rounded, chipped and cracked from river action. The interior is often excellent. In the lower right corner of the tray is a sample of a shape having poor usableness—the black area indicating the only portion usable for a 1″ sq. plate. Axes of quartz shown are essentially vertical. In the upper right corner of the tray is typical candle quartz. The edge striations



Photographs by the author

FIGURE 3

Left: Optical quartz, raw and semi-finished. Right: A simple quartz axis orienter.

shown always indicate a plane perpendicular to the axis. Other crystal shown is quite typical. The handheld slab resulted from two parallel cuts made at right angles to the axis of a large perfect end cap.

The two best sources of information I have found as aids in selecting quartz are a symposium on quartz oscillator plates (8) and a book by Heising (9). The requirements for oscillator plates are closely related to those for optical quartz. I also found a visit (courtesy of Dr. Francis Phelps) to the Quartz Crystal Research Laboratories at the National Bureau of Standards, Washington, D. C., worth several books, since it offered an opportunity to see quartz testing equipment and how it was used, as well as to observe the effects of all types of defects under proper inspection conditions.

The amateur does not need the elaborate equipment often used and recommended. A carbon arc, as used at the Bureau of Standards, requires direct current, and plenty of it, for operation. After much trial and error, I worked out a testing set-up which, for practical purposes, performs as well as more elaborate units.

A one gallon glass walled testing tank will take the sizes listed. I used a two gallon low cost electroplaters tank but would recommend one with plane glass walls, such as the glass aquarium tank of one or two gallon capacity No. 57008 sold by Central Scientific Co., 1700 Irving Park Road, Chicago, Ill. Check the walls between crossed Polaroids for freedom from strain. Many suppliers who test quartz use ordinary liquid petrolatum (white mineral oil). The index of refraction of this is considerably on the low side (approximately 1.48). One government laboratory uses HB-40 (Monsanto Chemical Co., Phosphate Div., St. Louis, Mo.) which has an index somewhat on the high side (about 1.57). I found that one part of ordinary heavy U.S.P. mineral oil (your corner drugstore) mixed *thoroughly* with two parts of HB-40 resulted in an excellent test oil having an index approaching very closely that of quartz. Please bear in mind that the supplier of HB-40 grants a favor in selling only a gallon, since this is normally sold in large quantities as a plasticizer. Other oils are listed in references 8 and 9.

As a substitute for the carbon arc lamp, an Eastman Kodak 35 mm No. 2 slide projector was fitted with two 1½″ diameter, 5″ to 6″ fl war surplus achromats taped to the front of the projection lens which in turn was placed close to the back wall of the tank. A converging bright cone of light now focuses about 3″ inside the tank. Quartz crystals held in this light cone may be viewed from above and rotated about in the beam for detection of the many varied defects which now become strikingly visible.

For certain defects, such as optical twinning, mercury light is required. The expensive sources often listed may amply be replaced with an ordinary bathroom self-contained sun lamp such as G.E. or Westinghouse 275-w, 110-v/a-c type R.S. No ballast is required. This sun lamp is placed at least a foot behind the tank. Between the lamp and the tank are placed in the following order: Corning (Corning Glass Co., Corning, N. Y.) 3″ molded filters Nos. 3484 yellow and 5120 didymium, a ground glass and a sheet of Polaroid. The glass filters and Polaroid must be kept 6″ or 8″ away from the lamp to avoid heat breakage and other damage. The ground glass *must* be on the lamp side of the Polaroid to avoid depolarization of the light. On the viewing side of the tank in path of the light from the sun lamp is placed a Polaroid sheet with its axis crossed with respect to the opposing Polaroid. Quartz may now be inspected, through the Polaroid and side of the tank, for locating the optical axis in stones having no natural faces to serve as a guide. Broad dark and light contour lines will be observed under this approximately monochromatic light. Too much light is lost by using a third filter (Corning No. 4303 blue green) for

strictly monochromatic light. A little experimenting and study of the references given will permit easily locating the optical axis in raw quartz and detection of minor strains and index variations, as well as axis location in rough-ground plates.

A heavy wire screen (½″ mesh) with edges bent down to support itself about an inch above the bottom of the test tank will avoid broken quartz, or tank bottom, and also avoid stirring up dirt from the bottom. Keep the tank covered as much as possible. Lint from paper towels or cloth depolarizes light and can interfere in testing if too much collects in the oil.

Upon immersion of the quartz in an oil bath of its own index of refraction, the quartz surfaces almost disappear and the intense cone of light from our projector reveals in a startling manner the multitudinous defects usually present. The common names of defects most often adequately describe these. Inspect for cracks or fractures, smokiness, bubbles, cavities, bubble sheets or phantoms, veils, clouds, haze, ghosts, chuva or white needles, blue feathers, and the all too common blue needles ranging from diffuse to fine sharp blue lines.

Quartz showing no defects under *moderate* illumination is OK for a usable filter for an amateur's own use and satisfaction. A few fine common blue needles could well be tolerated for work in the red. Use your red Corning filter in the projector beam; if they disappear the crystal will be satisfactory. Needles often occur in bundles of Vs with the apex of the V *always* toward the base. Inspect carefully while wabbling the base of the crystal about in the light cone, as this brings to view many of the defects. Careful inspection in nearly *all* positions is necessary. While I have used perfect (by test) quartz in filters I have made, I am sure some small departure from perfection will still permit construction of a practical and usable filter—much as a fine scratch or mar, not tolerated by the professional, may interfere very little in the performance of an otherwise perfect lens. A danger always lies as to where and how much to relax standards; therefore, indulge lightly.

Using the mercury lamp with a ground or opal glass replacing the Corning filters, we may inspect the quartz between crossed Polaroids for optical twinning in polarized unfiltered mercury light. Such twinning is merely an intergrowth of right and left hand quartz. Quartz can exist in two forms, one axially rotating polarized light in the opposite direction from the other, hence the designation right and left hand quartz. Since a crystal without some twinning is rare, one will see the conspicuous colored effect of such internal twins when looking through the quartz along a direction near the optical axis. Brazilian quartz usually shows the parasitic twin laminae of one hand as slim triangular areas in the margins of the host crystal. Much of the interior may be free from such twinning.

Since our plates are used with light traveling at right angles to the axis and since twinning is primarily an axial phenomenon, as is the characteristic of right and left handedness, theoretically twinning should not affect our use. However, it cannot be totally disregarded for several reasons. Besides interfering (if heavily twinned) in our optical orientation, twin boundaries, as stated by Gordon (8), are areas of weakness and thin plates may, therefore, be subject to cracking. While I have not used twinned material I believe it could be used with the possible exception of plates $\frac{1}{16}''$ thick or thinner. Otherwise the "hand" of the quartz is immaterial for our use. For further detail and excellent photographs see references 8 and 9.

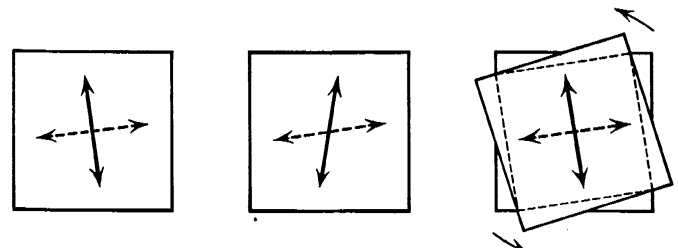
If we now turn to monochromatic light by placing the Corning filters described in the mercury light path the quartz may be inspected for location of the axis. If one inspects a flat plate cut perpendicular to the axis by viewing it along the axis, a series of concentric rings (isochromic rings) will be observed, the spacing depending on the thickness. In thin plates a shaded dark centerless Maltese cross or isogyre, as large as the rings, will be observed. In rough quartz near, or on, the axis these dark bands will become irregular and actually serve as contour curves as the crystal varies in thickness. When the crystal is positioned to show the fewest and widest dark bands one is looking along the optical axis. For detail refer to Heising (9). Finished plates may be inspected for slight deflects in birefringence and for strain in a similar manner at right angles to the axis by rotating the plate, tilting, etc., with careful study for defects in the isochromic curves, which are now not rings but two pairs of opposing parabolic wings, apex to apex.

Polaroid: Informative data concerning types of Polaroid has been hard to obtain. I would recommend HN-40 film, .010″ thick for our application. I have encountered three thicknesses, approximately .006″, .010″ and .030″. The thinnest seems to scatter the least light but is hard to handle and tends to curl. Availability may prove to be a determining factor. The letter H stands for the type or characteristic of polarizer used, N for neutral and the numeral for the percent transmission at what appears to be about 5500 angstroms. Type H film is very efficient in the red and hence is recommended. Care must be exercised *not to heat H films above 130° F* for very long. K type films have higher transmission at the hydrogen line (6563 A) than H films for a given film number (such as 24, 36, 38, 40), and withstand temperatures up to 200° F. Unfortunately, these K films, when crossed, leak red light with rapidly increasing intensity above 6563 A, and the high transmitting numbers are not recommended without special consideration such as use of an interference type prefilter, etc. Should K film be tried KN-36 is recommended. For our purpose we are interested primarily in the types that give the highest possible transmission consistent with low leakage at Hα either when crossed or as used (parallel) in our filter—therefore, the HN-40 recommendation. Using eight films our filter at best will transmit only in the ten percent range. This may be cut in half if one uses a Polaroid of *only* 2 percent less transmission, due to the cumulative effect of eight Polaroids—hence the concern for high transmission. If work in the ultraviolet or near blue is contemplated it must be specified that no u-v absorbing dye be present, as is sometimes the case in films.

Film squares are obtainable from the Polaroid Corporation, Cambridge, Mass., or the Pioneer Scientific Corporation, 295 Lafayette St., New York 12, N. Y., in 2″, 4″, 6″ and 12″ squares at *about* 10 cents a square inch (1952). As supplied in squares the direction of vibration is parallel to two sides, presumably to within one degree. For our application the direction of vibration must

be on the diagonal (45° from sides). One will want to check orientation for both direction and accuracy. Better than 1° would seem desirable. The Polaroid Co. will supply squares with the plane of vibration at 45° to the edges at twice the regular price (to cover waste), or you can cut your own. There are many complicated ways of accurately orienting film. However, some simple checks described here should suffice.

Take two squares as ordinarily supplied (direction of vibration approximately parallel to sides) and place them together in crossed position so that a minimum of light is transmitted. A light bulb viewed through this can be seen in deep blue color (with H film—red with K). Keep the line of sight perpendicular to the film. If edges are not parallel, make one pair of edges parallel by trimming a minimum amount from each sheet and "square" the other three sides. Now turn over the film nearest to you, top edge to bottom. If vibrations



a b c

FIGURE 4

are parallel to edges properly, minimum transmission will be maintained. This may not be the case, as shown in Figure 4, at *a*. Here the dotted arrow indicates the direction of vibration in the farthest film and the solid arrow the nearer film—both crossed with minimum light transmission. If we now invert (top to bottom) the near film as in *b*, considerable light will be transmitted. If we rotate the nearer film as shown in *c* until maximum extinction is again obtained, we can cut out a square by cutting through both sheets as indicated by the dotted outline which will maintain maximum extinction upon reversal of the top sheet, and thus be oriented properly (where vibration is desired parallel to sides). If the edges of the two squares still do not quite match at maximum extinction, make the slight correction required.

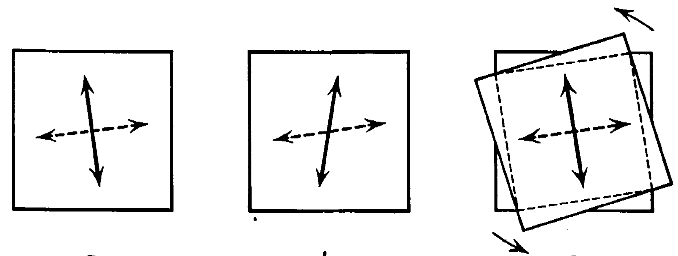
With Polaroid squares oriented at 45° (direction of vibration from corner to corner on the diagonal) the above procedure can be used, *except that* the top or nearest sheet must be inverted corner to corner, or on the diagonal, not top to bottom or side to side. Cut a few small squares and practice. Do not use too bright a light; it should be just nicely visible at least transmission. Assuming we have a 4″ square of 45° oriented Polaroid and the edges remain coincident on suitable inversion when again brought to minimum transmission, the subject to cracking. While I have not used twinned material I believe it could be used with the possible exception of plates $\frac{1}{16}$″ thick or thinner. Otherwise the "hand" of the quartz is immaterial for our use. For further detail and excellent photographs see references 8 and 9.

If we now turn to monochromatic light by placing the Corning filters described in the mercury light path the quartz may be inspected for location of the axis. If one inspects a flat plate cut perpendicular to the axis by viewing it along the axis, a series of concentric rings (isochromic rings) will be observed, the spacing depending on the thickness. In thin plates a shaded dark centerless Maltese cross or isogyre, as large as the rings, will be observed. In rough quartz near, or on, the axis these dark bands will become irregular and actually serve as contour curves as the crystal varies in thickness. When the crystal is positioned to show the fewest and widest dark bands one is looking along the optical axis. For detail refer to Heising (9). Finished plates may be inspected for slight deflects in birefringence and for strain in a similar manner at right angles to the axis by rotating the plate, tilting, etc., with careful study for defects in the isochromic curves, which are now not rings but two pairs of opposing parabolic wings, apex to apex.

Polaroid: Informative data concerning types of Polaroid has been hard to obtain. I would recommend HN-40 film, .010″ thick for our application. I have encountered three thicknesses, approximately .006″, .010″ and .030″. The thinnest seems to scatter the least light but is hard to handle and tends to curl. Availability may prove to be a determining factor. The letter H stands for the type or characteristic of polarizer used, N for neutral and the numeral for the percent transmission at what appears to be about 5500 angstroms. Type H film is very efficient in the red and hence is recommended. Care must be exercised *not to heat H films above 130° F* for very long. K type films have higher transmission at the hydrogen line (6563 A) than H films for a given film number (such as 24, 36, 38, 40), and withstand temperatures up to 200° F. Unfortunately, these K films, when crossed, leak red light with rapidly increasing intensity above 6563 A, and the high transmitting numbers are not recommended without special consideration such as use of an interference type prefilter, etc. Should K film be tried KN-36 is recommended. For our purpose we are interested primarily in the types that give the highest possible transmission consistent with low leakage at Hα either when crossed or as used (parallel) in our filter—therefore, the HN-40 recommendation. Using eight films our filter at best will transmit only in the ten percent range. This may be cut in half if one uses a Polaroid of *only* 2 percent less transmission, due to the cumulative effect of eight Polaroids—hence the concern for high transmission. If work in the ultraviolet or near blue is contemplated it must be specified that no u-v absorbing dye be present, as is sometimes the case in films.

Film squares are obtainable from the Polaroid Corporation, Cambridge, Mass., or the Pioneer Scientific Corporation, 295 Lafayette St., New York 12, N. Y., in 2″, 4″, 6″ and 12″ squares at *about* 10 cents a square inch (1952). As supplied in squares the direction of vibration is parallel to two sides, presumably to within one degree. For our application the direction of vibration must be on the diagonal (45° from sides). One will want to check orientation for both direction and accuracy. Better than 1° would seem desirable. The Polaroid Co. will supply squares with the plane of vibration at 45° to the edges at twice the regular price (to cover waste), or you can cut your own. There are many complicated ways of accurately orienting film. However, some simple checks described here should suffice.

Take two squares as ordinarily supplied (direction of vibration approximately parallel to sides) and place them together in crossed position so that a minimum of light is transmitted. A light bulb viewed through this can be seen in deep blue color (with H film—red with K). Keep the line of sight perpendicular to the film. If edges are not parallel, make one pair of edges parallel by trimming a minimum amount from each sheet and "square" the other three sides. Now turn over the film nearest to you, top edge to bottom. If vibrations



a b c

FIGURE 4

are parallel to edges properly, minimum transmission will be maintained. This may not be the case, as shown in Figure 4, at *a*. Here the dotted arrow indicates the direction of vibration in the farthest film and the solid arrow the nearer film—both crossed with minimum light transmission. If we now invert (top to bottom) the near film as in *b*, considerable light will be transmitted. If we rotate the nearer film as shown in *c* until maximum extinction is again obtained, we can cut out a square by cutting through both sheets as indicated by the dotted outline which will maintain maximum extinction upon reversal of the top sheet, and thus be oriented properly (where vibration is desired parallel to sides). If the edges of the two squares still do not quite match at maximum extinction, make the slight correction required.

With Polaroid squares oriented at 45° (direction of vibration from corner to corner on the diagonal) the above procedure can be used, *except that* the top or nearest sheet must be inverted corner to corner, or on the diagonal, not top to bottom or side to side. Cut a few small squares and practice. Do not use too bright a light; it should be just nicely visible at least transmission. Assuming we have a 4″ square of 45° oriented Polaroid and the edges remain coincident on suitable inversion when again brought to minimum transmission, the material is oriented close enough for our use. Proper sized smaller squares may now be carefully cut to maintain all edges parallel to original edges of the larger square. Small squares may be checked less accurately in the same manner. A pamphlet, "Polarized Light and Its Application," from the Polaroid Corporation (50 cents) may be helpful to the uninitiated.

Red Glass Filters: The finished seven-element quartz-Polaroid filter itself actually transmits a series of narrow pass bands about 500 angstroms apart. The band on the red side of Hα is practically invisible to the eye (which rapidly becomes insensitive visually to light of increasing wavelength beyond Hα) and may be neglected. The orange-yellow line on the shorter wavelength (blue side) of Hα must be removed by a sharp-cutting red filter. Corning Glass filters are *specifically* recommended. (Corning Glass Works, Corning, N. Y.) Obtain their literature. I learned to my regret that some types of red glass filters are colloidal, with quite detrimental light scattering properties. The molded glass numbers are given since one had best grind and polish his own to obtain desired surface quality. Corresponding polished numbers are also given since some may wish only to "refigure" a polished surface.

Many use a red filter at each end of the quartz-Polaroid unit. For these, molded glass No. 2408 (polished No. 2-60) should be used. This corresponds to the old No. 243 in the literature. I prefer a single darker shade filter No. 2404 (polished No. 2-59) at the incoming light end with a clear optical glass plate at the rear, primarily to reduce the number of red filters, the optical quality internally not always being that desired. In any event, make several and test for definition in front of a small telescope or by other means. For those who do not care to tackle the thinnest quartz plate on a four angstrom filter, a 2403 (polished No. 2-58) should be tried, as "cutting" closer to Hα to remove the now nearer (approximately 250 angstroms distant) pass band. Since these red filters will vary considerably in transmission at Hα from melt to melt in manufacture and with thickness, one has to exercise care and check with a spectroscope. Specifying to Corning that at least 65 percent transmission at Hα is desired on this latter filter may help.

Tools of Construction and Use: A minimum of shop equipment should be available, including a small lathe, drill press, and a simple vertical spindle. I had the pleasure of seeing a 2¾-angstrom filter which had been made almost entirely by hand tools by David Warshaw of Brooklyn, N. Y., over a four year period. This attests primarily to a high degree of skill and patience beyond that of most. A few details on more specialized equipment follow.

Many elegant diamond saws are available, for example, as manufactured by the Felker Mfg. Co., Torrance, Calif. However, the amateur will probably have to rig his own. Carborundum "mud" saws are not recommended. A diamond cut-off blade is almost a must for quartz plate cutting. Two types of diamond blades are available, the lower cost notched blade and the sintered metal bonded blade. The former tends to chip. The latter is more desirable for our work but quite expensive. I found that the manufacturer named above mass produces a blade of this type for tile and ceramics which works very well and can be obtained at about half the price (about $20) of the special types

usually recommended for quartz cutting. It is the Di-met Kimberley 8″ by .055″ blade. Such blades should be operated at 5000 edge feet per minute (2500 rpm for an 8″ blade) with a pumped (or gravity fed) liquid coolant forced to the working edge *at all times*. I suffered the odor and fire hazard of an otherwise very satisfactory 50–50 mixture of kerosene and light spindle (cream separator) oil before turning to the water emulsions. A 1:80 mixture of Quaker Cut No. 101 (Quaker Chemical Corp., Conshohocken, Pa.) with water works very well.

Other details of the machine can readily be worked out. Spindles should be protected. A close fitting bronze bearing will work well if oiled with light spindle oil at each use. *Avoid inhaling dangerous spray or mist* by properly locating a small fan nearby to blow it away.

Quartz Orientation: Quartz can be very accurately oriented (axis located where desired) by X-ray. However, the amateur will probably have to use optical means. Strong (12) gives a procedure which I have essentially followed with modifications. The orienter shown in Figure 3, right, with plate tilted to 15°, was constructed from a surplus large ball bearing housing. A glass (strainfree) plate about 6″ in diameter tilts on gimbals. An adjustable stop and edge scale to read tilt up to 20 or 30 degrees is provided. The unsatisfactory large light bulb shown was replaced with a bank of four ordinary G.E. neon (NE-40) 3-w lamps. These worked perfectly, showing the isochromic rings sharply even on thick plates. A small Polaroid is placed about 6″ above the unit, diaphramed to about a 3/16″ peephole. This Polaroid was crossed to a 4″ square Polaroid under the plate. A ground glass was placed *between* the neon lamps and the lower Polaroid. The unit works best if rotated mechanically, since the eye must be held steadily at the opening above. A rubber band to a ¼″ motor shaft was used to rotate the tilt plate unit *about* 60 rpm, as shown in Figure 3, left.

Set the plate at perfect right angles to the axis of rotation by observing the reflection of a distant lamp from the *upper* surface and adjusting to position of no wabble, as in lens centering. Zero the scale. A true axial cut (surfaces *both* parallel to each other and perpendicular to optical axes) placed on the plate and rotated will show no wabble of the conspicuous isochromic rings. A reference mark. such as a piece of wire laid on the Polaroid, serves to detect slight wabble to which the eye is very sensitive. If the orienter is built carefully, quartz plates showing no ring motion of a carefully zeroed (by light reflection) plate can be within ±5′ of arc. I had two plates checked by X-ray and high precision optical methods. Both were within ±3′. The scale in 1° divisions serves primarily as a reference in rough stages. Divide the reading by 1.54 before correcting a cut. When a bottom surface has been adjusted, the top surface must be made parallel to it before test, strictly so at the last trial and error phase of operation. Contact the ground surface to the orienter glass plate with the test tank oil, and in a like manner a glass plate to the top surface. The method for detection of optic axis of quartz in the test tank described earlier gives data for first rough cuts. Leave excess material at first. When oriented, one face is then reduced to give desired final thickness for the plate. The greatest care should be exercised in orienting the quartz intended for the thickest plates. I would recommend that all plates be held to 10′ of angle, preferably 5′, on the thickest two.

Grinding and Polishing: A vertical spindle is adequate. Variable speed of 50–150 rpm is desirable, or three speeds of 60, 100, 150 rpm, with about 100 rpm the most usable single speed. Laps to use are somewhat a matter of choice. I prefer a roughing lap as large as convenient, perhaps 10″ to 14″, of ordinary cast iron or boiler plate, 8″ laps of meehanite cast iron (stocked in standard sizes by Motors & Metals, 220 West 44th St., New York 18, N. Y.) and of Pyrex, with a 6″ Pyrex finishing lap. If a single material is chosen, use Pyrex. It does not tend to pick up grit in pores, or scratch on finishing operations. However, surfaces wear out of true rapidly. The three plate method may be used to maintain flats, but I prefer use of a spherometer (described later) coupled with corrective control as one grinds.

Mechanical Measuring Tools and Their Use: A filter which will show prominences can be and has been made, using an ordinary so-called ten thousandth micrometer. Considerable skill on the part of the user is required. For such 1″ and 2″ micrometers the newer carbide tipped types are highly desirable in avoiding loss of accuracy from small grinding powder residue. Brown and Sharpe, Providence, R. I., and L. S. Starrett of Athol, Mass., both have excellent tungsten carbide faced models at now reasonable cost for this worthwhile addition. The model 231FX by Starrett, with thimble friction, is very convenient to use. Were I to use micrometers *only,* I would choose for the 1″ a special one having a built in ten thousandth dial in the handle, retractable anvil, and carbide tips (model 200P-1 by Federal Products Corp., Providence, R. I.). This has given me years of faultless service since introduced, and accuracy well within the tenth claimed. It appears as part of Figure 7. Other handy measuring tools are shown in Figure 5. A surplus 1/100 mm gage on the right serves in a three point spherometer to hold the plates flat. A precision straightedge, such as Starrett No. 381-12″, and some .0005″ aluminum foil might do almost as well. See Dunn (1). The long travel (0.5″) unjeweled .001″ dial at the left is handy for rough work. The most important item is a 0.2″ travel .0001″ jeweled gage ***with*** telltale counting hand Starrett No. 25-T-6, 0–10 shown in the center in a homemade mount. The flat (made so by lapping) aluminum plate has grooves 1/4″ apart turned in on the face to collect scrubbed off dirt. The gage should be separable by 0–3″ and a protective spring point or dead end stop used to prevent gage damage.

If dial gages are used, a six-piece set of working standard gage blocks from 1/16″ to 2″ by doubling thicknesses is essential. These can be quite costly but the round type manufactured by the Van Keuren Co., Watertown, Mass., set M16, plus an extra 2″ block, are sufficiently accurate (.00001″) at a total cost of less than $20. Gage blocks should be kept clean and greased when not in use. A dial gage set-up is particularly useful in checking parallelism of faces by sliding the plate around (with some scratch hazard) under the dial foot. Gage blocks are necessary due to limited travel of the dials and as reference standards.

Spectroscopes and Their Use: An ordinary small laboratory table spectroscope is required for testing the thinner plates. However, the two or three thickest plates will require a higher resolving power instrument for the narrow pass bands. Yet the large instrument cannot be used on the thin plates since one pass band alone may more than fill the entire field of view. Two instruments are, therefore, usually recommended. The ancient instrument, a spectrometer, shown in Figure 6, was purchased at a very low price and repaired.

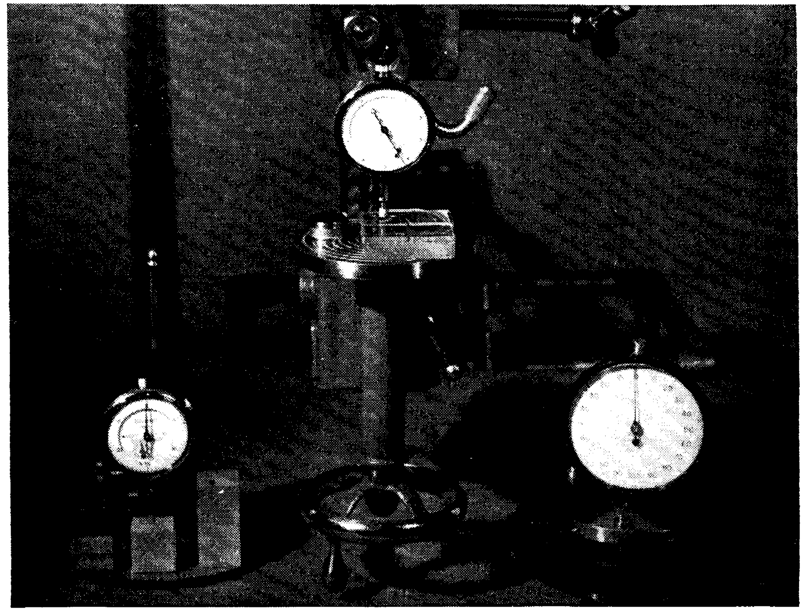


FIGURE 5

Useful dial gage set-ups

A little modification permitted it to be used for *both* thick and thin plates. This instrument has a 14″ fl collimator and telescope, about as large as practical to permit barely reaching the slit adjustment while looking in the eyepiece. A 25,000-line Grade A Wallace transmission replica grating No. 86745 from Central Scientific Co., 1700 Irving Park Blvd., Chicago, Ill., was fitted to the front of the collimator. This holder must be adjustable to bring the grating perpendicular to the collimator axis if precise wavelength measure is required, but for our use this is not critical. Using this grating, about a quarter angstrom could be resolved—more than adequate for the approximately 9 angstrom full band of a 2″ plate. Thinner plates were checked by the very simple expedient of placing an ordinary 60° flint prism in front of the grating holder (grating may be left in place) and using the instrument as a standard prism spectroscope.

This unit eventually proved ideal after the very annoying problem of devising a bright enough light source was solved, since transmission gratings are notoriously wasteful of light. Considerable time and money were wasted to arrive at an inexpensive solution. An ordinary automotive 6—8-v, 50 cp bulb, such as Mazda 1061 or Westinghouse 1183, operated at its peak voltage of 8-v (by test meter), provides a very high surface temperature filament source. Even in a well ventilated housing, the bulb life is only a few continuous hours. However, they cost little. Carbon arcs or ribbon filaments were not as satisfactory. The image of the filaments in the spectrum is not too annoying. It is best to apply the voltage slowly and have an accurate control. For this I used 5-amp Variatron (Allied Radio Corp., 833 Jackson Blvd., Chicago 7, Ill.) to feed into a 110-v:24-v, 4 amp stepdown transformer. A position was marked on the Variatron dial for 8 volts to the bulb (by test under operation) and the dial brought from 0 to this position at each use. Other voltage control systems would work. The powerful G.E. exciter lamps, such as type 7.5-amp T8SC (Allied Radio), might well be tried.

The filament is placed at the focal point of a 6″ fl achromat. Parallel light from the convex side of this achromat is fed by a prism up through a glass testing platform. Figures 6 and 7. The wooden rack is carefully slotted to take several square glass platforms which may be moved up or down to any slot. The parallel light column *must* be by test perpendicular to any of the platforms on which the quartz plates will rest. About 8″ should be allowed from top to bottom. A prism (or prisms in the set-up shown) at the top directs the light through a 6″ fl achromat focusing at the spectroscope slit. The lamp should be mounted separately, or thermally insulated from the testing unit to avoid annoying temperature changes in this unit. For this reason, it would be better to mount the light source above and bring the light directly down through the test unit and then by prism to the spectroscope.

A very small 45° prism or mirror arranged to cover half of the slit serves to feed an Hα comparison spectrum from a hydrogen discharge tube (No. 87235, Central Scientific Co.) into the same field of view. The use of this is almost essential. The satisfactory power source recommended by Central Scientific Co. might be replaced by a lower cost 4000- or 5000-v neon sign transformer of approximately 18 milliampere rating. In any case, the hydrogen tube requires special care if any length of service is expected. A voltage regulating device (such as 2 amp or more, variable transformer or suitable variable resistance) must be attached to the 110-v input side so that the high voltage to the tube can be reduced to a point where the tube operates satisfactorily without flickering. In this manner tube life can be increased from hours to many months.

Economy Measures: Should the cost of the major equipment mentioned, such as a spectroscope, discourage a start, let us consider minimum requirements and some substitutes for the more expensive items. One should be able to obtain lower cost partially twinned quartz. A mud saw using Carborundum with soapy water *could* be used to slab quartz even though slow ("What is a hobby, if not to murder time."—Haviland). The 100 rpm vertical spindle could turn in wood bearings and work perfectly. A simple quartz orienter

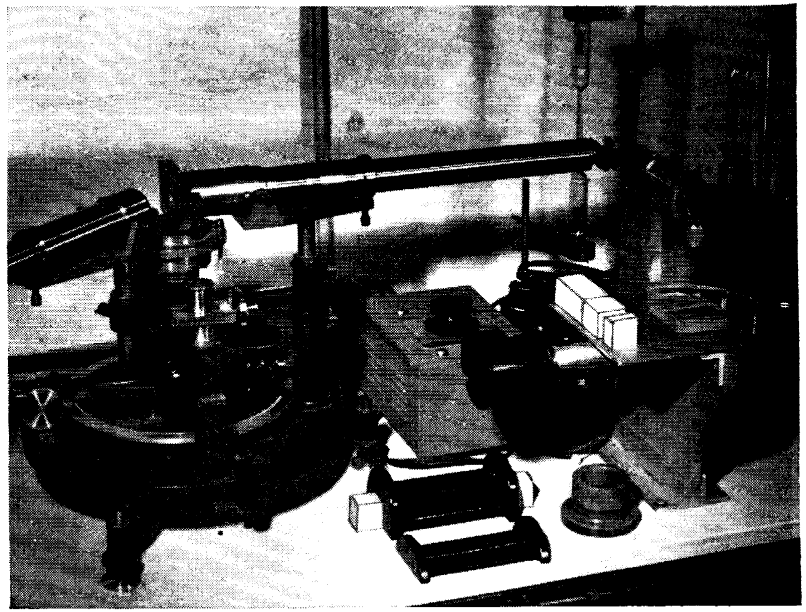


FIGURE 6

Combination grating or prism spectroscope with quartz plate testing unit first used—without constant temperature control.

can be inexpensively made. Any ordinary 1″ ten thousandth micrometer (even a good used one) will suffice—substituting two 1″ quartz plates for the 2″, as described later. In some climates a few mirrors and a clock drive will allow the sun to serve as a Hα reference source. See Strong (12), page 343, for home-made coelostat. Actually a home-made power supply for the low cost hydrogen tube might be simpler.

The rather essential spectroscope, particularly when simple mechanical measure only is used, does not really pose a problem if designed for the tests described later. I made one on a "breadboard" mount in four hours, which worked well, using molding clay to hold and adjust surplus lenses and prisms, etc. A simple but more permanent construction could be used. The slit can be fixed, consisting of a pair of injector type razor blades whose edges have been made straight by a light touch or two on a flat rotating lap. Fasten these facing each other with screws and washers on a wood block having a 1/4″ hole. Adjust separation to .001″ using a piece of .001″ shim stock (or aluminum foil-

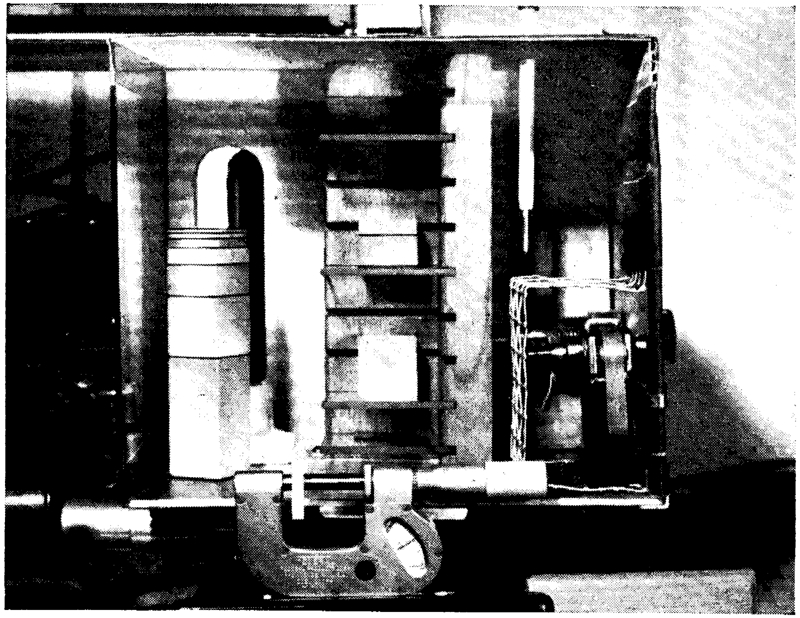


FIGURE 7

Final constant temperature quartz plate test unit with fan, thermostat (background), and tall 40-w bulb heater. Complete filter at left, also micrometer, are present to indicate scale and for themselves.

check) between the extending ends. Make a slit five or ten times this width for first adjustments, such as prism location, etc. Objective quality achromats (check) of 12″ to 15″ fl and 1 1/4″ or more diameter from Edmund Scientific Corp., Barrington, N. J. or from A. Jaegers, 619A, W. Merrick Rd., Lynbrook, N. Y. serve as collimator and telescope of our spectroscope with the slit and eyepiece at their respective focal points. One of these and the prisms mounted separately with clay on small squares of wood permits shifting about for preliminary trials. Passing the parallel light from the collimator lens through *two* suitably placed 60° dense flint prisms with about 1 1/2″ wide faces gives adequate

dispersion for testing a 2″ quartz plate. Fastening the telescope objective and a 1/3″ or 1/2″ simple Ramsden eyepiece to a support, allows it to be slid about as a unit, permits the use of one prism for thin plates or two prisms for thick ones.

Since good 60° extra dense flint prisms can be expensive, I took three large surplus Porro binocular prisms (from above sources, in sizes up to 41 mm high by 61 mm faces, flat to 1 to 2 fringes) and used a 45° angle of each as a prism, roughly sawing off the unwanted part to make 45° by 67.5° by 67.5° prisms. One, two or three of these suitably placed between the collimator and telescope (rapidly done by trial and error, checking for minimum deviation as each prism is added) nicely permitted testing any of the plates from 1/32″ to 2″. A single white silk fiber from white thread serves as a vertical crosshair, if one is desired at the field stop of the eyepiece.

Odd as it may seem, the two 60° flint prism, or the multi 45° prism unit, because of greater transmission, was preferred to the grating, even though dispersion was smaller and one had to be critical in adjustments. Since an Hα comparison spectrum is used and we are always working by matching, the fine adjustments of a commercial spectroscope are not essential. Such a flexible larger instrument will perform much better for your use at a *very low* comparative cost. The light source described is ideal and compact for this unit. What one learns from spectroscope construction will probably save an equivalent amount of time in later tests.

Optical Contacting: The most suitable method for finishing one of the thinner plates is to optically-contact it to a precisely planoparallel strainfree optical glass plate of the same size and in the range of 0.2″ to 0.25″ thick. This plate should be worked carefully to equi-thickness by your best measure (within a fraction of a ten thousandth) and the exact thickness marked by diamond on the edge: double check. The surfaces should be a quarter wave or better without turned edges on the contacting side (cut from a larger piece).

Little is readily available concerning the art of attaching surfaces together by optical contacting. Essentially it is simple. Cleanliness is the key factor. Prepare a test box one foot square or larger with a so-called monochromatic test light in the top and a plastic film drop curtain at the front. A bank of seven 3-w neon lamps, mentioned earlier, behind a ground glass works well. Another excellent but little known test light can be made from one or more G.E. 15-w *clear* fluorescent type tubular lamps. These are identical with the common variety, fitting standard fixtures, etc., except that the fluorescent powder has been omitted in manufacturing, giving you a mercury test lamp. Cost is under a dollar each. Keep the test box at high humidity with a wet sponge in a corner.

Assemble the following materials: The purest acetone available (preferably have a chemist redistill and store in clean glass stoppered brown bottle; evaporating a puddle of it from a clean glass surface should leave little or no visible film). High grade paper handkerchiefs (these may vary, so try different brands). A 1″ camelshair brush, preferably the static removing type, such as the "Static Master, Jr.," manufactured by Nuclear Products Co., Costa

Mesa, Calif.; this brush may require cleaning by dipping hairs in acetone—avoid solvent getting into the polonium radioactive part. A good, small test flat. A clamping device of some type (I used a sturdy 4″ C-clamp with a 2″ by ½″ *flat* plate fastened to the bottom face, the small upper foot pressing on a similar disk).

Clean the quartz and glass plates to be contacted with a detergent soap and include the hands in this thorough cleaning. Rinse everything. Some use distilled water for the final rinse. Dry with paper handkerchiefs. Moisten a portion of a paper handkerchief *lightly* with acetone and scrub thoroughly the surfaces to be contacted. Examine under a bright light at grazing incidence to see that no films remain from this process. You can also easily check for chemical cleanliness by breathing on a surface: a *uniform* gray haze will deposit on a totally clean surface. Dirty areas will show up sharply. Again examine at grazing incidence to a light. Usually much lint and miscellaneous airborne particles will be visible. Lightly brush these off with the static removing brush. Stand the plates on edge in the test compartment. Clean the other plate. Under the test lamp slide the two plates together, glass one on top, for about ⅛″ and tilt until fringes are seen and spread to indicate close parallelism. Slide the plates together. This procedure shoves off most old, or new, particles remaining. Light pressure will permit seeing dirt, particles, etc. in the colored fringes. Sometimes the plates will tend to stick (by premature contacting at a point). Pull them apart and start again. When the plates are entirely together, press hard in the center with a rounded plastic rod. Use care on thin plates! Under rare ideal conditions contact will start at this point and run out to the edges. Fringes and color then disappear. Usually encouragement with pressure here and there by the plastic rod is required. I place both plates in the C-clamp set-up with a sheet of paper above and below (to cushion) and squeeze quite hard. Be sure that squeezing surfaces are quite flat, or else. . . . This will contact even stubborn plates. A speck or two of dirt may remain as small visible "islands." For our work, this is of no concern. If unsuccessful start again at some point. Brush fingernail lacquer at contacted seam to discourage separation; remove with acetone before separating. After the first few hundred trials you will do all of this in a couple of minutes and marvel at the ease of it, and wonder why you ever used cementing with its uncertainties of wedge films, unknown thicknesses, cement warpage, two-way difference of quartz expansion, etc.

Following completion of a contacted quartz plate comes the trick of separating. This is rather easy for the thicker plates. Sometimes prying with a fingernail at the bevel of a poorly contacted edge will affect a separation. Warm in water almost unpleasant to fingers and suddenly chill the *glass side only* in ice water. Most often the plates snap apart. This method places the quartz under compression with less likelihood of breakage than when under tension. Observe operations under the test light. The thinnest plate is difficult. Dip the glass part in chilled acetone and pry *gently* at one edge of the quartz plate, preferably one that overhangs very slightly (the glass plate may well be 1/64″ to 1/32″ smaller than the quartz). If a corner or side can be raised enough to start acetone under, its capillary force will aid in counteracting the molecular surface attraction. The surfaces of thin plates need not to be too flat since they can be bent several fringes into contact. If the unit is now worked planoparallel for a flat second surface on the quartz, the surfaces will be parallel. When the thin plate is uncontacted the thickness will still be uniform, which is far more important than flatness since in final use an index near that of quartz will be used in the contacting oil film, eliminating surface deviations.

Calculations and Formulas: Certain fundamentals must be considered. Birefringent quartz has two slightly different refractive indices. Light passing through quartz is split into ordinary and extraordinary rays which can differ in speed according to the index path followed. The index of quartz for the ordinary ray is about 1.544. This index, and therefore the speed of light, remains the same regardless of the direction light passes through the quartz crystal. The index of quartz for the extraordinary ray, and the speed of the ray, varies according to the direction of the path through the crystal, from almost the same as the ordinary ray along the optical axis, to a maximum difference when traveling at right angles to the axis. The index of quartz for this ray has now increased to about 1.553, giving a maximum index difference of 0.009 (varying slightly according to temperature). Plates for our birefringent filter use this latter orientation with light traveling perpendicular to the optical axis. For our square plates the *faces and two opposing edges* are therefore parallel to the axis. See Figure 3, left, in which the optical axis passes from top to bottom of all quartz in the picture. Fortunately, for ease of construction a degree of freedom is left. This may best be visualized for a thin plate by considering the rotational freedom left to a playing card supported on a vertical taut thread through a small hole centrally located near the edge of each of two opposing edges, the thread representing the *direction only* of the axis. This permits the plate to be cut from any area within the quartz, maintaining only the requirement that the faces and two sides (edges, if thin) remain parallel to the axial direction. As described in the introduction, the Polaroids with vibration planes at 45° to the quartz axis orient the entering and emerging light to permit interference.

One should be familiar with the fundamental unit plate thickness value called d_0. This is simply the thickness of a plate cut for maximum birefringence as described, which will permit completion of one "out of phase" to back "into phase" cycle. Light of a given color or wavelength (such as Hα at 6562.8 A in the red) enters the quartz from the Polaroid vibrating in a plane 45° to the plate axis. The birefringent quartz will split this light into two components, one parallel and one perpendicular to the axis. Light in one path will be slowed with respect to the other, so that at the halfway point of a theoretical d_0 plate the vibration of one will be opposed to that of the other. Continuing through the plate the slow ray will be retarded a complete cycle and will be back in phase again on emergence and recombination by the Polaroid. Maximum transmission at 6562.8 A now occurs. At any integral thickness of 2,3,4,5, etc., times this d_0 value, full transmission of our chosen

color of light will occur. At ½, or 1½, 2½, 3½, etc., times this thickness no transmission (complete extinction) takes place. As thickness increases by integral values of d_o the width of the transmission band or area, as viewed with a spectroscope and white light source, becomes proportionately narrower and narrower as do the adjacent absorption bands on each side of our reference band centered at 6562.8 A. See also Dunn (1).

To compute d_o use the formula $d_o = \lambda/(n_e - n_o)$ where the wavelength lambda (λ) is expressed in microns (one micron = 10,000 A = 1/25,000″). The value of the difference $n_e - n_o$ can be accurately determined and is given as 0.0090493 at 0° C (32° F) by Dunn (1) referring to Sosman "The Properties of Silica" (Reinhold Pub. Co., 330 W. 42 St., New York). Correction of *this* value to any other temperature in centigrade may be made according to Sosman by the following formula $-10^{6}t\ (1 + t/900)\ (1.01 + 0.2\ \lambda^2)$ in which lambda is expressed in microns.

I have found 40° C (104° F) to be a suitable filter operating temperature. Substituting in the above formula we obtain a value for $n_e - n_o$ of 0.0090036 at 40° C. By substituting in our formula for d_o for Hα we obtain .65628/9.0036 = .07289 millimeter, or .00287″. By using values for quartz and temperature correction from The International Critical Tables, Vol. VI, pp. 341–342, and by actual practice, I found the value of d_o to be nearer .072873 mm or .002869″. This small difference of a millionth of an inch can accumulate to almost the total allowable tolerance in our thickest plate, showing the limitations in use of computations alone.

Having calculated d_o for our 40° C filter we must now consider how to select the thicknesses for our seven plates, the thinnest of which locates the distance of the secondary pass bands from the Hα band while the thickest plate regulates the narrowness of our final effective band at Hα. We would therefore like as thick a plate as possible at one end of our plate series for a narrow pass band, and at the other end one thin enough so that the adjacent secondary pass bands will be cut off on one side by a suitable red filter and on the other by lack of "far red" sensitivity of the eye or photographic film.

Careful consideration of the many factors involved, such as optimum band width for prominences, measuring tools, total filter length, usable filter angle, quartz, etc., led to selecting 11 d_o (.031558″) for the thinnest plate, fixing the thickest at 704 d_o (2.0197″). The thickness of the other plates is of course either half or twice that of an adjacent plate; i.e., starting with the 11 d_o the thickness of each succeeding plate is obtained by multiplying .031558 by 2,4,8 . . . 64 (see Table 1). As plates are stacked in this fashion every alternate pass band of the preceding plate is blocked out. Yet, as computed, the pass band at Hα coincides for all plates and is transmitted by the completed series. Filters for other wavelengths may be calculated in a like manner using d_o computed for that particular wavelength and desired temperature.

Evans (4) has shown that the adjacent maxima passed by a completed filter (less red filter) is governed by the thinnest plate and are at $N\lambda/(N + 1)$ on the blue side of our selected Hα transmission band and at $N\lambda/(N - 1)$ on the other side. N equals the number of times a plate is thicker than d_o. For our red line Hα filter of Table 1 the adjacent shorter wave transmission band becomes 6562.8 × 11/12 or 6015.9 A, visually an orange line separated by 546.9 A from Hα. It is entirely removed by the red filters recommended. The band on the other side of Hα is 6562.8 × 11/10 or 7219.1 A, a deep red line barely visible in the spectrum, not recorded by most films, hence neglected.

TABLE 1

Construction Data for 7 Plate 4.2 A, Hα Filter Operating at 40° C. (104° F.) d_0 = 0.002869″

Plate Designation	N	Plate Thickness (inches)	± Tolerances			
			Fraction of d_0	Inches	Waves	Fringes
2″	704	2.0197	1/20	.00015	7.5	14
1″	352	1.00985	1/40	.00008	4	8
1/2″	176	0.504925	1/80	.00004	2	4
1/4″	88	0.252462	1/160	.00002	1	2
1/8″	44	0.126231	1/320	.00001	.5	1
1/16″	22	0.063116	1/640	.000005	.25	.5
1/32″	11	0.031558	1/1280	.0000025	.125	.25

To determine the width of the final narrow band passed by a filter, as determined by the thickest plate, locate the adjacent *minima* by using $N\lambda/(N + ½)$ and $N\lambda/(N - ½)$. For our filter 6562.8 × 704/704.5 = 6558.1 A, and 6562.8 × 704/703.5 = 6567.4. By difference we obtain a 9.3 A minimum-to-minimum transmission band width centered at Hα. In actual operation the "effective" width, according to Evans (6), is approximately the band separation divided by 2^k where k is the number of plates. For our Hα filter the effective width is 547 A/2^7, or about 4.2 A.

For those who may want a somewhat simpler six-element, 5 angstrom Hα filter, an 18 × d_o thinnest plate is recommended. The next pass band toward the blue will compute to be about 360 angstroms from Hα, permitting use of a Corning 2404 type filter (ask manufacturer for melt transmitting less than one percent at 6200 A and 70 percent or more at Hα). The thickest plate of 576 × d_o will still have a satisfactory *effective* width of about 5 angstroms. This complete filter will be about 1″ shorter and accordingly easier on quartz.

We have thus far considered only a filter or plates operating at 40° C during construction. As one slowly changes temperature a given pass band as observed in the spectroscope will move toward the red as the temperature is lowered and toward the blue as it is increased. Since several different values appear in the literature for wavelength shift per degree centigrade change, I made a careful test of my own and arrived at a value of 0.7 angstrom per degree C in the Hα region. This agrees with the recent value given by Evans (6). One can readily compute the shift in angstroms by taking the difference between 40° C and the room temperature in C and multiplying by 0.7 angstrom. For Fahrenheit multiply the difference by 0.33 angstrom.

Required Accuracy: The question of tolerance on plate thickness has been a bone of contention between several who were concerned with these filters. There is no absolute answer. There do, however, exist maximum and minimum permissible errors. For the plates described I would recommend that each plate thickness be held to at least plus or minus a ten thousandth (0.0001″) of the plate thickness value given in Table 1. Certainly one should not exceed 1½ ten thousandths. Evans (4) has indicated that this amount of error in any plate is tolerable. It becomes evident that one could, with care, construct a usable filter by good mechanical means of measure as described without a spectroscope, using care in selecting and orienting the quartz used. However, there are easier methods.

To jump to the other extreme, let us calculate values for a near-perfect set of filter plates. Such values are given in Table 1, being similar to values favored by Pettit (13). To exceed these is a waste of time. A set of plates manufactured to these tolerances will, upon examination with high intensity illumination through a suitable spectroscope, present a picture of widely spaced primary pass bands separated by low intensity uniformly banded areas of background light leakage. See Figure 2 and Figure 8, *E* (four-plate example). In contrast, a filter made to plus or minus a ten thousandth throughout, tested in a like manner, will show numerous unmatched bands of light leakage between the primary pass bands. Fortunately the situation is not as bad as it appears to the eye since these apparently bad light leaks are primarily a *redistribution* of the background and the decrease of contrast and total loss of energy to the primary transmission bands is still not great enough to prevent reasonable functioning.

In any event one should keep in mind the fact that our filter is being used to partially isolate an *absorption* line or band from the sun and excessive leakage can cut contrast and definition. The use of a spectroscope, even a home-built simple one, is to be recommended, not the least value of which is its educational function. Many other reasons will become apparent from time to time.

One should at least shoot at the tolerances given in Table 1. With similar care on other components we can be assured of fine performance. The method of testing to be described lends in a natural manner toward attaining this accuracy. During construction of five sets of seven plates each, only two of 37 plates that were made failed to meet the requirements of low intensity background described. One 2″ plate made ½ d_0 thin by mistake was later salvaged with a mica wedge after learning this technic. It could also have been used as assembled in Figure 1, by rotating the outer Polaroid 90°.

Several describe the use of temperature correction formulas as already given to offset a crosshair in the spectroscope to correct for final operating temperature and permit testing at room temperature. I have not found this procedure too satisfactory, for a number of reasons which become apparent on trial. In fact I would actually prefer to bring all plates to operating temperature for testing. Such a drastic procedure is not, however, necessary. Another pitfall is the attempt to make the plates as separate entities, or to start with the thinnest plate and add each thicker plate in order.

The following method has proved very satisfactory, permitting ease of operation and precise control. A crude constant-temperature housing is constructed around our spectroscope test platform (Figure 7). A 25- to 40-w light bulb heater will suffice. Keep direct light from the plates. If necessary use temporarily the temperature control elements of your final filter housing. Operate at the final set temperature of 40° C (104° F) for values given. Now make the thickest plate (2.0197″) as close to the calculated thickness as possible by mechanical measure, checking for near coincidence of pass band center with the Hα reference line. Be sure that the plate is *at 40° C;* it may be brought rapidly to this temperature, first in a water bath, then by placing it in the test chamber. Assuming we are within one or two ten thousandths of the proper value there should be no question of the band concerned. If we have missed slightly we adjust the temperature until the band is centered at Hα. In the case of our so-called 2″ plate, using round figures, a full d_0 error of 28 ten thousandths would produce a 9 angstrom shift (center of one transmission band to center of next band). This same shift can be produced by a temperature change of 13° C (28° F). Therefore an error of a ten thousandth (.0001″) in thickness may be corrected by a temperature shift of 0.47° C (1° F). If too thick the band will be displaced toward the red. A slight temperature increase will shift the band toward the blue to coincide with Hα, or in this case we can polish off a little more quartz.

If slightly too thin our band will be on the blue side and temperature must be lowered slightly. Unfortunately quartz cannot be added. We can, however, operate the final filter at a slightly lower temperature. Oddly enough a temperature increase actually makes a plate *optically* thinner, and vice versa.

Small differences in index of quartz, slight tilt of axis, slight error of computed thickness in special cases, can cause a similar band shift, hence the preference for *first* making the thickest plate as close as possible to the calculated value—*then* determining the temperature of operation. This should be close to 40° C for the example given and will be the final operating temperature of the finished filter which will be fixed from this point on. The slightly relaxed requirement permitted on the thickest plate is usually appreciated because of mechanical measurement problems. Of course with good quartz, good orientation, exact measure to .0001″, and good luck, one might omit this test *at operating temperature.*

We may now make all our other plates at varying room temperatures, using a homemade spectroscope if necessary without offsetting the crosshair, computations, and problems of temperature shiftings, with one important caution—the two (or more) plates under test at any given time *must be at the same temperature.* If we also maintain exactly the 1,2,4,8, etc., relationship of multiples of our thinnest 11 d_0 plate we can also match bands at *any* point in the visible spectrum—a decided help because of increased visibility of bands in the yellow and green when using a transmission grating which is noted for its poor light transmission. We may now proceed with ease.

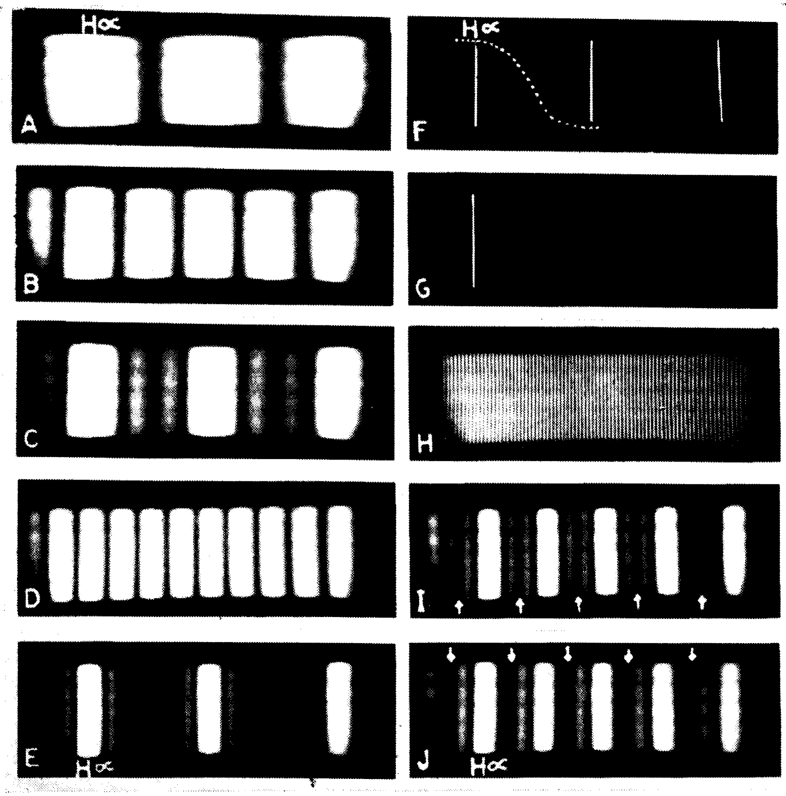


FIGURE 8

Pass bands of various filter plates and plate combinations as actually seen through the eyepiece of a medium sized prism spectroscope.

Designating plates by approximate thickness, the 1″ plate is now matched to the 2″ by the simple process of bringing it to *plus* a ten thousandths or so mechanically and then centering the alternate interfering absorption bands by final "figuring" with fine emery or polishing. The ½″ plate is now matched to the 1″, the ¼″ in turn to the ½″ and so on in pairs until the filter is finished. As work proceeds occasionally stack all the plates (at same temperature) together to check for cumulative error. Using a ½″ square aperture stop in the test beam, sliding the plate around allows one to check and correct variations in thickness which cause band shifts. Before starting, study Figure 8 which

was prepared by taking photographs with a 35 mm camera directly through the eyepiece of the spectroscope (with prism) shown in Figure 6. In Figure 8, at *A*, are the transmission and absorption bands of the 1⁄32″ plate sandwiched between 45° cut Polaroids. (Hα location is indicated at the top and bottom of a column of photographs.) The transmission picture of a 1⁄16″ plate is shown in *B*. Combining these two plates, with Polaroid between, results in the transmission picture *C*, where the absorption bands of the thinnest plate almost cut out every alternate transmission band of the thicker plate. At *D* we have the transmission of a ⅛″ plate. This plate, combined with the two thinner plates, results in the transmission picture shown in *E*. If we continue the process shown from photographs *A* through *E* with the rest of our plates we obtain the final seven-element quartz-Polaroid filter pass bands which are shown in photo *F*. Whether red transmission is to right or left depends on whether we use a prism or grating and which side of the collimator we operate. As shown in these photographs, red is to the left and the far left line in photo *F* is Hα accompanied by orange and yellow-green primary pass bands. Lightly dotted is the absorption curve for 2408 Corning type filter. With this in place we have only transmission of a 4.2 angstrom band at Hα as shown in photograph *G*. Photograph *H* shows narrow bands of a 1″ plate. It was feared that those of a 2″ plate would be too closely spaced to reproduce in the engraving.

Let us give particular attention to photograph *I* of a matched pair of ⅛″ and 1⁄16″ plates, with 45° Polaroids between and on both ends. Every alternate transmission band of the ⅛″ plate (photograph *D*) is almost blocked out by the *absorption* bands of the 1⁄16″ plate (photograph *B*). Note that these absorption bands indicated by arrows are centered with uniform slight light leakage on each side. In photograph *J* we have the picture produced by a 1⁄16″ plate being too thick, that is, the absorption bands indicated by the arrows are toward the red. As we gradually reduce the thickness these bands will shift to the right toward the blue until a match is revealed as shown in photograph *I*. Our testing is now completed.

Other pairs of plates, where one differs from the other by exactly half or twice the thickness, will present the same picture except for the relative spacing of the bands. For example, using a high dispersion grating a similar picture will result from perhaps a 1″ and ½″ pair. As we proceed *from the thickest* plate, each next thinner plate is matched to its thicker mate, stopping after finishing each plate to stack all the plates together with Polaroids to check final uniformity of the secondary absorption band spacing between the primary pass bands. See Figure 2 and Figure 8 at *E*.

In this test confusion may well arise in knowing whether the plate is too thick or too thin, since direction of shift is involved with use of prism or grating, side of collimator used, temperature shift, etc. A simple way to solve this question is to tilt the plate being worked slightly up from its mate by the edge *through which the axis passes*. If the band in question shifts in the direction desired the plate is too thick. If away from desired point, too thin—and too bad. Note: Tilting the plate by and up on edges parallel to the axis gives the reverse picture. I first saw this useful trick employed by David Warshaw, who contributed to several phases of the test outlined.

During testing watch out for temperature effects caused by handling, particularly with the thinner plates. Thick plates come to temperature slowly. In both cases moving the plates around in a pan of water at room temperature (check by thermometer and watch for evaporation effects) speeds up temperature stabilization. As a final check, let a pair of plates stand in contact for from 15 minutes for the thin ones to an hour for those 1″ and over, while starting on the next plate. If a thick plate is made too thin salvage by going to the next d_0 thinner (or ½ d_0, as described by Dunn (1) with crossed Polaroids), to again obtain a match at Hα. In this case testing must be a Hα, not anywhere along the spectrum as for even 1,2,4 functions, since progressive lack of match will now occur as we shift toward the blue. This is one crude way to tell whether you are on the correct single d_0 unit, except perhaps on thickest plates. As we progress away by one or more d_0 this condition becomes even more apparent. A filter plate *exactly* one or perhaps two d_0 units off will still perform well at Hα. Polaroids must *all* be parallel and 45° to the axis of the quartz. Of course they could *all* be rotated 90° and still work. The deliberate crossing of a few here and there presents quite a mixed up picture in the spectrum. Try it. Glass used anywhere between any of the Polaroids *must be free from strain.* Test between crossed Polaroids. It is best too to use strain-free glass throughout the filter since you may wish later to add some sort of wave shifting plate at one end.

Although not mentioned elsewhere I see no reason why two carefully made 1″ plates could not be used to replace the 2″ plate, of course without Polaroid between. This solves a quartz problem in some instances. All in all, three 1″ plates might be easier to make as a batch (up to the final stages). The thickest element could then later be converted to a wide angle element. See Dunn (1) and Evans (5).

As a possible alternative to the two thinnest plates, and the problem of optical contacting, one could possibly substitute a commercial multilayer interference filter obtainable with a transmission band at Hα only about 50 angstroms wide. This could be used in place of the red Corning filter as a pre-filter. The Baird Associates, 33 University Road, Cambridge 38, Mass., make such filters. They also make an elegant 1 angstrom Hα filter from dihydrogen ammonium phosphate and quartz (7). It is rather expensive. Newer developments in multilayer interference filters may make any of the filters described here or elsewhere commercially obsolete provided problems of light scatter and reflections can be solved. The amateur may, however, be unable to make these and the cost might still be well beyond his means.

At the start one might profit by first carrying all the way through a ¼″ or ½″ plate of sub-grade quartz or, when seriously tackling the first plate, deliberately add one d_0 thickness (.00287″), carefully working to this larger value by micrometer or gage and, finally, also by spectroscope at Hα. In case of the thickest plate at a fixed temperature such as 40° C, one will feel much

more at ease knowing that a practice mistake can be corrected by taking off the rest of a d_0 thickness. Should it be the desire to salvage a sub-thickness plate, refer to Draisen *et al.* (7) for use of optical mica (muscovite) shims. Their thickness will vary with the axial angle of the mica obtained. Rotate a thin sheet between a thick plate and one of its Polaroids and observe the band shift back and forth with rotation. Use a thickness that corrects at the point of maximum band shift. If your error was small you may not be able to split a sheet thin enough. Use what you have and polish off a little more quartz. Check mica sheets under your monochromatic light for uniformity of thickness and defects. As sources, try Ford Radio and Mica Corp., 542 63 St., Brooklyn 20, N. Y., surplus condenser mica, or your quartz sources for information. Best optical grade India clear splitting muscovite can cost much more than quartz, but little is needed.

Cutting, Grinding and Polishing Quartz: A crystal may be roughly oriented in the test tank as described, or by inspection if enough faces remain. Make a large rough cut near the base, perpendicular to the axis, where quartz is rarely good, and a small parallel cut at the cap end. Grind with 220 Carbo. Using test tank oil as a contacting medium for quartz to orienter plate and for a glass plate on top of crystal rotate the crystal and tilt the plate until the isochromic rings do not wabble on rotation of orienter plate. Divide the angle of tilt by 1.54 and correct, by cutting if error is great or grinding if error is small, the lower cut area. Now make the top parallel to this, more carefully so as perfection is approached. When no ring wabble appears as the crystal rotates on the orienter plate rotating in a plane made exactly perpendicular to its axis of rotation, orientation should be within ± 5 minutes of angle. If this quartz plate is thick enough for splitting down the middle parallel to the two finished surfaces, do this by saw and refinish the two new surfaces parallel to the two remaining reference surfaces.

Reduce one surface uniformly until the final slab is of the thickness desired for the finished filler plate (1″ or 1¼″ suggested). Now take time to reinspect in the oil bath to work out the best cuts to make to get the most out of your quartz. This will depend somewhat on which plates you need. Assuming we wish a single square bar as long as possible, later to be sliced to plates, we pencil mark and make a right angled cut (parallel to axis). This new surface is adjusted by grinding and a precision square to be at right angles to our two other surfaces. The precision squares No. 542 of Brown and Sharpe or No. 55 of Starrett are recommended. The 3″ size is nicest to use but the 4½″ shown in Figure 9 has more other applications, such as using the back level as a straightedge. Cut and bring the opposite side to thickness and parallelism. In reducing a second surface and at the same time keeping it parallel to the first, as is the case even later with plates, the dial gages are quite a help since one can slide the blocks or plates about under the foot and rapidly correct non-parallelism as well as thickness, using gage blocks to zero the dial gage.

Using our square we now work one end of a quartz bar to a finished surface perpendicular to all sides. A simple jig may help. The other end may be worked by either making it parallel to the first by dial gage or by use of the square. Thinner plates are best made by finishing one surface while still part of a bar which is too short for a 2″, 1″, or ½″ plate. For the two thinnest plates which we will optically contact, a thickness of about 3/32″ should then be sliced off with the saw. Cementing with 50–50 beeswax and rosin and extending plate of ¼″ glass on the bottom of a quartz bar and a back plate on the side

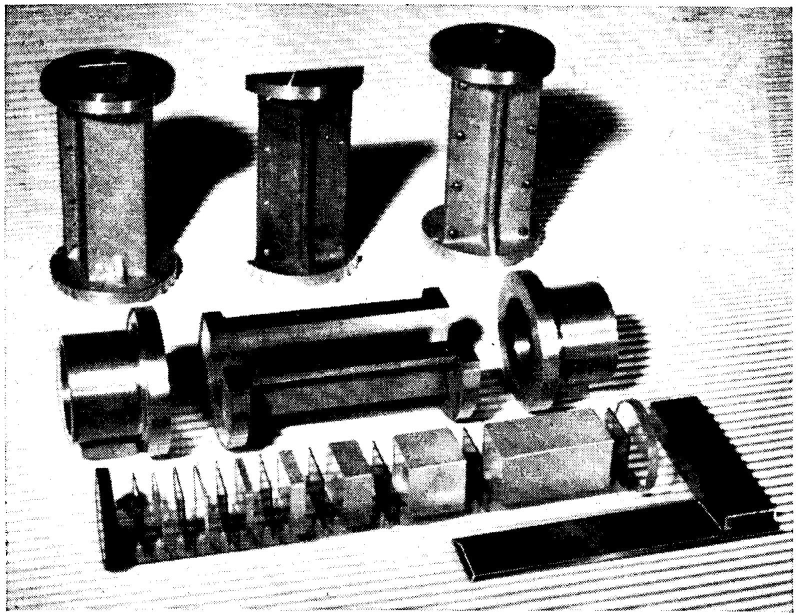


FIGURE 9

Exploded view of a complete quartz-Polaroid IIa monochromator. The lid and parts of two other units stand in the background. Also shown is a 4½″ (inside edge) precision bevel-edge square.

away from the saw will avoid damage to these edges and corner while sawing. A little calculation is required to figure the best and easiest use of your quartz. Place at least a small bevel on all edges with 280 or 400 Carbo before fine grinding stages, otherwise fine edge chips may cause scratches. Use a separate brush and Carbo for this to keep hazardous quartz chips out of your regular grinding material.

Common practice in grinding and polishing is described elsewhere and need not be repeated. However, some special phases need consideration. One problem in working to an exact thickness is that of knowing how much to remove

with each grit. Carbo 80 is used only in roughing operations and No. 280 for special use. I found Carbos 120, 220, 600 and American Optical Company 303½ and 305 emeries to be best and adequate for making plates on a machine spindle. Table 2 gives approximate sizes in thousandths of an inch, which represents close to the minimum thickness that should be removed by each grit to insure freedom from pits. An added factor in the use of coarse grain is edge chipping, in fine grain it is curvature of surface.

TABLE 2

Abrasive	Approx. Grain Size thousandths of inch	Minimum Removal With Grain Indicated thousandths of inch	Safer Limits thousandths of inch
80	7.5	—	—
120	5	20	30
220	2.5	10	15
600	1	3	5
A.O. 303½	.4	1	1.5
A.O. 305	.2	.4	.6
Polish	?	.1	.2

To fall much below minimum values may result in chipped edges, particularly where not beveled, or pits in corners if surfaces are curved before the final stage. Too much tolerance is very wasteful of time. Levigate all grits, particularly if you get a scratch. Quartz chips cannot be levigated out readily, hence a separate grinding supply is recommended for edging. Watch for unclean fingernails. Use clean towels and the same one with each grit. View anything above the lap with suspicion. Use 1000-tissues-to-a-roll paper for cleaning and drying laps and optical plates where adaptable. Pure talc (U.S.P. at your drug store) levigated and mixed at 20 percent ratio with the emeries acts as a lubricant and avoids rapid settling and sticking of the emery to the laps, resulting in turned edges. Some varieties scratch; try a different source. Keep the lap flat, using a spherometer or .0005″ aluminum foil and a straightedge such as Starrett No. 385—12″. By constantly checking the lap with a spherometer, as mentioned, little correcting need be done. Optical testing may well begin shortly after the 303½ is started on the last thousandth. If transmission is not good enough, stick on a strainfree square glass plate with test tank oil. Correction for small variations in thickness might now be made by the spectroscope band shift method described. Once planoparallel by test, constant rotation with the fingers while working will tend to maintain this condition. Working by the clock, under the fixed conditions you establish, you will soon know how much quartz removal to expect per minute or other unit of time for a given emery or Carbo. Running emery too thick or dry will turn edges.

Follow the surfaces, at grazing incidence, with a test flat during the last two emery stages to maintain near flatness, preferably within one fringe.

For polishing use a lap on the hard side to maintain shape. One half Universal Shellac medium pitch No. 835 (Universal Shellac and Supply Co., 425 Morgan Ave., Brooklyn 22, N. Y.) combined with half wood rosin serves very well. Cold press on an optical flat as often as needed. Proper sized corrugations can most easily be made in the 6″ lap recommended by pressing the strings on an old tennis racket between the softened lap and the flat. The polishing material I found best and fastest is called Rareox. This cerium oxide powder may be obtained from Universal Shellac and Supply Co., as may emery or other supply of this type.

All work is done by hand on a rotating spindle. Plates are not blocked in plaster, etc., but worked individually by hand, although all the other methods have been tried. The approximately 1/4″ plate optically contacted to the thinner plates serves to aid in holding by the fingertips. Plates are rotated constantly in working. Surfaces may be controlled somewhat by location of pressure by fingers at top or edges. Thick plates must be grasped by the sides and as near the bottom as possible, exercising care to avoid damage to the corners and rapid removal of material from one corner—a defect difficult to correct if too great, unless a precision jig is used. Plate surfaces intended for optical contacting may have to be blocked in plaster with glass pieces to maintain edges flat enough. To avoid serious internal reflections rub a thin film of Higgins waterproof India ink into the ground surfaces and bevels of all plates.

Housing the Filter: Once a set of plates is finished we are well along toward a working unit. Space does not permit great detail from here on. However, most amateurs are adept at construction of the type required. A few comments: Aluminum conducts heat rapidly and should be used in the housing of the plates themselves. Figure 9 shows an "exploded" housing and its optical elements. Patterns for the housing may be seen in the foreground of Figure 6. While designed totally independently, its similarity to that shown on page 275 of Dunn's (1) article as well as to that of another amateur attests to probable correctness of design. Engineering type oil resistant "O" rings 3/16″ to 1/8″ thick made of Buna-N (trade names Hycar, etc.) may be used at each end on each side of the round glass plates to prevent leakage and take up expansion and contraction differences. One will have to work out his own multitude of details. U.S.P. heavy white mineral oil (drug store) has proved to be a safe oil to use in a filter. The question of safety involves the gaskets and the Polaroid.

In the design shown the two erecting lenses between which the filter rests are fitted in the end flanges with threaded retaining rings. Allow a minimum of 2 thousandths and a maximum of 4 thousandths added to the plate size in milling out the square trough. Allow a minimum of a quarter thousandth to a maximum of one thousandth for *each* oil film between plates in computing length of unit before fitting end plates—18 films in the unit described. Too much squeeze may strain various plates and should be avoided by making the trough part of the housing a few thousandths longer than the computed or

measured thickness of all square plates plus oil films. It has been said that the axis of the thickest plate should be rotated 90° to the others. Dunn (1) states that this is not necessary. Therefore our filter plates may be at 90° to each other. If they are used in converging cones this should be investigated.

The immediate unit described must be fitted in a temperature controlled housing with heaters, fan and thermostat. Many fancy electronic controls might work very well but the simplest may be most practical. I have tried all kinds of systems and prefer the simple one described.

Assuming *about* a 4 by 5 by 5 air chamber of approximately 100 cubic inch volume surrounding the unit, three small 7½-w, 120-v, a-c bulbs with a three-way switch to use one to three will serve as quick response heaters. These may be black lacquer coated to avoid certain radiation effects. A 10- or 20-w resistor could supplement these but is too slow in response for final control. Use a small fan motor, such as Pettit (2) used, No. YAA 707-2 made by the Barber-Colman Co., Rockford, Ill., plus your own blade, or purchase a small motor and blade from Allied Radio Corp. An excellent sensitive thermoswitch is made by Fenwall, Inc., Ashland, Mass., such as their basic cartridge No. 17010 which is the shortest and most compact compared to the same unit in various mounting heads. A hard-to-find short 4″ thermometer with easy reading red column 0–50° C for your unit is 4919-Z from Arthur H. Thomas Co. If the unit loses heat too rapidly insulate it. In hot weather ventilate it with adjustable slot. The fan motor also contributes about 6 watts. Heat stabilization may take a little begrudged time. Why not operate continuously at the cost of a few small bulbs?

Accessory Optics: As a primary objective a single lens is recommended. However, a *clean* achromat works quite well. This primary lens should be as free as possible from scratches, bubbles, dirt, dust and anything except clear glass. Non-reflecting coatings are not advised. All first surface mirrors should be avoided, at least ahead of the occulting disk. The irregularity of the molecules on such evaporated surfaces causes a narrow angle scatter that is deleterious to our filter. Back surface prisms and probably wedge mirrors should be usable. Newer dielectric mirrors with high reflectance in the red without scatter may be useful. Reflecting telescope mirrors as we commonly think of them should not be used because of excessive surface scatter.

A 4″ aperture 80″ focus ($f/20$) lens is ideal for amateur use. However, even a 3″ aperture of 45″ to 60″ focus will surprise one in performance and convenience. Our particular filter is limited in angle to not over 1.5° off axis (3° total angle) for parallel light through the filter, or to a bundle of $f/20$ cones having parallel axes. Much depends on the secondary optical system chosen. In Figure 10 at *A*, is shown a system which can be recommended. It uses parallel light through the filter. The scale of the primary lens *a* and its focal length are reduced to about half that of all other components.

Our primary lens at *a* focuses the sun's image on the occulting disk or cone at *b* which just covers the sun itself. Lens *c* picks up the light and renders the rays parallel to pass through the filter *d*. Lens *e* brings these rays to focus at *f*. A field lens *g* may be added a short distance (1/4″ or 1/2″ to avoid dust spots at focus) behind the occulting disk. It should be calculated to focus the edge of the primary objective *a* at the diaphram *h* just ahead of the filter. This diaphram is just slightly smaller than the image of the edge of the primary lens. The field lens serves two purposes. First it helps to cut out, with

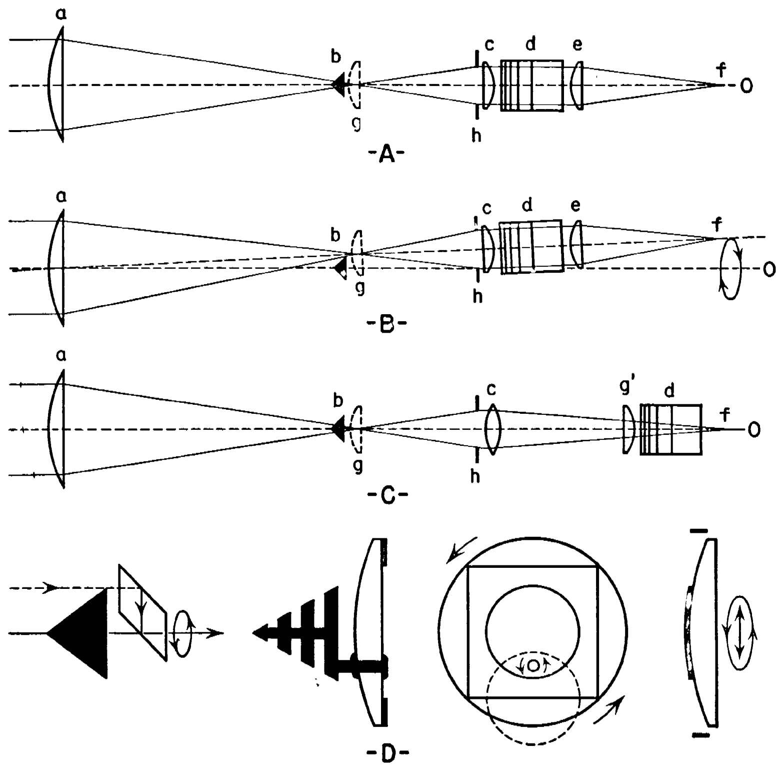


FIGURE 10

diaphram *h*, edge diffraction from the primary lens *a*. It also reduces vignetting and permits us to use a smaller aperture filter at *d*; for example 1″ aperture, whereas 1¼″ or more otherwise. The system *c-e* serves of course as an erecting system and the image at *f* can be proportionately greater than that at the occulting disk by increasing the focal length of *e* over that of *c*. This ratio should not be exaggerated, certainly not over 2×. On large telescopes this is sometimes reversed to get small images for movie cameras.

At the expense of a long system, lenses *c* and *e* could have about 20″ fl each for the 4″ objective or 15″ for the 3″ objective. This would provide a fine wide sharp field. With some compromise on edge of field definition these secondary lenses might be ⅔ but not less than ½ the fl values given. Lens *g* may be computed by simple object-image formulas. These lenses may all be single plano-convex lenses facing as indicated; however, achromats may well be substituted at *c* and *e*. Length could be reduced by using prisms *after* the occulting disk to fold back the system, etc. Numerous modifications are possible. Many prefer the occulting disk to be centered at the main axis of lens *a*, with the secondary axis of the filter unit and lenses offset and tangent to the occulting disk passing through the center of primary lens *a*. This secondary lens-filter unit rotates mechanically about the main O axis in Figure 10 at *B*, permitting rapid scanning of the sun's edge. Evans (13) states that a small rotatable rhomboidal prism as shown at the left in *D* might well replace this awkward mechanical construction. Its shape can be modified slightly so that the entering beam is actually diverging from the center of lens *a*. Gee (13) suggests as another alternative a rotating mount holding lens *e* in a decentered position. (Corrections, *D* Dashed line to converge. Disk edges to line up *with disks stacked.*)

I believe an entire system centered on the axis will serve well to most, with a sliding and rotatable occulting disk movable from a position of the edge on the axis to center on the axis. *C* in Figure 10 shows the filter used in a bundle of parallel *f*/20 cones of light. Field lens *g′* focuses at *c*. This system may reduce scatter but suffers from taking the entire allowable tolerance over the *entire* field. I prefer systems giving maximum contral definition, particularly for small amateur units.

I have calculated a working modification of system *A* using a 4″ primary of 55″ fl, a sliding occulting disk at *b*, a 10.5″ fl lens at *g* to focus edge of objective *a* at *h*, a 13″ fl lens at *c* and an 18″ lens at *e*. All small lenses are 1⅝″ diameter. Round figures are used. The ½″ diameter sun's image with surrounding prominences at *b* can be viewed in entirety as a .7″ image at *f* or taken on a 35 mm film. For high power eyepieces or camera combination, occulting disk *b* is slid to one side and the sun's edge observed in the center of the field. Its mount can also be rotated. The instrument will be optically folded by means of two right angle prisms *following* the occulting disk, permitting a total length of about 60″. Of course, the whole instrument will have to be moved to view the entire edge of the sun when the disk is not centered. The disk may well be a polished metal cone or modified cone, or perhaps a partial transmission film on lens surface *g* to permit seeing sunspots and surface at the same time. Such modifications are shown in *D*, Figure 10. A small fan near the disk could *draw* cooling air past it and blow the motor heat out the tube side. Polonium strips near the edge of the field lens would reduce tendency to pick up and retain dust.

For photographing, panchromatic type C film should be used, or Eastman Kodak 103aE 35 mm spectroscopic film by special order. Pictures can be made directly at focus without eyepiece or camera lenses for the entire sun, or the camera lens and eyepieces can be coupled for image size up to about

4 × that at the eye end. A sliding Barlow lens might well be considered as a substitute for eyepieces to increase image size at the film.

At the time of writing of this chapter (on short notice) [from old Simon Legree.—*Ed.*] I have used only crude so-called breadboard mounts without photographic attachments. A complete mount, as indicated by measurements

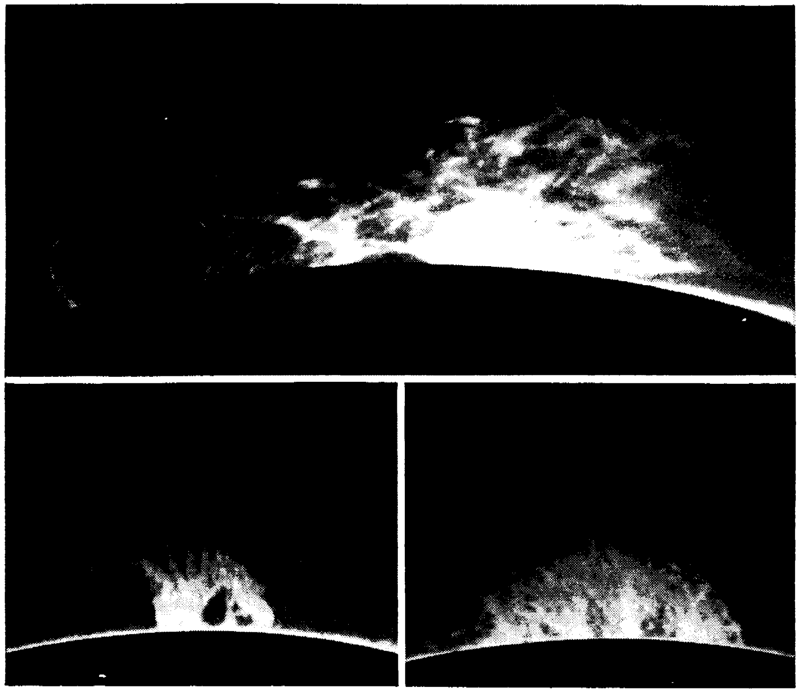


FIGURE 11

Solar prominences photographed by an Hα quartz-Polaroid monochromator similar to the one described. Courtesy R. B. Dunn.

given, is under construction. What may be seen and photographed by this type of filter is shown in Figure 11 through the courtesy of Richard B. Dunn.

The preceding information, together with that already published, should make the construction of these filters considerably easier. Good luck.

Acknowledgment: It was a marked help as well as a pleasure to exchange correspondence with others who have built these filters or who are expert in some phase of optics closely related to their construction. I wish particularly to thank such friends as Dr. Edison Pettit, Dr. J. W. Evans, Lieut. Col. Alan E. Gee, Dr. Francis Phelps, Richard Dunn, William Draisin, Ralph Dakin and David Warshaw. I am also appreciative of the courtesies extended at the U. S. Naval Observatory, Harvard College Observatory, the National Bureau of Standards, and by the many optical research laboratories visited.

REFERENCES

Quartz-Polaroid Monochromator

(1) Dunn, Richard B., How to Build a Quartz Monochromator. *Sky and Telescope,* Cambridge 38, Mass., Vol. 10, Nos. 6 through 12, April–October (1951). Series may become available as Harvard Reprint.

(2) Pettit, Edison, The Interference Polarizing Monochromator. *Publications of the Astronomical Society of the Pacific,* 675–18th Ave., San Francisco 21, Calif., Vol. 53, No. 313, pages 171–181 (1941).

(3) Lyot, Bernard, Le Filtre Monochromatique Polarisant. *Annales D'Astrophysique,* Vol. 7, pages 31–79 (1944).

(4) Evans, John W., The Quartz Polarizing Monochromator. *Publications of the Astronomical Society of the Pacific,* Vol. 52, pages 305–311 (1940).

(5) Evans, John W., The Birefringent Filter. *Journal of the Optical Society of America,* 57 E. 55th St., New York 22, N. Y., Vol. 39, pages 229–242 (1949).

(6) Evans, John W., The Solar Flare Recorder of Sacramento Peak Station of the Harvard College Observatory. *Science,* Lancaster, Pa., Vol. 114, pages 539–544, Nov. 23 (1951).

(7) Billings, Bruce H., Sage, S., and Draisin, W., A Narrow Passband Polarization Interference Filter for Hydrogen Alpha. *Review of Scientific Instruments,* 57 E. 55th St., New York 22, N. Y., Vol. 22, pages 1009–1017 (1951).

(8) Symposium on Quartz Oscillator Plates, *American Mineralogist,* Vol. 30, pages 205–468, Nos. 5–6, May–June (1945). Reprints may still be available from Earl Ingerson, U. S. Geological Survey, Washington 25, D. C., approximately $1.50.

(9) Heising, R. A., "Quartz Crystals for Electrical Circuits," D. Van Nostrand Co., Inc., 250 Fourth Ave., New York, N. Y.

(10) Willard, G. W., Inspecting and Determining the Axis Orientation of Quartz Crystals. *Bell Laboratory Record,* Vol. 22, pages 320–326, No. 7, March (1944). Bell Telephone Laboratories, 463 West St., New York, N. Y.

(11) Johannsen, A., "Manual of Petrographic Methods," McGraw-Hill Book Co., 330 W. 42 St., New York, N. Y. For a very clear text see Gibb, T. R. P., "Optical Methods of Chemical Analysis," same publisher.

(12) Strong, John, "Procedures in Experimental Physics." Prentice-Hall, Inc., 70 Fifth Ave., New York, N. Y.

(13) Private communication.

[Editor's Note: The Chief of the Photoduplication Service of the Library of Congress, largest library in the nation, states that "the Library of Congress can furnish at a nominal cost photostat copies of articles appearing in publications held in its collections unless restricted by copyright. Estimates will be made upon request. Inquiries giving complete references should be addressed to the Library of Congress, Photoduplication Service, Washington 25, D. C." The Photographic Service Division of the New York Public Library, New York 18, N. Y., will speedily supply to anyone anywhere on a non-profit basis photostat and microfilm excerpts from over 40,000 periodicals current or in bound volumes, when correct and complete references to periodical, volume or year, and pages are furnished. From these data it estimates prices in advance of order. Negative photostats (white type on black background) cost about half as much as positives (in 1952 about 25 cents per pair of facing pages, plus small service and mailing charges) and are good enough for all but the ultrafastidious. The Army Medical Library, Washington, D. C., and the U. S. Dept. of Agriculture Library perform similar services not confined to their subjects, as do other large libraries.

Caution: To avoid possible serious eye injury do not look through the optical train (telescope) without the filter in place.]

The Interference Polarizing Monochromator *

By Edison Pettit
Mt. Wilson and Palomar Observatories

Until within recent times solar prominences have been observed with spectroscopic devices. The most attractive of these is the spectrohelioscope, but that instrument is bulky and requires an expensive grating. Recently, the Lyot telescope has been used, with a simple filter to isolate the Hα line, but the transmission band is so wide that the superimposed skylight makes it usable only at high elevations in a clear atmosphere.[1]

The interference polarizing monochromator first used by Lyot and Öhman and later perfected by Evans[2] is a great improvement over the Lyot telescope for studying prominences. It is an attachment to a small telescope, preferably a refractor. It can be used at any elevation even with a white sky, and the materials and means of construction are within the reach of any who may desire to construct one.

The monochromator consists essentially of a composite prism built up of plane-parallel plates of a uniaxial crystal (such as quartz), pieces of polaroid, and a red glass filter, and can be made to isolate a band of any desired width and wavelength. The instrument acts as a simple filter and contains no essential moving parts. The writer has constructed (1940) one of these instruments which, attached to a 6-inch refractor, can be used either visually or photographically. With it the prominences show great detail, and in good seeing the details of the lower chromosphere, vividly described as "prairie fire," stand out with a sharpness not equaled with other instruments. Its optical principles, construction, and uses are described in this paper.

Optical Principles

As will be seen in the following description, the operation of the monochromator depends upon the optical principles of interference and polarization. Plates like P cut from a uniaxial crystal parallel to its optical axis, M, as in Figure 1a or 1b, are shown in Figure 1c as p_1 and p_2. A piece of polaroid, X, polarizes the light in the direction of its own axis which is set 45° to the axis M_1 of the crystal plate. Upon entering the plate p_1, the beam of light is broken up into two parts, an "ordinary" beam vibrating in a plane parallel to the axis M_1, and an "extra-ordinary" beam vibrating in a plane perpendicular to it. On emergence there is a difference of phase, yet no interference is observable unless the beams are again brought into the same plane of polarization by another polaroid, Y, with its axis parallel or perpendicular to that of the first.[3]

* Revised paper originally read at the Pasadena meeting of the Astronomical Society of the Pacific, June 1941.

[1] Pettit and Slocum, "Observations of Solar Prominences with a Lyot Telescope." *Publications Astronomical Society of the Pacific*, 45, 187, 1933.

[2] *Ibid.*, 52, 305, 1940.

[3] This was the original evidence that light travels in transverse vibrations.

If the beam incident at A is white light, its spectrum viewed at B is broken up by interference into regular sections separated by equally wide dark spaces, because the relative velocities of the ordinary and extraordinary rays vary with wavelength.

The number of bright sections and dark spaces depends directly on the thickness of the crystal plate. Suppose a thin plate is used which forms a few

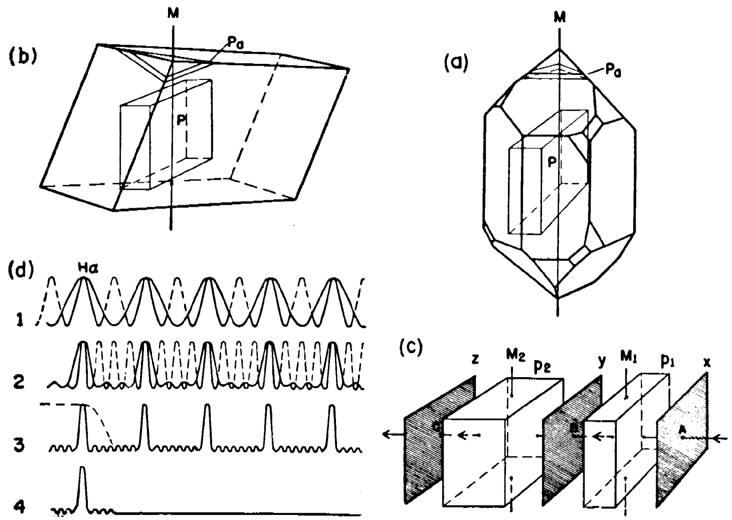


FIGURE 1

Theory of the monochromator. a. *quartz crystal.* b. *calcite crystal.* p. *monochromator plate parallel to the optical axis.* Pa. *test plate perpendicular to the axis.* c. *crystal plates and sheets of polaroid arranged as a monochromator (light may travel in either direction).* d. *interference bands in the spectrum formed by the light passed through a monochromator: 1, with two plates as in c; 2 with 3 plates; 3, interference pattern (3 plates) and the transmission curves of red glass (broken line); 4, resultant pattern after light has passed through the red glass.*

broad sections of the spectrum, one of which is centered on the wavelength of Hα. A plot of the resulting light-intensity against wavelength is a sinuous curve like Figure 1d, No. 1. If another plate, p_2, of twice the thickness, and another polaroid, c, is added, twice the number of maxima are formed, but the alternate ones, centered upon the dark spaces of the original pattern, are missing. The resultant is shown by the outer full line in Figure 1d, No. 2. A third plate, twice as thick as the second, and a fourth polaroid produce four times as many maxima as at first, but three out of every four maxima fall on the dark spaces and are invisible. The final result is several widely separated narrow transmission bands as shown in No. 3.

If a red glass is added, the transmission curve of which is shown by the broken line in No. 3, the transmission bands to the violet of Hα are absorbed, and the narrow band centered on Hα remains alone as shown in No. 4.

There is a certain fundamental thickness, d_0, for which the number of waves in the ordinary beam on emergence from the crystal is one more for positive crystals, or one less for negative crystals, than in the extraordinary beam. The thickness of each crystal plate in the composite prism will be some multiple of d_0.

Suppose that in a positive crystal plate of thickness d_0 the number of waves in the ordinary ray is n and in the extraordinary ray, $n+1$. Then if μ_o is the refractive index of the ordinary ray and μ_e that of the extraordinary ray[4] of wavelength λ outside the plate, the following relations exist:

$$\frac{d_0}{n} = \frac{\lambda}{\mu_0} \qquad (1)$$

$$\frac{d_0}{n+1} = \frac{\lambda}{\mu_e} \qquad (2)$$

Combining these equations to eliminate n we find

$$d_0 = \frac{\lambda}{\mu_e - \mu_0} \qquad (3)$$

CHOICE OF MATERIALS

Only two substances form uniaxial crystals that can be readily obtained in sizes sufficient for our purpose: namely, quartz (positive) and calcite (negative). Calcite is soft and liable to fracture, and d_0 is so small that it is not practical to make a plate thin enough to produce a wide separation of bands. Quartz therefore seems to be the best substance to use.

In the commonly available "Brazilian" or "low" quartz[5] crystals the optical axis is parallel to the lateral faces, Figure 1a. Usually a complete crystal cannot be obtained, but only a broken portion. To determine the direction of the axis a plate P_a is cut as nearly perpendicularly to the axis as can be estimated. This is fine-ground and placed for examination between plates of window glass with Canada balsam, oil of bitter almond, or oil of anise seed between the glass and the crystal plate.

This specimen with a polaroid above and another beneath is supported over a paper on which a mark is made with the aid of a plumb line directly below the center of the specimen. When the eye is placed close to the upper polaroid a series of concentric fringes is seen whose center is the optical axis. By tilting the plate, this center can be made to coincide with the mark on the paper, and

[4] In positive crystals $\mu_e > \mu_o$, in negative crystals $\mu_o > \mu_e$.

[5] Crystal quartz of optical quality is expensive. It may be obtained from the General Electric Co. or from Fredrico G. Hecht, Pan American Trade Development Corp., 40 Wall St., New York 5, N. Y., price (1953) $70 to $95 per pound. A pound is about 10 cubic inches and, with some care, a monochromator can be made from it.

by measuring the angle of tilt the optician can make another cut perpendicular to the axis of the crystal. With this plane of reference, plates parallel to the axis are sawed out. The specimen should be examined before cutting, because quartz is subject to most of the defects of glass.

The refractive indices of quartz at 18°C for Hα, λ6562.8, are $\mu_o = 1.541899$ and $\mu_e = 1.550929$. From equation 3 these data give $d_o = 0.0727$ mm. A temperature control is necessary since an increase in temperature of 1°C decreases $\mu_e - \mu_o$ by 0.0000010961, causing the transmission band to shift 0.71A to the violet.[6]

Dimensions of the Plates

It is difficult to make a plane-parallel plate thinner than 0.5 mm, which is about 7 times d_o, and the dimension of the thickest plate is fixed by the material available. A composite prism more than 100 mm long would, moreover, be difficult to handle. Table 1 shows the dimensions of the plates made by the author.

Table 1—*THICKNESS OF QUARTZ PLATES*

($t = 44°C$; $d_0 = 0.0729$ mm)

Multiple of d_0	Thickness mm	Thickness tolerance in μ
9	0.66	± .05
18	1.31	± .11
36	2.62	± .22
72	5.25	± .43
144	10.50	± .86
288	21.00	±1.73
576	41.99	±3.46

The rather high temperature 44°C was chosen since radial velocities are sometimes encountered in prominences. If the motion is away from the observer, the prominence can be brought back into the field by reducing the temperature.

Making the Composite Prism

An ordinary micrometer suffices to measure the thin plates, but the thicker plates are not so easy to measure and errors become increasingly dangerous in determining parallelism, but less so in measuring thickness. Table 1, column 3, shows the tolerance in thickness expressed in μ (one thousandth of a millimeter) for the various plates calculated from equation (3) which will keep the transmission band within ±½ angstrom (⅕ the band width) of the right position. The reader will see that even 3½ thousandths of a millimeter is much beyond his capacity to measure the 41.99 mm and he must, as in parabolizing a mirror, depend on optical testing to finish the parts. For this reason the author adopted the following procedure in constructing the plates.

After the rough blocks are cut, ground to approximate size, and tested for the position of the axis, they are made approximately plane-parallel by testing with a micrometer. They should then have an excess thickness of about 0.15 mm. The plates, 34 mm square (25 mm is sufficient for small instruments), are mounted one at a time in a plaster-filled tool with thin quartz arcs completing a disk 70 mm in diameter to protect the edges of the plate. The parts are laid on an oiled piece of plate glass, in the tool, which is blocked up about 1 mm from the glass and the tool is then filled with plaster (U. S. Gypsum Co. Hydrocal A-11 is recommended by the editor). The whole face is fine ground, polished, and brought to figure. The excess of thickness at this stage is about 0.09 mm.

The piece is now reversed and, if thin, must be attached to a thick piece of glass with balsam for better support. The plaster is cut away from the back leaving only a narrow overlap so the piece can be tested either mechanically or optically as the work progresses. Fine grinding is continued with the faces parallel until the excess thickness is about 0.05 mm, when optical testing is necessary. Two spectroscopes were used in testing for final thickness and parallelism, one an ordinary small laboratory spectroscope for the thin pieces, the other, a 1-meter concave-grating spectroscope for the thick pieces. Simple spectroscopes using replica gratings are sufficiently accurate for this purpose. Both spectroscopes are provided with a wire in the field of the eyepiece.

Three plates of glass are mounted horizontally, one above the other, the middle one carefully leveled. Polaroids are placed on the upper and lower plates with their axes parallel. The quartz plate in the tool, with its ground face smeared with oil of bitter almond, is placed on the middle glass plate with the axis of the quartz 45° to the axes of the Polaroids. Light passes through this setup perpendicularly to the faces of the plate and then through a right angle prism horizontally to one of the spectroscopes.

The spectrum is seen split up into bands with the one on the red side of Hα displaced considerably because the plate is too thick. The difference between the temperature in degrees centigrade at which the prism is to be used and the air temperature in the testing room, multiplied by 0.71, gives the number of angstroms the band must be to the red of Hα when the proper thickness is reached. The field wire is set at this wavelength. The original adjustment of the wire can be made with a hydrogen discharge tube if sunlight is unavailable; thereafter any source of continuous light may be used.

Parallelism of the faces can be tested by sliding the tool around over the glass plate support. If any shift in the band in the spectroscope is seen, the faces are not parallel.

---

[6] The actual formulae are

$$\frac{d}{dt}(\mu_e - \mu_o) = -\left(1.0961 \times 10^{-6} + 2.4356 \times 10^{-9}\,t + 0.001\,\frac{d\lambda}{dt}\right)$$

$$\frac{d\lambda}{dt} = -(0.71158 + 0.00171\,t)$$

Fine grinding is continued until the band is about 125A to the red of the wire, after which polishing is commenced. The faces are kept parallel by the shift test, and the polishing proceeds until the maximum of the transmission band is centered on the field wire.

If in figuring the plates the required thickness given by the table is passed, a thickness d_0 less may be used without displacing the Hα band. The only bands displaced would be those absorbed by the red filter. The author unintentionally made one plate thinner than it should be, but the small error in thickness was compensated by adding a thin plate of mica, which saved some optical work.

The composite prism contains seven quartz plates, eight polaroids, and two red glass plates (Corning No. 243), one on each end of the prism. Each piece is smeared with mineral oil as the prism is built up. The thickest quartz plate is set with its axis at right angles to the rest of the block to reduce the indistinct focus of paraxial rays, a procedure suggested by Evans. Experience shows that failure to make this adjustment reduces very greatly the usable field.

The completed prism, 92 mm long, is mounted in a close-fitting brass box with end frames which overlap the margins of the plates 2 mm, thus leaving a free aperture 30 mm square. The transmission of the prism is roughly 12 percent.

Use of the Monochromator

The prism P, Figure 2, is placed in the parallel light between the two components A_1, A_2 of a motion picture projector objective of 4 inches original focal length. The disk, D, to occult the solar image is 8 inches in front of one component. It is mounted on a micrometer slide which permits motion perpendicular to the optical axis of the instrument. This adjusts the prominence in the field of the eyepiece or on the photographic film of the camera. The motion picture camera, C, and the eyepiece, E, are 8 inches behind the other component. A guiding eyepiece, O, can be inserted at Y to examine the image while photography is proceeding without interfering with the exposures.

This guiding eyepiece shown in the lower diagram WY_1, uses a thin pellicle Y_1, stretched over the end of the eyepiece tube cut at 45°, thus intercepting 10 percent of the light from the monochromator for visual viewing when photographing is in process. This avoids the double images if a parallel plate were used, or the necessity of withdrawing the tube during an exposure if a right angle prism were employed.

As the making of the pellicle about 0.005 mm thick is not a well known process a description may interest the reader. One gram of pyroxylin (Parlodion, Mallinckrodt Chemical Co., St. Louis, Philadelphia, or New York; 1 oz bottles) of volume 0.633 cc, is dissolved in 30 cc amylacetate. If 3 cc of this solution is poured on a leveled plane glass plate 5 inches in diameter which, by tipping, is made to entirely cover it will, when dry, produce a pellicle 0.005 mm thick. Films much thinner are difficult to handle. It is important that the

plate be free from significant scratches, for these will be reproduced on the pellicle.

The plate is then covered with a large bell jar. Dust motes may be removed with a pointed stick before the film begins to dry. Drying will require a couple of days, but is somewhat hastened if the bell jar is removed and the vapor blown out after the first 8 hours.

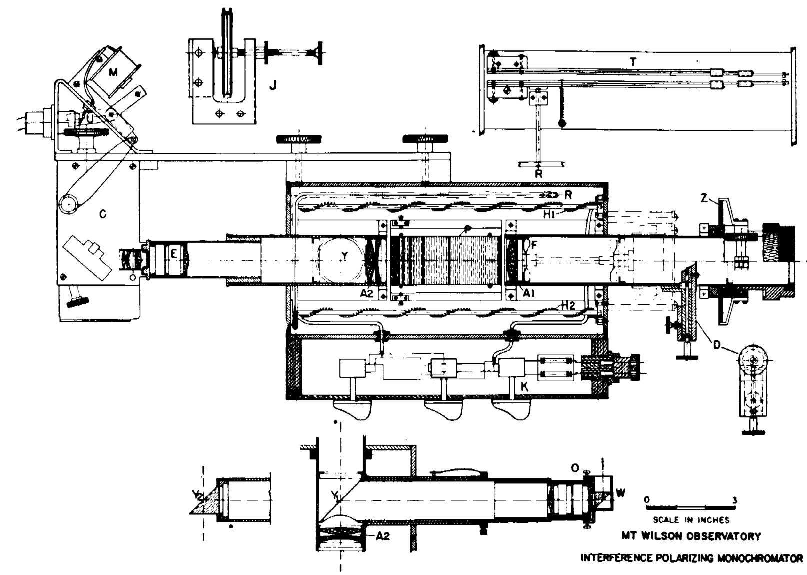


Figure 2

Diagram of the monochromator. Z. position circle; D. occulting disk mounted on micrometer support; F. circulating fan. R. thermometer. K. circuit control box. T. bi-metallic thermostat. J. alternative form of thermostat (ether-filled wafer). H_1H_2. heater coils. P. composite prism. A_1A_2. collimating and image-forming lenses. O. guiding eyepiece for photography. An alternative form with prism Y_2 to replace the pellicle Y_1 is available to scout the field with full illumination. E. collimating and viewing eyepiece. C. 35 mm motion picture camera focused for infinity. M. exposing magnet.

The end of the tube Y_1 on which the pellicle is to be stretched is ground flat in preparation for the cementing process. Probably the best way to remove the pellicle from the glass plate and to transfer it to the tube Y_1 is as follows. The glass plate is placed in a deep jar of water upon a piece of white cloth to make it more visible. After a couple of hours the pellicle will become detached and lie wrinkled upon the plate.

The ground surface Y_1 is painted with shellac and allowed to partially dry. This is repeated several times until a thick syrup-like layer is formed. It is important that this layer be not too thin. The tube is now placed in the water with Y_1 down and this surface is pressed upon the pellicle, raised and slowly righted under water until the pellicle hangs in folds around it like a tablecloth. The whole is then slid out of the water slowly and the excess pellicle removed with a knife. The pellicle is now stretched by pressing down and out on the edge of the tube with the thumb, the shellac acting at once as a lubricant and as an adhesive. It is then washed in distilled water to which a few drops of Aerosol (Eastman Kodak stores) have been added to avoid spotting; a tuft of cotton can be used to facilitate washing. After drying a few hours the pellicle

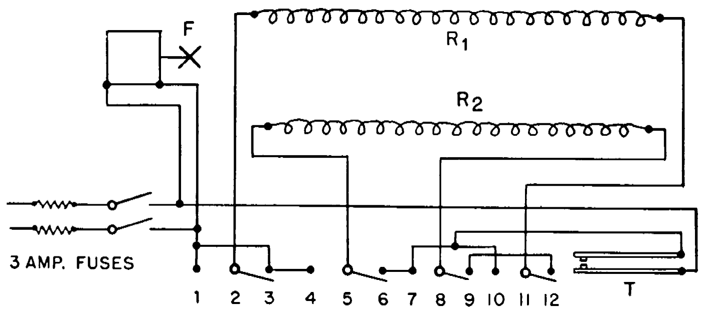


FIGURE 3

Wiring diagram of the monochromator. A wafer switch can be used to control the circuits 1 to 12 with a single button. R_1R_2. *heater coils.* T. *thermostat.* F. *circulating fan.*

will be a flat reflecting surface. A removable prism W is provided over the eyepiece O as the instrument sometimes gets into positions inconvenient for observation.

Two heater coils, H_1 and H_2, are in series with the thermostat, T, and carry 0.5 ampere at 110 volts. The thermostat can be adjusted from outside the aluminum case. The coils can be operated in parallel for quick heating. An alternative form of thermostat unit K can be installed and is designed to operate at the particular temperature of the monochromator.

Figure 3 is the wiring diagram for the monochromator. The two d.p.d.t. switches of Figure 2 may be replaced with a single 12-point wafer switch if desirable. The heater units R_1, and R_2 are made from No. 30 nichrome wire which has 6.8 ohms per foot. Two 16-foot lengths are needed in each heater unit. The fan motor F is a Barco (Barber Colman Co., Rockford, Ill.) of the smallest size.

A thermometer, R (Figure 2), a small (1.25-inch) circulating fan, F, and a position-angle circle, Z, complete the instrument. The thermometer is a chemical type of solid glass graduated from 10° to 150°F. It is bent in a bunsen flame in the manner of ordinary glass rod. The mercury in the heated part of the tube evaporates, but condenses again when the tube cools. An

FIGURE 4

Monochromator attached to 6-inch telescope (Alvan Clarke 1875). The objective is mounted on a turret with a single plano-convex lens of the same focal length with which it is interchangeable for prominence photography. An exposure meter with red filter is attached to the finder. The exposing timer which operates the camera electrically is shown at the lower left.

acetylene tank burner which heats a very short length of tube gives best results. The scale will be changed somewhat and it should be checked against another thermometer, thereafter making the proper allowance.

Figure 4 shows the instrument attached to a 6-inch refractor. It will operate on a reflector, but, with average conditions of the mirrors, the scattered light in the field is greater than with a refractor. Even the scattered light of the refractor can be greatly reduced by adopting the basic principle of the Lyot telescope. This consists in replacing the objective with a simple plano-convex lens, curved side toward the sun. Since we are working in monochromatic light chromatic aberration is virtually null, but spherical aberration should be corrected.

The correction for spherical aberration consists in the removal of glass by polishing chiefly in a zone which has maximum depth at 0.71 radius from the center and falls gradually to the spherical lens figure at the center and edge. The depth of the zone at the maximum departure 0.71 radius from the center is given for crown glass by

$$\Delta X = 0.0123d/R^3 \qquad (4)$$

where ΔX is the departure in the same units that the diameter d of the lens is given and R is the focal-aperture ratio of the lens.

Suppose we take a plano-convex lens of 6 inches aperture and 90 inches focal length. Then $R = 15$ and d is 6 inches or 152 mm, and ΔX is 0.56×10^{-3} mm or 0.56μ. This is almost the wavelength of the green mercury line $\lambda 0.546\mu$. The correction can be put on either face of the lens, as Figure 5 *A, B* shows, but it is easier to follow the progress of the figuring if we put the correction on the plane face, since this can be tested against a test plane.

We may compute the amount of the correction ΔX at any distance y from the center of the lens, where y is given in fractional part of a lens radius by the formula

$$\Delta X_y = \frac{A}{4F^3}\left(\frac{n}{n-1}\right)(h^2y^2 - y^4) \qquad (5)$$

where A, the aberration coefficient, is 1.08 for crown glass, F is the focal length, n is the index of refraction, 1.52 for crown glass, h is the radius of the lens (half the aperture) and y is the distance of the zone to be corrected from the center, expressed in the same units as F and h (mm or inches). Figure 5*C* is a plot of ΔX_y for crown glass. The dashed line is the shape of the interference pattern as seen against the test plane when the figuring has been completed. As Figure 5*C* shows, the bright crest of an interference fringe bends the distance between two crests (one wave) in mercury light and returns to normal position at the edge of the lens. These tests may be made with a common fluorescent lamp which is rich in mercury light.

If we make an $f/16$ lens of 6-inch aperture, equation (4) gives a maximum departure $\Delta X = 0.46 \times 10^{-3}$ mm, which is 0.84 the wavelength of the green mercury light and the scale of ΔX in Figure 5*C* should read from 0 to 0.84, instead of 0 to 1.0. This plano-convex lens is mounted on a turntable with the 6-inch telescope objective so that either can be used by simply rotating the mounting, as shown in Figure 4.

On the left of the monochromator in Figure 4 is the automatic exposing device (on a white table), a brass cylinder in which a triangular slot is cut to operate the contact key. This cylinder, rotated past a sliding contact, operates the shutter through a relay and magnet, *M* (see also Figure 2).

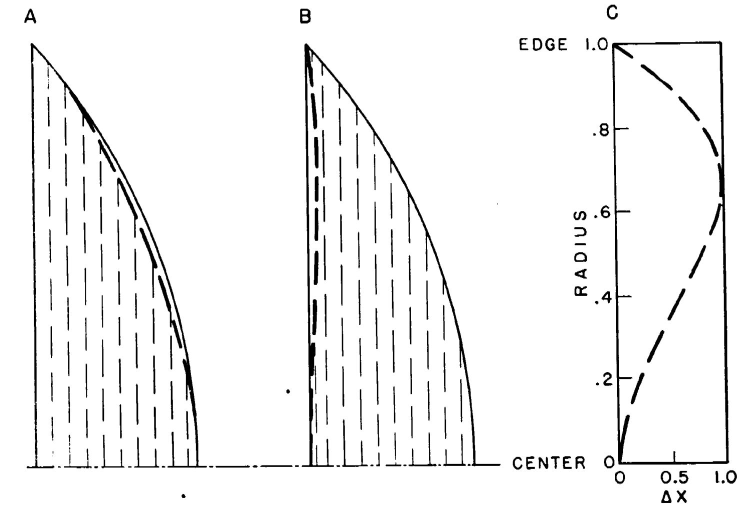


FIGURE 5

Spherical aberration corrections on plano-convex lens. A. entire correction put on curved surface. B. entire correction put on plane surface. C. deformation of the interference pattern when correction on plane face B of an f/15 lens is viewed against a test plane with mercury light (maximum deviation Δx is 2 fringes or 1 wave).

Figure 6 shows the automatic exposing device which is used to operate the magnet that controls the camera shutter. A brass drum 3 inches in diameter by 6 inches long has a triangular slot 5 inches long with base ¼ inch wide cut in one side. The ends are plugged with Bakelite and the brass shaft which passes through them is supported at each end by a Telechron motor. One of these motors operates at 1 rpm, the other is geared up to 2 rpm. By tightening the set-screw on one motor shaft and loosening that on the other, either speed can be had on the drum. A second unit, which operates at 4 rpm can be easily exchanged for the first, if faster motion pictures are desired.

The contact mechanism is entirely insulated from the drum with plastic parts. The finger which falls into the slot as it moves past the contact is made of plastic (piece of a screwdriver handle). The contact operates a 110-v a–c relay, which in turn operates the exposing magnet on the shutter, which is another large-size relay magnet. A second relay operates the pen of a standard form of chronograph to time the exposures. The slots in the drums permit exposure times less than 1.5 second. Rough timing adjustment is made by sliding the contact along the slot to the proper place. Changes of about a tenth of a second can be made by turning the contact screw which changes the dis-

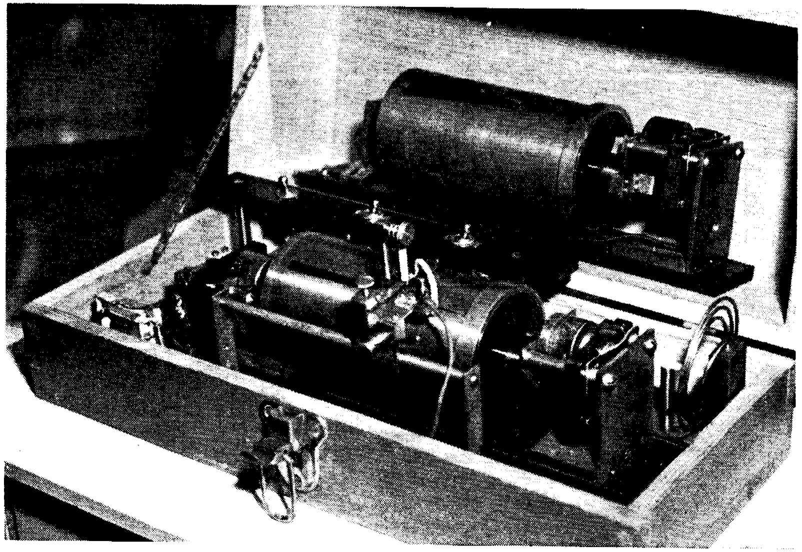


FIGURE 6

Exposing timer for camera control. The slotted drum is supported between two Telechron motors which drive it at 1 or 2 rpm, depending on which is clamped to the axle of the drum, the other acting as a bearing. A pin in the band on the right end of the drum trips a gong hammer to signal 8 seconds before exposure. A timing unit for 4 rpm is shown in the lid of the box.

tance the contact lever must travel. If exposures of several seconds are desired, split bands with various openings are provided which can be slipped upon the drum to replace the slot.

A pin on one end of the drum strikes the lever of a gong hammer, thus warning the observer that exposure will take place within 8 seconds. This is just enough time to adjust the image before the picture is exposed. Short exposures are hard to control, so the objective is diaphramed to 3 inches in order to lengthen them. With this setup exposures of 0.2 second are required for prominences on a 2-inch solar image on Eastman Hα film. If eyepieces (*E*,

Figure 2) are changed to change the size of the pictures on the film, the exposure will vary inversely with the square of the power of the eyepiece. Thus a 4-inch image will require 0.8 second.

To photograph with the instrument under the best conditions push-button control of the telescope in right ascension is desirable. This is accomplished by inserting a motor-operated differential *D* between the worm and the clock

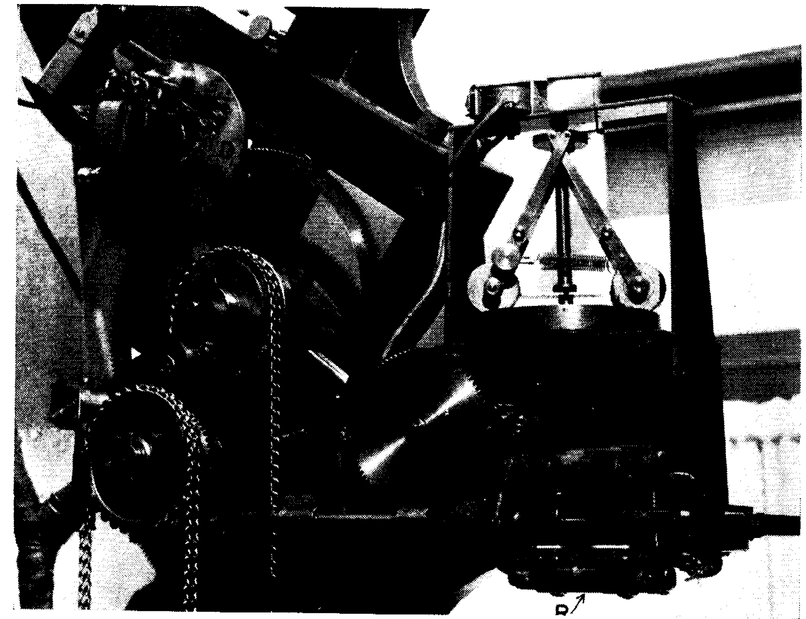


FIGURE 7

Slow motion differential D in the telescope driving train. A toy-train motor drives a fine tooth worm gear through a gear train. The circular motor base is attached to one of the clock-train pinions and the worm gear to its shaft. Four insulated rings with brushes on the other side of the circular motor base feed current to the field and armature of the motor from push button operated a-c relays (12-v). The a-c rewind motor R of the driving clock and its worm are also shown.

train of the telescope (Figure 7). The motor is one used on toy trains and operates from a 12-v transformer through a–c relays. A switch on the push button handle shorts the commutator of the motor through a low resistance to reduce the motor speed for guiding purposes.

The motor drives the pinion upon the worm of the telescope through a reducing worm of ratio 177 to 1. This was made on a lathe using an ordinary ¼-inch machine tap of 28-thread pitch as a hob.

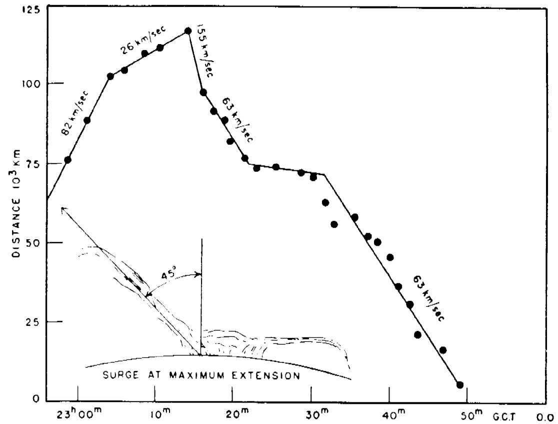


FIGURE 8

Time-distance diagram from visual measures of a surge prominence on Jan. 3, 1941. The rapid initial advance, sudden changes of velocity, and slow final retreat are characteristic of these prominences.

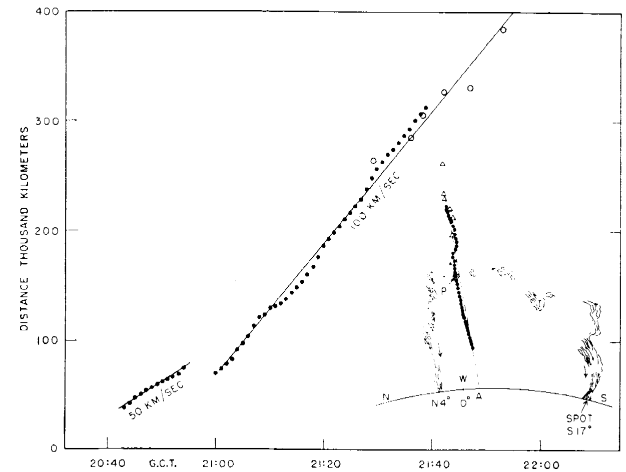


FIGURE 9

Motions of the eruptive prominence of Dec. 4, 1941. The trajectory of a knot in the prominence is shown in the lower right and the time-distance diagram is shown above to the left. Dots from monochromator pictures; open circles and triangles from the spectroheliograph. Note that as the prominence rises matter is returning to the sun, as the arrows indicate. This is characteristic of eruptives.

PROMINENCE STUDIES

Prominences may be measured with a micrometer attached to the monochromator. Figure 8 shows a plot of the measures of a surge which was ejected from and returned to a sunspot on the limb. The rapid rise and slower decline of the prominence are illustrated.

Photography offers the best method of studying prominence motions and formations. Ordinarily, photographs are made with 20 or 30 feet equivalent focal length at the rate of one per minute. Any large or very bright prominence is unstable and likely to go into the eruptive state. The character of the motions is shown in Figure 9, photographed with the monochromator on December 4, 1941.

The film was measured by projecting it in a 35 mm motion-picture projector upon a milk glass screen. Upon the screen was drawn an arc in ink of

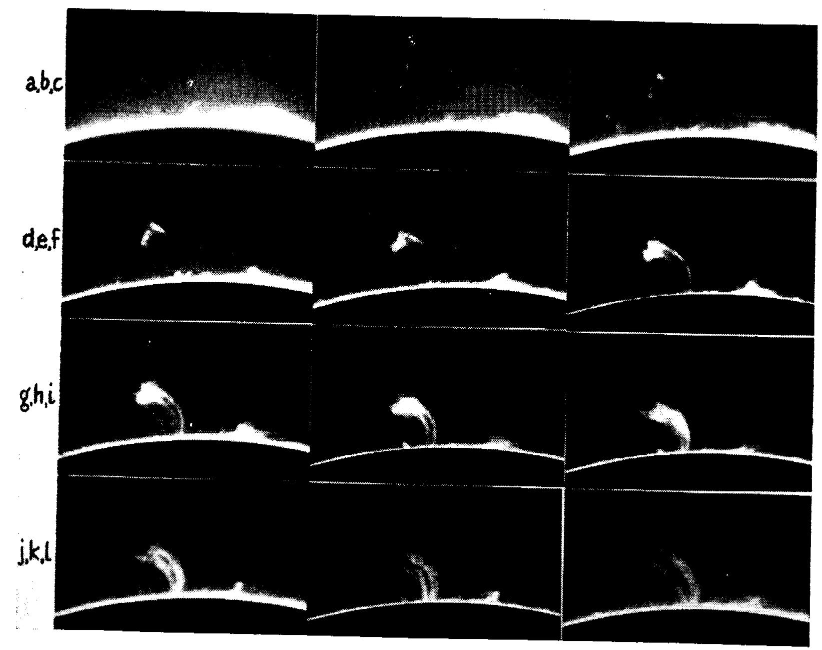


FIGURE 10

The coronal cloud type prominence of Sept. 23, 1941. Taken from a film made with the monochromator (Figure 4) at 5-minute intervals. Note that the prominence ab forms as two dots in coronal space above a sunspot at the middle of the arc of solar limb below. Other dots form cdef and the whole rains down ghijkl into the sunspot below. Time interval of the entire picture 55 minutes.

radius 35 cm. On this scale 1 mm is 2000 km on the sun. The film images of the arcs of the solar limb were made to match this ink arc and a point near the crest of the prominence was inked upon the screen for each picture in succession. This gives us the trajectory of the prominence shown in Figure 9, lower right, where a sketch of the solar limb and prominence is seen. The black dots are from the monochromator pictures and the triangles from plates taken with the spectroheliograph on Mt. Wilson. Note that the trajectory is nearly a straight line, though there are some evident deviations. Above this sketch is the plot of the measures made with a plastic millimeter scale (obtained at a ten-cent store). The measures were made along the dashed line on the sketch and, plotted against the time (Greenwich Civil Time is given), they reveal the character of the motion and the velocities involved.

Figure 10 shows the development of a prominence of the coronal cloud type, Sept. 23, 1941; exposures at 5-minute intervals from a film taken with the monochromator. Note that this prominence develops from space above a sunspot on the limb of the sun and eventually rains streamers down into it. The entire picture covers an interval of 55 minutes.

There is a large field of investigation open to the observer with a monochromator in the study of prominences. If an eruptive is found and followed with 1-minute interval exposures a distinct contribution to our knowledge of the motions of these objects can be made by determining the trajectory and measuring the film to secure data such as is analyzed in Figure 8. Two other types of prominences are also of special interest, tornadoes and interactive prominences. While tornadoes are fairly common, good examples in which we can study the spiraling motion are rare. Prominences which exchange streamers are interactive. It is of interest to study the exchange of these streamers.

For studies on the solar surface, such as those of solar flares, a narrower transmission band is desirable in the monochromator. The author has seen many flares with the monochromator described here, but the fainter ones demand a transmission band of about 1 angstrom. This can be accomplished by adding two calcite plates $4\frac{1}{2}$ and 9 mm thick with axes at right angles to each other. With this arrangement the temperature must be controlled within one degree F to keep the $H\alpha$ line centered on the transmission band. Thermostat unit J of Figure 2 would be suitable for this modification.

The Caustic Test

Capable of Accuracy within One Hundredth of a Wavelength

By Irvin H. Schroader

In 1859 Leon Foucault publicly described his test at the center of curvature of a mirror, which has since been used in making thousands of excellent mirrors. Despite its great usefulness, certain disadvantages show up in applying the test to non-spherical surfaces, such as the paraboloid, that make it difficult to use and which set a practical limiting accuracy of zonal measurement at about 2 millionths of an inch. Some improvement results when the zonal mask is discarded, testing then being done by observing shadow edges and the over-all shape of the surface (Everest, Gaviola). However, shadow edges are never very sharp and the over-all curve, such as the doughnut, can be studied only in the case of moderate f ratios. Hence a zonal mask is needed for a short focus paraboloid and for any other aspherical surface.

Let us start on familiar ground with a description of the Foucault test. An illuminated slit is placed a little to one side of the center of curvature of a spherical mirror, so as not to obstruct the returning cone of light reflected from it. To simplify the discussion let the knife-edge be mounted on the same block that carries the slit, so that both are the same distance from the mirror and move as a unit. (In actual use the slit will be kept fixed in the caustic test, as is the usual practice in the Foucault test.)

The knife-edge is cut across the reflected cone of light and the center of curvature of the sphere is located as follows. If the knife-edge and the shadow on the mirror travel in the same direction, the knife-edge is inside the center of curvature; if they travel in opposite directions it is outside. In the case of a perfect sphere the mirror appears to be perfectly flat, and darkens evenly all over without any trace of shadow motion when the knife-edge is at a distance from the mirror equal to its radius of curvature R. Thus, for a sphere, this is a null test. The accuracy to which a spherical surface can be figured then does not depend upon measurements of any kind but depends only upon the sensitivity of the test set-up and the worker's skill.

When the above outlined procedure is carried out we soon learn by experience several facts. Very minute zonal errors, perhaps $\frac{1}{5}$ of a millionth of an inch high, can be seen by delicate adjustment of the knife-edge as it cuts across the optical axis. On the other hand, if the problem is to measure the radius of curvature of a sphere (by moving the knife-edge along the optical axis until the mirror looks flat and darkens evenly with no shadow motion either to left or right as the knife-edge cuts across the cone of light) it is difficult to judge just where to "call" it. Even the average of several settings can easily be off as much as .01 inch, which corresponds to an uncertainty of several millionths of an inch on the mirror surface (Ritchey). Thus we conclude that the Foucault test is very sensitive when used to *detect* zonal error but is much less sensitive when used to *measure* error.

For any mirror surface other than spherical, a paraboloid for example, simplicity is replaced by complexity, for no setting of the knife-edge can be found anywhere along the optical axis that will cause more than small areas of the surface to darken evenly. In fact the test is now characterized by an apparent deviation of the surface from flatness and by moving shadow edges over most of the surface. Everest has described this behavior in great detail for the case of a paraboloid, so we shall here discuss it only in sufficient detail to enable the reader to understand later developments. Briefly, the explanation is that the mirror surface has been deliberately distorted by figuring so that there is no longer a single center of curvature for the whole surface as in the

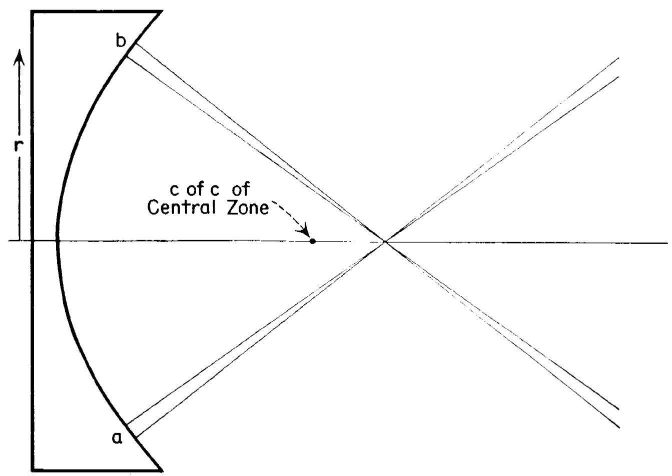


FIGURE 1

case of a sphere but, rather, now there are many centers of curvature spread out in a small space near the center of curvature of the center zone of the mirror.

The problem is to determine the amount of correction that has been given the mirror. Since for non-spherical surfaces the test is no longer a null test, a scheme of measurement must be resorted to, which in turn raises the question of how accurate our measurements are.

Although some read shadow edges in testing paraboloids, most workers use a zonal mask in which a row of holes is cut out across the horizontal diameter of the mirror. The idea is that each hole exposes a part of the surface which can be considered very nearly spherical if taken small enough. But then their size is too small to make possible the accurate measurement of the radius of curvature of each of these small spheres individually. A more accurate procedure is to take a pair of these openings, a and b, Figure 1, exposing the two

sides of the mirror zone ab: the centers of both a and b are at a distance r from the optical axis. The focal length of this zone is measured by trying to locate with the knife-edge the point where the cones of reflected light from a and from b cross over the optical axis (the crossover point).

A great deal of confusion has grown up in the literature describing this quantitative form of the Foucault test with regard to this measurement. The assumptions usually are (see Figure 1): (1) the two sides, a and b, of a zone ab are spherical, for all practical purposes; (2) the center of curvature of sphere a and that of b lie on the optical axis at the crossover point, no matter what curve the mirror surface has—paraboloidal, ellipsoidal, etc. In other words, it is assumed that the little spheres a and b are segments of a single sphere whose center is at the crossover point. Therefore, if a knife-edge intercepts the two cones of light at this crossover point, the two sides a and b should act the part of spheres by appearing to be flat, and by darkening evenly all over simultaneously, with no moving shadow edges. In the case of a perfect paraboloid, the knife-edge should then be at a distance $R + r^2/2R$ from the vertex of the mirror (from here on R is the radius of curvature of the central zone of the mirror, unless otherwise stipulated).

Let us check these two assumptions against experimental results. If one starts with fairly large holes in the screen, no such behavior can be observed, so our first guess is that assumption No. 1 has been overdone—the holes are too large. To avoid this mistake we go to the opposite extreme and cut slots only ¼ inch wide in the mask. Now, however, we are on the other horn of the dilemma for it is impossible to decide whether these narrow zones are flat or whether there are any moving shadow edges. In other words, the test is now reduced to judging a photometric balance between two widely separated slots. All will agree that here the proper setting of the knife-edge is very difficult to judge accurately, the more so for lower f ratios. (Note also that it would take many such slots to test the whole surface of a mirror.) Moderate sized holes in the mask, next chosen in an attempt to avoid the dilemma just described, only add confusion to the uncertainty since now confusing details can be seen in the shadow behavior. A narrow slit gives rise to prominent diffraction effects, whereas a wide slit is less troublesome but is also less sensitive. Just what goes on in one of these holes is hard to see experimentally because the eye is blinded by the bright diffraction glare around the edge, and it is even harder to see theoretically because of the mathematics required by diffraction theory. Linfoot has worked it out (*Monthly Notices*, Royal Astronomical Society, No. 6, 1948) for holes $R/600$ inches wide, ignoring the diffraction fringes due to an assumed slit width of .001 inch. He concludes that under these conditions the accuracy of the test still depends essentially upon the ability of the worker to judge a difference in brightness between two widely separated holes.

The final clincher by way of experiment would be to cut two holes in a mask, about ¾ inch in diameter, each with its center say ⅔ of the distance from center to edge of the mirror along the horizontal diameter. Set the knife-edge so that (as nearly as can be judged) the two sides of the zone darken evenly and simultaneously. Now remove the mask and it will be easy to see that the shadows on the mirror move in the same direction as the knife-edge across both sides of the zone previously exposed by the two holes; that is, the knife-edge is inside the center of curvature of these two areas of the mirror surface. We can only conclude that experimental facts do not verify our two assumptions. Let's examine them.

In *Popular Astronomy*, Volume 10 (1902) pages 337–348, the late Professor F. L. O. Wadsworth demonstrated that our second assumption, that the centers of curvature of both sides of a zone lie on the optical axis, is incorrect and that Figure 1 should be redrawn as in Figure 2. If the latter is correct, it would explain why the knife-edge was inside the center of curvature of both a and b when it was set at the crossover point in the experiment just described.

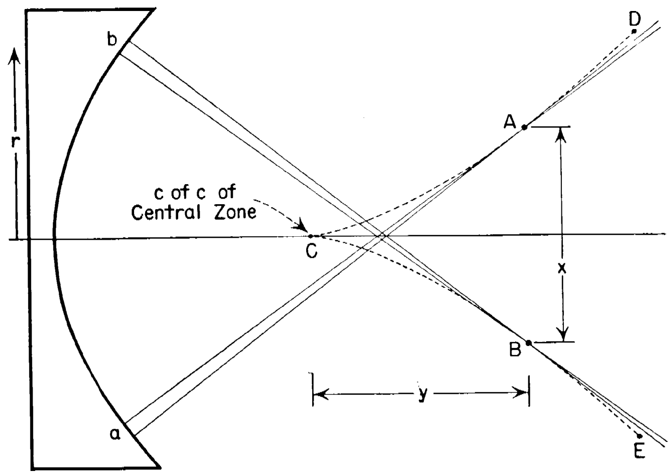


FIGURE 2

That something like Figure 2 must be correct can be argued from the method used in parabolization. Glass is worn away in amounts increasing from none at the mirror's edge to a maximum at the center; in other words, as the center is approached the radius of curvature of the surface is gradually shortened. In doing this the tilt or slope of each zone is also changed. It therefore would be an extraordinary coincidence if the change in slope and the shortening of the radius were to keep exactly in step for all zones, permitting all their centers of curvature to remain on the optical axis.

Again let us approach the situation from the purely experimental point of view. Figure 3 is a series of photographs of the images of a slit, taken at 13 points spaced along the optical axis near the "average center of curvature" of a paraboloidal mirror, masked so as to expose the two sides of a single mirror zone. The ninth photograph from the left shows the images at A, B, Figure 2. The sixth shows the image at the crossover point, that is, where the two cones of light from a and b cross the axis as in Figure 2. (This is the *so-called* center of curvature of zone ab in the Foucault test.) The image on the sixth is not sharp because neither the cone of light from a nor that from b has yet come to a sharp focus at the crossover point, where this photograph was taken. On the ninth, the images are sharp because it was taken at the *actual* centers of curvature of the two spheres a and b (Figure 2 at A, B).

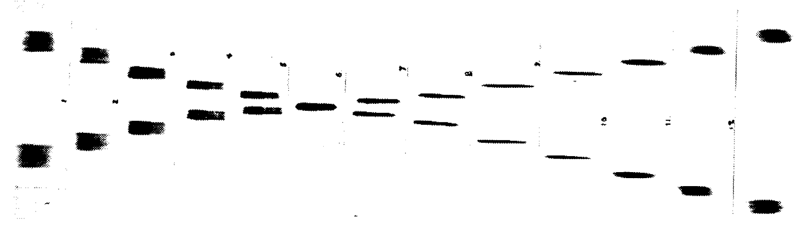


FIGURE 3

Images of a slit about 1/635 inch wide and 1/25 inch high, taken near the average center of curvature of a 6-inch paraboloidal mirror. The mask openings were 7/8 inch wide and their centers were 2.16 inches from the center of the mirror, which was at the left of the images. Slit and plate were moved as a unit along the optical axis distances of 1/15 inch from numbers 1 to 3, 1/30 inch from numbers 4 to 8, and 1/15 inch from numbers 9 to 13. The principal fact revealed by this series of photographs is that the sixth image, which was taken at the crossover point on the axis, where the knife-edge is placed in the Foucault test, is not sharp, while the ninth pair, taken about 1/8 inch farther from the mirror and at the true foci of the areas isolated by the mask, are sharp. These photographs were originally published in an article by Platzeck and Gaviola, of the Argentina, in the Journal of the Optical Society of America, *Volume 29 (1939), pages 484–500. Prints from the original plates were numbered and kindly furnished by Dr. E. Gaviola.*

These images speak for themselves about testing along the axis. To the tyro they may even speak too loudly, exaggerating some relations and throwing undue doubt on the Foucault test, which will not be supplanted by the test to be described. Briefly, they were made with a short focus mirror and then further enlarged to make the effect large enough to show up clearly. It is easier now to see the why of some of the odd shadow behavior of the Foucault test. Although each side a and b of a masked zone is very nearly spherical, the centers of curvature A and B (Figures 2 and 3) of these two spheres are separate from each other and do not lie on the optical axis. In performing the Foucault test, then, we placed the knife-edge at the crossover point (that is, *inside* the actual centers of curvature) and then struggled to force the shadows to behave as though it were at the center of curvature of both a and b simultaneously; a little like trying to force a nut when the thread is crossed.

If now anyone has read these revelations and worked up a temperature let him relax. In practice the Foucault test made with masks as described by Ellison, Porter and others, is adequate for a large majority of surfaces, where it makes possible measurements in good hands accurate to about $1/10$ wavelength, which is better than the standard tolerance of $1/8$ wavelength of good optics. Thousands of good mirrors made by it in the past 90 years or more provide tangible proof of this fact. Yet, for the more experienced worker a test that will not reliably measure more closely than the needed tolerance, thus having no reserve, leaves something to be desired. For short focus mirrors, where many zones would have to be measured, a finer test is almost a must, as is also the case for other and more strongly aspherical surfaces.

The preceding paragraph may seem contradictory. Briefly, the situation is this: In the case of a 6-inch $f/8$ mirror, one would make knife-edge settings at the focus of the central, (.707) and edge zones, and in addition would check the surface between these zones to make sure that it was smooth. Since the total departure from a sphere in this case amounts to only about $1/2$ wavelength, it is very reasonable to assume that three measurements accurate to $1/10$ wavelength made on a smooth surface would assure adequate mirror performance. But now consider a 12-inch $f/5$ mirror, which will depart so far from a sphere that it is not easy to be sure by inspection that the surface has a smoothly flowing curve. It is easy to overlook zonal errors in the diffraction fringes preceding the main shadow. Here measurement of many zones is necessary and, for reasons previously explained, they must be narrow to attain $1/10$ wavelength accuracy. It is generally assumed that the errors committed in setting a knife-edge are *accidental,* that is, the displacement measured along the optical axis is just as likely to be too large as to be too small and thus errors cancel out in the average of several settings. On the other hand a *systematic* error is committed when the knife-edge is set always too close or always too far from the mirror, due perhaps to a repeated mistake in judging vague shadow behavior. Suppose then that five zones are measured on the 12-inch mirror, each with a systematic error of $1/10$ wavelength. The total error at the mirror's edge would be 5 times $1/10$ wavelength, or $1/2$ wavelength, a very considerable amount.

Conclusion: Either errors must not be systematic or they must be kept much less than $1/10$ wavelength; otherwise claims regarding a mirror's accuracy may prove illusory. Since $1/10$ wavelength accuracy for each zone measured has been shown to be about the best consistently obtainable with the Foucault test, and since judging a photometric balance between two widely separated holes in a mask has been shown to be definitely subject to systematic error, a more accurate test is needed. (The zonal Foucault test itself has no systematic error.—Linfoot, *loc. cit.* It is human fallibility that may introduce systematic error into the test results.)

To summarize, then: We have tried to show that (1) the premises on which the zonal Foucault test is based are not exact; (2) nevertheless the Foucault test remains the basic testing technic to be mastered (and perhaps better understood) before attempting advanced methods; (3) and a better test is

needed as soon as the worker's figuring skill is capable of taking advantage of its superior accuracy.[1]

In the preceding part we saw that Foucault's test was a null test for a sphere and that it therefore was natural to try to divide an aspherical surface into a number of small, practically spherical segments and to test each little sphere separately. Lacking an accurate method of doing this, we then resorted to testing these little spheres in pairs by locating their foci. But with the knife-edge at the crossover point it was still inside the center of curvature of both little spheres, so no use was actually made of the nice properties of a sphere under the Foucault test. Rather, testing was reduced to reading a poorly designed photometer (one with very wide spacing between holes).

In that which follows the technic of testing at the real center of curvature of a zone will be introduced one step at a time.

Consider a mask of height sufficient to cover the mirror and more than twice as wide as the mirror, with a half-inch hole in its center. Start with the mask so placed that the left edge of the hole is just even with the left edge of the mirror as viewed from the testing stand. The average center of curvature of the small portion of the mirror exposed by the hole will be at *D,* Figure 2. Then, as the hole is moved across the horizontal diameter of the mirror, the center of curvature traces out the dotted curve *DCE.* Since this is called a caustic curve, the test to be described will be called the caustic test.

Thus there are two modes of expression—at the center of curvature, or on the caustic curve. It will be convenient when dealing with a single zone to speak of its two centers of curvature, say *A* and *B,* Figure 2, which of course lie on the caustic curve; whereas when reference is made to the mirror as a whole it will be convenient to speak of all its centers of curvature as a whole, which form the caustic curve. The process of parabolization starts with a spherical mirror whose caustic curve is a single point (since a sphere has but one center of curvature). It proceeds with the center of curvature of each zone slowly being changed by figuring until the mirror produces a caustic curve of the proper shape.

The simplest kind of test dingbat, a razor blade on a block of wood, will suffice to introduce caustic testing. However, knife-edge settings instead of being made along the axis as in Foucault's test, are made along the caustic curve. The knife-edge is first set at the center of curvature of the central zone and then is pulled away from the mirror a small distance. It will be noticed that as it cuts across the axis from left to right the very first part to darken is

---

[1] Editor's Note: Nearly all more advanced mirror makers will be able to recall their own wide grins after going back to test their first mirror after completing their of course practically perfect second; and the same on testing their second after completing the much superior third; and so on and on, up to the point where their curve of improvement flattened off to an asymptote of perfection (or else dipped downward again). Yet did not each mirror at the time it was made seem to give satisfactory performance on the stars at least until the observer's eye and mind had become more sophisticated and exacting? In 1929 Russell Porter was in your editor's shop just after mirror No. 3 had been finished and, after testing it, suggested a test of No. 2. The test was made, glances and chuckles were exchanged.

a small patch on the right half of the mirror, and the very last part to darken is at the same distance from the center of the mirror on the left half. In Everest's technic these two areas, the first and the last to darken, are called the regions of greatest slope. The following theorem will hold for any smooth curve, not necessary paraboloidal. *When the first faint shadow appears on the right-hand half of the mirror, the knife-edge is at the center of curvature of the shadowed area; when the last glimmer of light fades from the corresponding area on the left half of the mirror, the knife-edge is at the center of curvature of that area.*

An important application of the theorem is made in a qualitative form of the caustic test (hereafter called the smoothness test) to reveal very small zonal errors that may be lost in the deep shadows when short focus paraboloids are tested by conventional methods. Starting at the center of curvature of the central zone, the knife-edge is moved in small steps away from the mirror, attention being paid at each step only to the modest sized area that first darkens as the knife-edge cuts across the axis. In effect this amounts to dividing the mirror into a string of small areas across its diameter (without using a mask), each area small enough so that it darkens evenly all over. Any small irregularities will be shown up with maximum sensitivity. Here a reasonably narrow slit and a delicate touch on the knife-edge will help.

This qualitative test may be made quantitative if a stick with brads driven in at measured intervals is hung in front of the mirror to measure shadow location and a scale is provided on the knife-edge to measure its displacement. The knife-edge is first set at the center of curvature of the central zone. Then it is moved a distance y along the axis so that, as it is cut across the axis, the first and last areas in shadow are centered on the first pair of brads, one on either side of the center of the mirror. This is repeated for each pair of brads. For a perfect parabola it turns out (if the slit is fixed) that the displacement should be $Y = 3r^2/R$ where r is the distance from the center of the mirror to a given brad, and R is the radius of curvature of the central zone. This displacement is just three times as large as that measured in Foucault's zonal test. Thus the displacements measured in the caustic test may be divided by 3 and then compared with the old familiar formula r^2/R. A suitable test dingbat, a little more refined than a block of wood but no more complicated in principle, will be described in a later section.

The advantages of this test over Foucault's test are: (*a*) masks are not used; (*b*) attention is fixed on only one side (then on the other) of a zone while making settings, with no comparison between them required; (*c*) the position of the shadow is essential rather than its comparative brightness; (*d*) measured knife-edge displacements may be interpreted as in Foucault's test after they have been divided by 3 (for a paraboloid); (*e*) it serves to introduce the worker to testing along the caustic curve; (*f*) it is particularly useful for very short focus mirrors, say $f/1$ to $f/2$. The principle disadvantage is the difficulty in estimating the center of the first and last areas to darken. After a little practice it has been found to give accurate results and has the advantage of requiring less fancy equipment than the advanced (and more accurate) form of caustic testing now to be described; though the latter will divorce the test procedure from all vague shadow behavior much to its advantage.[2]

In the *Journal of the Optical Society of America, 29* (November 1939), appeared a paper by Richard Platzeck of the LaPlata Observatory and E. Gaviola of the Córdoba Observatory, Argentina, entitled "On the Errors of Testing, and a New Method of Surveying Optical Surfaces and Systems." This new method is a caustic test with a different measuring technic than that described above, so we will backtrack a bit.

It is shown, by a derivation we will dodge, that if a hole (say *a*, Figure 2) has a diameter of about $R/100$ inch the small segment of the mirror thus exposed can be fitted to within 1/100 wavelength by some sphere; and this sphere will have its center of curvature at A, Figure 2. This is a very large hole compared to those used in Foucault's test. For a 12-inch $f/5$ mirror it would be $R/100 = 120/100 = 1.2$ inch! However, in order to take advantage of this fact, it is necessary to test at the actual center of curvature A.

The next step is to set up a test procedure that will measure the amount of correction a mirror has received. In Figure 2, the two cones of light reflected from the mirror at a and b will have directions determined by the simple law of reflexion; that is, incident and reflected rays make equal angles with the normal to the surface. We can therefore make use of the cones as long optical pointers that will be very sensitive to small changes in the shape of the surface (which changes the direction of the normal), provided the cones can be accurately located by measurements.

Roughly speaking, one can locate the two cones by making measurements anywhere along their lengths, but in practice only a few positions are useful. Foucault's test uses the crossover point, which looks good until it is tried. The best place of all is at the actual centers of curvature A and B where the cones of light have narrowed down to a sharp focus (Figure 3, No. 9) and the two holes a and b, Figure 2, actually test like spheres. Two measurements will be made—the distance y measured along the optical axis from the center of curvature of the center zone out to where a line joining A and B, Figure 2, crosses the optical axis; the distance x from A to B, measured perpendicular to the optical axis.

For making this measurement a knife-edge is poorly suited since it is a one-sided device, a circumstance that subjects settings on A and B to systematic error. It can, however, be made a two-sided symmetrical device by substituting for the one-sided knife-edge a simple vertical wire. One can see around both sides of a fine wire, and thus tell when it is exactly centered.

There is good reason to expect this form of testing to give more accurate results than Foucault's test. In the latter test the knife-edge is moved *along*

---

[2] The caustic test described above is neither new nor original, though the writer worked it out independently by comparing Everest's material in ATMA with the paper referred to in the next paragraph. Subsequently a paper by M. G. Yvon in *Revue D'Optique 4*, page 8 and following, has been found in which this quantitative form of caustic test is described, and which has proved invaluable.

the optical axis to locate by trial and error the point where two out-of-focus cones of light (Figure 2, Figure 3 No. 6) cross over each other at an angle of about 5° or less. Accuracy depends upon the correctness of this rather uncertain setting. In practice, in the caustic test the fine wire is displaced along the optical axis merely to locate it *near enough* to a line joining the centers of curvature A and B, Figure 2, so that a transverse or cross-the-axis motion will cut the wire almost at right angles *across* the two cones of light where they are in sharpest focus. Centering a fine wire on a sharply focused image of a narrow slit can be done very precisely. Figure 3 shows that in this rather extreme case "near enough" means at least 1/10 inch, the distance between No. 9 and No. 10 which are almost equally in sharp focus. For paraboloids the easiest way to take care of this matter is to calculate the theoretical value Y, set the wire at exactly this distance from the center of curvature of the central zone and measure x. As figuring progresses, the centers of curvature draw nearer and nearer the test wire, and if perchance a perfect mirror is produced, the last test will be run with the wire exactly at the center of curvature.

In summary, testing is done with a fine wire, near or at the true center of curvature. The wire is displaced a calculated distance Y from the center of curvature of the central zone, so that the critical measurement is that of the distance x between the two sharp images of the slit; this distance can be measured very precisely.

Benefits result as follows:

(1) The accuracy of measurement can be increased as much as five to ten times.

(2) Only one hole in the mask is observed at a time, the wire being set so that the light from that hole is a minimum; and this kind of observation is much easier than matching two widely separated areas.

(3) Or, alternatively, two other observing methods entirely eliminate the observation of shadows on the mirror, with an increase in precision.

(4) Considerably wider holes can be cut in the mask.

Such a promising array of advantages makes a tryout of the test seem almost imperative.

In the following sections a step by step procedure will be given, followed by an example. Then a simple but suitable test rig will be described. If at first these instructions look formidable, it is because they are given in detail to help the uninitiated to get started. The actual steps involved are italicized and are seen to be concise. In fact, steps 1 through 3 and the calculation in 9a are done once for all at the beginning of testing. With this simplification and with increasing familiarity by use, the whole test can be run and the results analyzed in less time than it takes to study through this material. The tolerances specified hold the error in the final results to 1/100 wavelength or less for each measurement in question. Essentially this makes the accuracy of the test depend largely on the accuracy with which the distance x is measured, which can be adjusted to changing needs without starting from scratch again.

NOTE: FROM THIS POINT ON, THE SLIT WILL BE FIXED, WITH ONLY THE TEST WIRE BEING MOVED.

Procedure

1. *Measure the radius of curvature R of the central zone* of the mirror with an error less than ½ inch for an $f/8$ mirror, less than ⅛ inch for an $f/5$.

2. *Cut a mask* out of thin cardboard. The holes may have a diameter as large as $r/100$ inches if the mirror surface is smooth. The distance r from the optical axis to the center of each hole must be known within .05 inch for an $f/8$ mirror, within .02 inch for an $f/5$. There should be an odd number of holes so that one exposes the central zone. If the holes are carefully laid out with a compass and the cutting is neatly done, the value of r for each hole is known. If narrow zones are present, the holes will have to be smaller so that they will show up in the test results.

3. *Calculate the theoretical value Y* for each pair of holes corresponding to a mirror zone. $Y = 3r^2/R$. Note that this is just three times the displacement in Foucault's test.

4. *Line up the test rig* so that the fine wire stays on the optical axis as it is moved away from the mirror.

5. *Set the wire at the center of curvature of the central zone* and read the scale. While watching only the central hole in the mask set the test wire so that as it cuts across the optical axis the shadow moves neither to the right nor to the left—the zone darkens evenly, exactly as in Foucault's test. (For a better procedure see the section on Accuracy.)

6. *Move the wire away from the mirror a distance y*, along the axis, as calculated for the first zone to be tested. y must be correct within 1.5/1000 inch for an $f/5$ mirror, within 2/1000 for an $f/8$. (The slit remains fixed.)

7. *Measure the distance x.* Set the wire so that the light from one hole of the zone is a minimum and read the scale; move the wire until the light from the other hole is a minimum and read the scale. The difference in readings is x. To get a sharp minimum, the illuminated slit should be narrow and the wire about the same size as the sharp image of the slit. After a little experience more accurate results will be obtained by use of the alternate setting technics described in the section on Accuracy. x must be measured to within .0002 inch.

8. *Repeat steps 6 and 7 for each zone in turn.*

9. *Interpret the results.* This may be done in at least three ways.

9a. Compare the measured values x with the theoretical values X for the corresponding zones given by $4r^3/R^2$. If the measured value x is larger than the calculated value X for a given zone, that zone is undercorrected, and vice versa.

9b. Best of all, the actual shape of the mirror surface can be easily calculated. This is done by calculating the amount and sign, + or −, of the deviation from correct for each zone and adding them algebraically. Thus: deviation of a zone $= K\ (X - x)$ where $K =$ width of hole in mask$/4R$. K is a constant having the same value for all zones. Since a mirror is figured by leaving the edge alone and wearing away the central zones we will consider the deviation to be zero at the edge. Then at the inner edge of each zone the deviation of the mirror surface from a perfect parabola will be the algebraic sum of all errors from the mirror's edge up to that point.

9c. Since most workers are used to thinking of mirror correction in terms of the longitudinal displacement of the knife-edge in Foucault's test, it may be more convenient at first to put the results of the caustic test in the same form. This can be done by finding an equation which will transform an error in the measured value x for a given zone into an equivalent error in the longitudinal displacement of a knife-edge along the axis in Foucault's test. Without showing the derivation, this can simply be stated as knife-edge error $= R/2r$

TABLE 1 *

zone	radius r	Y	calculated X	measured x	error $e = (X - x)$	adjusted error $e = e - cr$	deviation of zone h	deviation of mirror from true parab. sum of h's
0	0	0	0	0	0	0	0	0
1	1.1	.030	.0004	.0004	.0000	−.0002	−.0000004	−.0000001
2	2.2	.120	.0029	.0021	+.0008	+.0005	+.0000011	+.0000003
3	3.3	.270	.0098	.0082	+.0016	+.0011	+.0000025	−.0000008
4	4.4	.480	.0232	.0224	+.0008	+.0001	+.0000003	−.0000033
5	5.5	.750	.0455	.0463	−.0008	−.0016	−.0000036	−.0000036
edge								.0000000

* All dimensions in inches.

$(X - x)$, where the measured values x are taken from step 7 above, and the theoretical values X are given by the equation in step 9a. Thus if x is measured to be too large, the equivalent longitudinal displacement would be less than r^2/R and the zone is undercorrected.

An example will serve to tie all these directions together. Take a 12-inch diameter $f/5$ mirror and run through our procedure.

1. Make $R = 121$ inches, measured to the nearest ⅛ inch.

2. Maximum diameter of holes in the mask $R/100 = 121/100 = 1.2$ inch (approximately).

A mask is laid out with centers 1.1 inch apart, giving 11 holes. The holes are cut out a little smaller than this to separate adjacent holes a little, or two masks are made, as suggested. Record values of r in column 2, Table 1.

3. For the first zone $Y = 3r^2/R = 3\ (1.1)^2/121 = .030$ inch. Since 3/121 appears in each calculation of Y, it will save time to divide out at the start. Thus, for zone 2, $Y = .0248(2.2)^2 = .120$, and so on. Record the values of Y in column 3.

4. Line up the test rig.

5. Set the wire at the center of curvature of the central zone.

6. To measure the first zone, move the wire along the axis a distance $Y = .030$ inch from its position found in step 5 (move away from the mirror).

7. Measure x several times and record the average in column 5.

8. Repeat steps 6 and 7 for each zone.

9. Calculate the theoretical value of X for each zone, putting them in column 4. For zone 1, $X = 4(1.1)^3/121^2 = .0004$ inch. In calculating X the factor $4/121^2$ appears each time; divide it out to save time and mistakes. For zone 2, $X = .00027(2.2)^2 = .0029$ inch.

INTERPRETATION

A detailed analysis of our example is given under 9a and 9b for illustrative purposes. A short cut for routine testing is given at the end of 9b which will decrease the numerical labor involved.

9a. *The mirror is figured until the measured values x in column 5 match the corresponding theoretical values X in column 4 within the desired tolerance.* As a rule of thumb for any mirror tested with a mask having holes about $R/100$ inch in diameter the error $(X - x)$ for each zone (recorded in column 6) can be about 400 times the allowed error per zone of the mirror surface. For example; If the mirror's surface must be tested to the nearest ½ millionth of an inch for each zone, then the allowable error is $(X - x) = 400/2\ (.000001) = .0002$ inch. For this tolerance, values in column 5 may differ from those in column 4 by as much as ⅕ of 1/1000 inch. This would be a very tight tolerance if it were not possible to do some juggling of figures. (Skip the next paragraph if the alternative procedure was followed in Step 5.)

The values of X in column 4 were calculated for a certain radius of curvature R for the center zone. In practice R will not be exactly the actual or true value for the mirror under test, and if it were the wire probably would not be set at exactly this distance from the mirror under Step 5. Furthermore, some other paraboloid having a slightly different radius of curvature might fit the mirror better. Perhaps the most instructive method of adjustment is to plot a graph of the errors $(X - x)$ as in Figure 4-*a*. The horizontal zero error line corresponds to a paraboloid whose radius of curvature R was used in calculating Y and X. When R is changed to a different value this zero error line rotates about the point $r = 0$ as an axis. A clear plastic straightedge is very convenient for drawing in a new line such that the average error is zero; that is, using the new line as a reference the errors are made as small as possible. This line is shown dashed in the figure. Those who prefer numbers will note that this method of adjustment corresponds to subtracting (r multiplied by a constant) from each error, the constant being .00015 in this example. In practice the constant must be found by trial and error, so the graph is simpler. The adjusted errors are recorded in column 7.

9b. It is possible to plan the strategy for the next spell of figuring by a study of the adjusted errors in column 7, just as has been done all along with knife-edge settings in Foucault's test. Strategy is much simplified, however, by a knowledge of the actual shape of the mirror surface in relation to the desired paraboloid. Deviation of zone = $K \times$ adjusted error. K = width of holes/$4R$ = 1.1/4 (121) = .0023. Since an important point of interpretation is involved, several sample calculations will be given.

Sample Calculations

Deviation of zone 5 = .0023 (−.0016) = −.0000036 inch. Assuming the desired parabola and the actual surface to be coincident at the very edge of the mirror this means that at the inner edge of zone 5 the mirror surface is 3.6

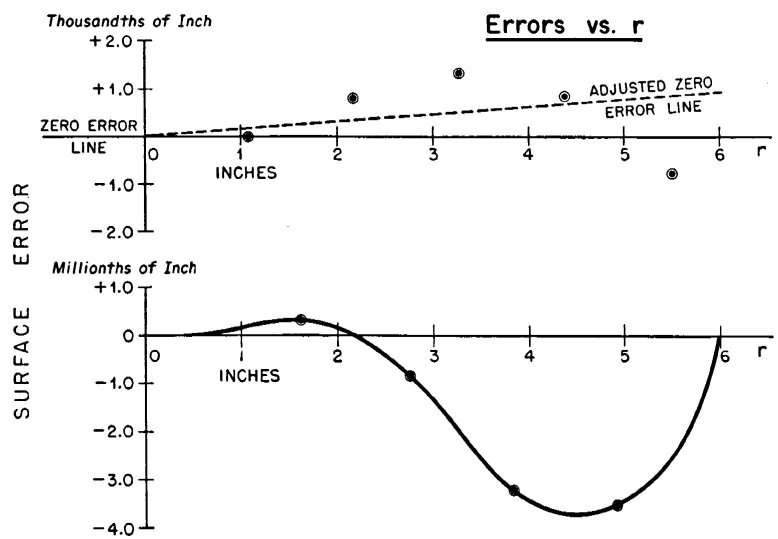


Figure 4, *a* and *b*

millionths of an inch too low (low because of the minus sign). This value is recorded in both columns 8 and 9.

Deviation of zone 4 = .0023 (+.00014) = +.0000003. Record in column 8. This deviation, added to that already existing where zone 4 joins zone 5, makes the surface 3.3 millionths of an inch too low at the inner edge of zone 5. Record −.0000033 in column 9. Similarly adding the deviation of zone 3 leaves the mirror .8 millionths of an inch too low at the inner edge of this zone.

To summarize, values in column 8 are K times those in column 7; column 9 is obtained by writing 0 for the edge of the mirror and summing up algebraically the values in column 8. Column 9 is plotted in Figure 4-*b*, showing the distance of the actual surface above (plus sign) or below (minus sign) the

paraboloid chosen when column 7 was worked out, which is represented by the dashed line.

From Figure 4-*b*, it is evident that the adjusted zero reference line of Figure 4-*a* was not drawn in a manner calculated to make the next stage of figuring easier, even though it looked like the thing to do under step 9a of the procedure. It would be much better to adjust so that the error for zone 5 is reduced to zero by drawing the dashed line sloping downward through the outermost point in Figure 4-*a*; in Figure 4-*b*, this would result in the actual surface following the paraboloid over zone 5 and then rising steeply to a central bulge about 11 millionths of an inch high. Thus we see that rotating the dashed line of Figure 4-*a* about the point $r = 0$ corresponds to rotating the curve of Figure 4-*b*, about the point $r = 6$. A little time spent in juggling these two curves will give an insight into the problem and will emphasize the value of drawing the curve of shape.

Having gone through the whole process in great detail, as one might do it during final stages of parabolization, a short cut is in order for the early stages when superior accuracy is not needed. The numbers in the first four columns of Table 1 will not change during the parabolization process unless R changes by a significant amount—they need not be recalculated for each test. Values of x can be measured with a gradually tightening tolerance, starting at .0005 inch. The errors $(X - x)$ are found and recorded, without attempting an adjustment for the time being. With sufficient accuracy K = .002. Thus the approximate deviation h of a zone (in millionths of an inch) is simply twice the error of the zone (in thousandths of an inch). The surface is given by summing the deviations algebraically. After a look at the plot of this surface, a try at adjustment can be made and new deviation calculated from the adjusted errors as in Table 1.

The whole analysis—the table work—can be completed in five to ten minutes. It goes without saying that care must be exercised in keeping plus and minus signs where they belong. Further, there is no need to carry along useless decimal places; record X, x, and the errors to the nearest .0001 inch and deviations and surface to 0.1 millionth of an inch. It will be noted that even in the detailed analysis two significant figures sufficed to give the required accuracy in practically every equation.

9c. Although the writer feels strongly that the method outlined above is by far the best, some may wish to throw the results of the caustic test over into the more familiar longitudinal displacements-along-the-axis of the Foucault test. For zone 5, taking $(X - x)$ from column 6,

$$\text{knife-edge error} = \frac{R}{2r}(X - x) = \frac{121}{2(5.5)}(-.0008) = -.0088$$

The calculated displacement of the knife-edge for Foucault's test would be one third the value given in column 3, or .250 inch. Thus the equivalent Foucault test reading for this zone would be .2500 −.0088 = .241 inch. This calculation enables us to make at least a rough comparison between the caustic and the

Foucault test. The difference between measured and calculated displacements is about at the limit to which most workers can make knife-edge settings, and that only with mask holes much narrower than 1.1 inch. From column 6 the deviation of this zone is 1.8 millionths of an inch, about four times the easily-obtained limiting accuracy of the caustic test using the test dingbat now to be described.

Test Rigs
(one of which is also suitable for the Foucault test)

Three methods of caustic testing have been described. The first, being used for studying surface smoothness, involves no measurements and so requires no elaborate test equipment beyond that which the worker already possesses. The second (Yvon) method is a quantitative version of the first method and requires a simple but carefully made test rig. The third test method developed by Gaviola and Platzeck requires an accurate measuring device. In this section several forms of test rig will be described that can be made with a minimum of tools and yet will perform with the required accuracy. At the beginning it is emphasized that the examples described are offered to illustrate certain design principles rather than to be copied slavishly. The individual worker is then left to his own ingenuity as has been the tradition in telescope making.

Test Rig for Second Method: Except for small mirrors of long focal length the old trick of pushing sidewise on the test bench will not work in the caustic test. In the worked out example the distance x between the two centers of curvature for zone 5 was nearly .05 inch. Hence some means of moving the knife-edge perpendicular to the optical axis must be provided. A device similar to that shown in ATMA page 19, Figure 18, would be satisfactory if the transverse motion were provided. This may be provided by a lengthwise arm on top of the k-e block, pivoted at the end farthest from the eye and carrying a knife-edge at the end nearest the eye, with a machine screw working against a spring to supply the cross motion at the side. The cleat on the lower piece serves to keep the block sliding parallel to the optical axis and the screw adjustment makes easy the examination of the first and last areas to darken. An accurately made Barr scale may serve to measure displacement along the axis, or a steel rule (such as a Brown and Sharpe or a Lufkin) reading to .01 inch may be fastened to the slide and an index provided for reading. With the help of a magnifying glass settings may be read to about .002 inch. Another simple arrangement involves fastening a thin sheet of brass to the lower board and making a short scratch mark along the straightedge with a needle for each knife-edge setting. The needle can be stuck into a stick for a handle; a few trials will show how to make the scratch mark so that no variation is introduced into the readings by the way the needle is held. A steel rule graduated to .01 inch used with a magnifier can be used to estimate the distances between marks to the nearest .002 inch.

There may reasonably be some question whether a test rig can be home-made without special machinery capable of measuring to the tolerances indicated in our example. The answer is affirmative in the same sense that it is possible to make a mirror to a tolerance of ¼ wavelength without special equipment. In both cases it is a matter of intelligent application of proper procedure, considerable work, and of pride over a job well done.

Test Rig for Third Method: As outlined in the section on test procedure, a short piece of wire about .005 inch in diameter (B & S gage 30 to 40) must be held parallel to the slit while moving along the optical axis a distance y and moving perpendicular to the axis a distance x. Imagine the test wire to be held at first by hand on the optical axis near the center of curvature of the central zone and parallel to the slit. It can be moved to any other position by some combination of these three motions: (1) along the axis, (2) perpendicular to the axis, left or right, (3) perpendicular to the axis, up or down. Furthermore, the wire can be made no longer parallel to the slit by some combination of three rotations, one rotation about each of the above-mentioned three mutually perpendicular directions as axes. *Thus the wire is said to have six degrees of freedom.* The plan is to add four *constraints* to the wire in the form of a test rig so that it can move only in two directions—along the axis and perpendicular to the axis left or right. The wire will then have only two degrees of freedom. If any motion other than the two desired be attempted by the wire, some *restoring force* equal to the disturbing force must be brought to bear to inhibit such undesired motion. These principles go by the name of "kinematic" or "geometrical" design, which is well known among instrument makers.

A few pictures will be worth reams of words in explaining the application of kinematic design. In Figure 5 note the four steel balls, each seated in a

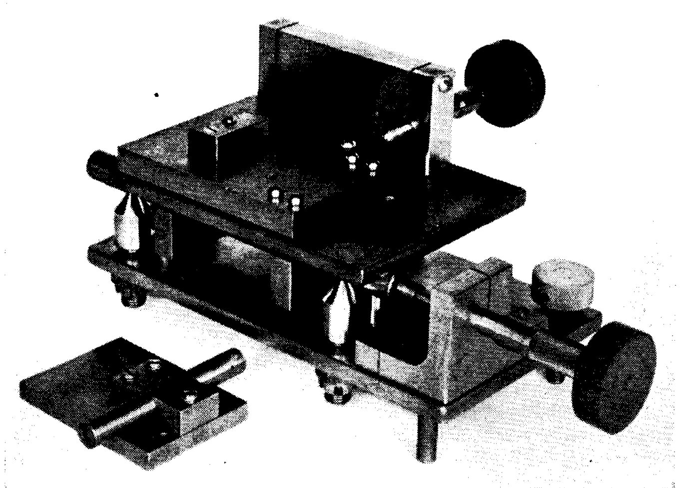


Figure 5

hole in the base plate and a fifth ball by itself in a hole in the block. The slide has been temporarily removed and inverted to show construction details. In use it is replaced so that the group of four balls form a guide on which the rod can slide, and the fifth ball supports the farther side of the plate. This slide is thus supported, that is, it is constrained, by five points of support. There is only one manner in which it can slide (the balls do not roll) while maintaining contact with all five balls—that is, along the length of the rod. Gravity holds it in contact with the balls and acts as a restoring force if the rod tries to ride up out of contact with any of them. The working principles

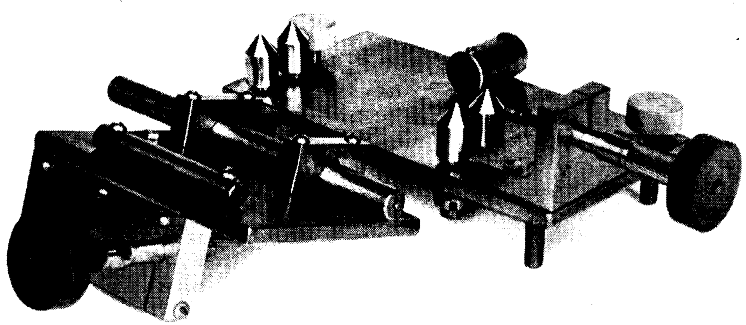


FIGURE 6

are then: (1) use of supports that are points, or at least very small in area, so that the point of support is definitely located; (2) 6 minus the number of support points equals the number of degrees of freedom remaining, provided that no useless or "redundant" points are used; (3) gravity (or sometimes a spring) is used as a restoring force.

The part of the plate sliding on the fifth ball has been ground flat, an operation calling for a special machine. Figure 7 shows how a piece of commercial flat-ground stock can be bolted on to accomplish the same purpose.

The slide just described is mounted on top of another slide with their directions of travel at right angles so that the test wire will have the desired two degrees of freedom. The slide underneath in Figure 5 was built on the same design principles carried out in a different manner, as shown in Figure 6. There the rod slides on four cones turned in a lathe. The cones could as well be filed and polished with fine emery cloth, or, simpler still, a V notch can be cut in each of two blocks with the inside of the V rounded somewhat so that point contact is made with the rod. Together the two slides make a rugged instrument whose main disadvantage is a rather large amount of friction on the lower slide.

Figure 7 shows how sliding friction can be replaced by rolling friction. Shown also is the piece of flat-ground stock on which the fifth ball rolls.

The top slide of Figure 8 shows still another arrangement that has, however, proved rather unsatisfactory because of its small size and weight—the restoring force is too small. Three rods are clamped in position side by side. Two of these support the micrometer head and form a way in which slide two balls which are fastened to the under side of the slide. A fifth point of

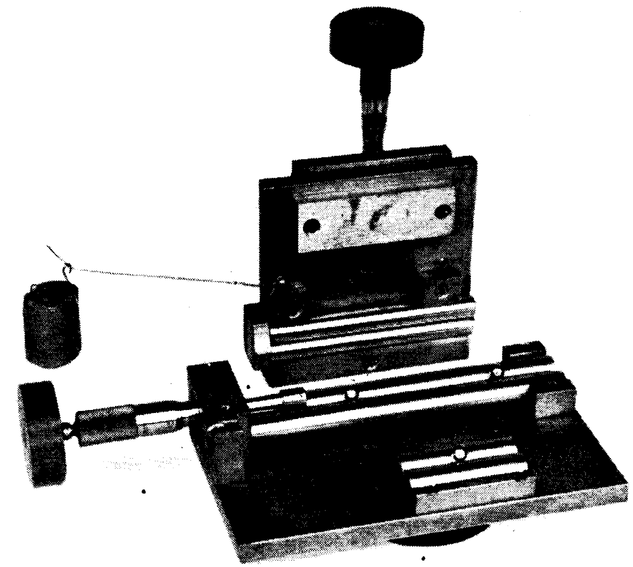


FIGURE 7

support is provided by the third rod and a small rod mounted at right angles to it on the underside of the slide. In principle this might be called an upside down version of Figures 5 and 6.

Some means of pushing the slides and measuring the distance moved must be provided. A screw pushing each slide gives delicate control. For all purposes except the most exact testing, the distance y along the optical axis can be measured by mounting a steel rule graduated to .01 inch on the slide, with a fine index mark attached to some fixed part of the instrument. A magnifying glass will help in estimating fractions of divisions. Another trick is to scribe a special scale on sheet brass, using the micrometer screw next discussed, with marks at the calculated values of Y from the first mark. For all-around convenience and accuracy a micrometer screw is better, and for measuring x it is a necessity. Such a micrometer screw is commercially available in the form of a micrometer caliper which sells for about $8.00 and is accurate to a fraction of .0001 inch. For those already in possession of such a caliper the slide described can with a little ingenuity be arranged so that they can be pushed by the spindle (unthreaded end of the screw); the distance the slide is pushed can be read off to the nearest .001 inch and estimated to the nearest .0001. A neater arrangement for those not already outfitted uses the so-called micrometer head (Figure 7) which is built just like a micrometer caliper except that the horseshoe shaped frame is absent. Where the frame usually joins

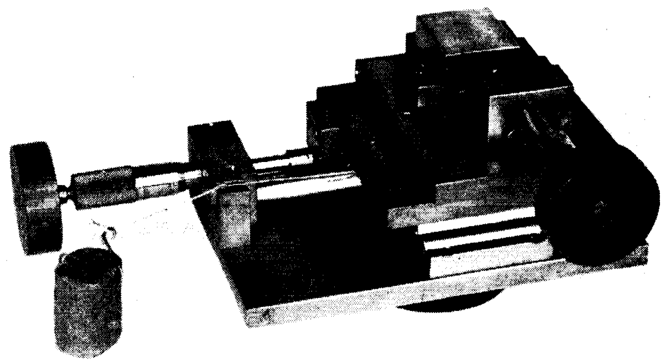


FIGURE 8

the nub of a micrometer caliper the micrometer head has a cylindrical shank that can be clamped in a ⅜-inch hole. The writer has purchased two for about $8.00 each. Cheaper still is a model having a screw ½-inch long which is enough for measuring x.

In the first two slides discussed, the micrometer head is clamped in a hole in line with the rod it pushes; a disadvantage shows up in trying to line up the rod and screw. If they are not in line the slide does not move the distance indicated by the micrometer division; this is a systematic error. Figure 8 shows how to take care of the objection automatically. A U-shaped piece of metal is cut out too small and carefully filed on its inner sides until it just slips over the two rods and holds them in place without shake or binding. Similarly the inner side of the bottom of the inverted U is filed very carefully so that the micrometer head, which lies in the groove formed by the two rods, is just clamped in place when the screws are tightened down. This trick again illustrates the idea of *designing errors out* of the system, rather than depending too much on super-accurate workmanship.

Also shown in Figure 8 is a weight attached to the slide by means of a heavy thread running over a small pulley. This serves to keep the rod tight against the end of the micrometer spindle, thus minimizing *backlash*. Actually it is not the best practice to allow the flat end of the spindle to push against the rod since it might not be cut off exactly square and it may not be exactly flat, introducing a small error in the readings which repeats with each full turn of the screw—*a periodic error*. This is of importance only in measuring x and then perhaps only for the finest measurements. In Figure 8 a short sleeve can be seen on the end of the spindle. It was made from a piece of rod by drilling a hole in it to make a tight sliding fit over the end of the spindle; a steel ball of the same diameter is then pushed in the end. Thus contact between spindle and the rod it pushes is limited to a point. A similar device (Starret) can be purchased with the micrometer head.

The following are a few practical points concerning use. The writer works right-handed; others may prefer to put the x micrometer on the left side. In any case, if a micrometer head is used to measure y, it will almost have to be on the side toward the mirror to be out of the way of one's nose when the eye is brought close to the test wire. Considerable thought should be given to the arrangement of parts for convenience in use, and in relation to one's facial protuberances, for one prerequisite for accurate measurements of any kind is a reasonably comfortable position for the observer. On the other hand the test wire should be as close as possible to a line drawn through the length of each micrometer screw for the sake of accuracy. Under usual basement humidity conditions the breath will condense on the metal. It is therefore best to make all the flat plates of brass, which is also much easier to work than steel. Coat all steel parts including the micrometer with a thin film of vaseline.

The rods used are drill rod, which is very straight and accurately round in sizes over ½ inch. It is probably best selected for straightness and freedom from nicks, and it can be obtained from machine shop or machinery supply houses. Handle it carefully while cutting, to avoid marring it. The steel balls were two bits a dozen at a hardware store. Brown and Sharpe, Providence, R. I., and L. S. Starret, Athol, Mass., are among the reliable makers of steel scales, micrometer calipers, micrometer heads, flat ground stock and other small tools. Purchases can be made through machinery supply houses or directly. Investigate discounts, given by some, by others not. Both companies named put out small tools catalogs which are more interesting than a mail order catalog to the tool-minded and a source of helpful ideas.

The writer has the following equipment, listed only as suggestions since similar equipment by other makers or the same maker are equally useful.

Six-inch steel scale calibrated in 1/16, 1/32, 1/64, 1/100 inches.
L. S. Starret No. 607 No. 7 graduation.

Micrometer head, one-inch thread, with vernier reading to .0001 inch.
Brown and Sharpe No. 295 RS.

Micrometer head, one-inch thread, without vernier, estimate to .0001 inch.
Lufkin.

Brown and Sharpe has a micrometer head with ½-inch thread, No. 290 which is $1.00 less than the one-inch thread model. Some may wish to purchase a regular micrometer caliper and modify the slide for use with it, in order to have a regular shop tool; No. 8 and No. 11 are typical among a wide choice. Another suggestion is to use a micrometer depth gage. The long rod running through the screw could be clamped so it can rotate but not move longitudinally. Then, as the screw is turned, the base will travel like a slide if prevented from rotating by letting it slide along a rod placed parallel to the screw on one side.

Tools used include hacksaw, file, several small drills, hand drill (or drill press if available), hammer, center punch, 6–32 tap and holder. The tap and holder can be dispensed with if the work is bolted together with screws and nuts. Those having more tools than these can perhaps do a fancier job, those with less may get around on ingenuity or ability to borrow. It is emphasized again that careful workmanship plus attention to design features will produce a good job, more than fancy tools used without imagination.

Perhaps some new justification might be needed for attempting the test rig described. Besides its use for caustic testing it is also useful for Foucault testing if a razor blade is mounted near the test wire. It can also be used for shadow analysis testing as described by Gaviola in ATMA and for the Zernike test, also in ATMA [printings prior to 1944, June.—*Ed.*]. If two slides are made somewhat larger than required for testing purposes alone and a low power microscope with cross-hairs is set up over it, the worker will have a combination toolmakers microscope, star plate coordinate measurer, spectrum plate comparator, measuring microscope; or the microscope might be mounted on a slide to make a traversing microscope. The eyepiece for a microscope can be borrowed from a telescope, the objective of the microscope can be made, bought second hand, improvised from available or surplus lenses or purchased at a modest price from Wm. Gaertner Scientific Corp., 1201 Wrightwood Ave., Chicago, Ill. A Hastings triplet will serve quite well as an objective, especially if stopped down. The micrometer heads can be removed from the dingbat and used in a spherometer or perhaps in a double star micrometer such as described in ATMA. In fact they can be used anywhere an accurate screw is called for.

Only a few possibilities have been discussed above. Much help will be gained by studying the section on kinematic or geometrical design in such books as

"Fundamentals of Optical Engineering," Jacobs, McGraw-Hill Book Co., New York, 1943, pp. 286–295.

"Procedures in Experimental Physics," Strong, Prentice-Hall, Inc., New York, 1943, pp. 585–590.

"Kinematical Design of Couplings in Instrument Mechanisms," Pollard.

"Design and Use of Instruments and Accurate Mechanisms," Whitehead.

"Optical Measuring Instruments," Martin.

"Dictionary of Applied Physics," Glazebrook, National Bibliophile Service, Gloucester, Mass.

The first two are especially good and at the same time concise. Strong's book has thought-provoking diagrams. The others are more detailed and show

diagrams and photographs of helpful examples. Also included are discussions on error of such devices as we have described, how measured and corrected. To the latter subject we now turn for a short discussion. While the Pollard and the Whitehead books are out of print they may be consulted in some libraries.

Accuracy

After making the test rig, most makers will have to lift themselves by their own bootstraps in checking and perhaps improving its accuracy. This obviously is not impossible for it merely puts one in the same position as the originator of such devices. Several of the books listed above discuss at length the procedures involved. The author had the good fortune to have access to a Gaertner toolmakers microscope; the lower slide of Figure 8 (which is used to measure x) checked correct to within ±.00005 inch over a distance of ¾ inch and the upper slide within ±.0001 inch. The upper slide of Figure 5 checked as well against one of Rowland's ruling engine screws. These tolerances give an idea of the accuracy of the commercial micrometer heads used and of results obtainable by kinematic design.

The drill rod should be reasonably straight. A length of it can be placed in two V notches and rotated to detect any wobble. It should not be bent when clamped in place on the slides; hence the short hold-down blocks. If the assembly has been done properly, the test wire will remain parallel to the slit during its displacement along the optical axis.

While it is likely that the test rig is good enough as it is, it is fun to check up on it. Those having faith in their own handiwork may skip this paragraph. There will be no doubt about the micrometer, but the slides may not move the distance indicated by the screw. Either systematic or periodic error may be present. Systematic errors are most likely to arise from the screw and the rods not being parallel and can be checked for by measuring a known distance. For example, the width of some object about ½ to ¾ inch wide, having sharp edges, can be measured with a micrometer caliper and the measurement checked by placing the object on the test dingbat and measuring it with the help of an improvised microscope. Gaertner makes a glass scale especially for this purpose, a luxury if one has the price. Periodic error can be checked for by making two fine scratches about 1/10 inch apart at the edge of a slide and arranging a movable index mark. With the help of a magnifier, set the scratch mark opposite the index, read the micrometer, set the second scratch mark opposite the index and read the micrometer again. With a little practice the settings can be accurately made. Now move the index over about .005 inch and repeat; this makes the readings fall at a different place on the micrometer scale. Repeat until the readings have traveled around the scale several times. Now the distance measured is always the same; the measurements would be expected to differ somewhat, due to errors in setting against the index mark, but the error should not repeat with each complete turn of the screw. A repeating error is a periodic error. If present, the trouble may be in the coupling between the end of the screw and the slide it pushes.

Some idea of whether the test results are up to the standard of accuracy desired can be obtained from the measured values of x. For a given zone make 3 sets of 5 measurements of x, taking the average of each set. All the readings in a set will differ from their average and the size of this difference has significance. It was shown under step 9*a* in the example, how to find the allowed error in measuring x for a given error on the mirror. As a rough rule of thumb, half the readings in a set of 5 should differ from their average by no more than this allowable error in x. If the three averages are compared with the average of all 15 readings, the differences will be much smaller; the size of the differences will give some indication of the ultimate accuracy of the test in the individual worker's hands. From this another rule of thumb can be derived. During rough figuring take the average of two readings per zone, the second serving as a check against gross error. As more accuracy is required, increase the number of readings per set on each zone up to 5, beyond which there is little advantage. For the final test, use the average of 3 sets of 5 readings each. Of course no amount of averaging will remove systematic error, which we have tried to design out of the test.

Accuracy can be increased by changing the manner in which the test wire is judged to be centered in the reflected cone of light. A method already mentioned is to set the wire so that the light from a given hole in the work is a minimum. A slit whose width is adjustable is a help in easily getting the maximum sensitivity, but several different wire sizes can be tried with a fixed slit. A movement of a few ten thousandths of an inch of the wire should make a noticeable change in brightness of the hole. Two other methods entirely eliminate shadows on the mirror from consideration, a very considerable help when wide holes are used on short focus mirrors. Testing is done on the images of the slit.

Method 1. A positive eyepiece of about ½ to 1 inch focal length is mounted on the slide that measures x so that the test wire is in sharp focus. The test wire then serves as a cross-hair to be centered as precisely as possible on the sharply focused images of the slit at A and at B, Figure 2.

Method 2. This is a little more complicated at first, but becomes very precise with practice. The eyepiece is fixed about 6 inches back from the test wire so that the two beams of light from a and b, Figure 2, are out of focus. Then, paying attention to only one of these two blobs of light, set the test wire so that the diffraction fringes observed are symmetrical. What happens is that as the test wire is centered in the beam at its focus it does not simply block off the light with a clean shadow but, rather, diffraction fringes are set up on either side in the shadow. If the wire is precisely centered, the pattern of fringes will be the same on both sides of the shadow of the wire; a slight error in centering shows up as a noticeable lack of symmetry in the pattern. Better than many words is to try it, moving the wire very slowly across the beam of light a number of times. Again the relative size of slit and wire is of importance in producing good fringes.

A trick that will eliminate much of the adjusting called for under step 9*a* is this. Instead of starting the test as described in step 5, by setting the wire at the center of curvature of the central zone, set it so that the measured value of x for the edge zone is as close as possible to the theoretical value X, a cut and try method. Move the test wire toward the mirror a distance equal to the value of Y for the edge zone and proceed with step 6. This assures that the error $(X - x)$ for the edge zone will be small, and the setting easier to judge accurately.

If a mirror is to be tested with a mask, the error allowed for each zone must be less than the desired ⅛ wavelength tolerance usually allowed for the surface as a whole. In addition, some allowance must be made for possible errors on the Newtonian flat or the secondary mirror in the completed telescope. As a rule of thumb, if a mirror is tested in N zones, the allowed error per zone is wavelength/$11\sqrt{N}$ if errors are accidental and is wavelength/$11N$ if systematic error is present. Since wide zones are allowable in the caustic test, probably most amateur mirrors can be tested with not more than 9 zones, making the allowed errors per zone wavelength/33 and wavelength/100 respectively. The advantage of minimizing systematic error is obvious. If wavelength/40 per zone be adopted as a fair goal (about ½ millionth of an inch), and the holes are $R/100$ inches wide, then, from step 9*a*, x must be measured to within .0002 inch, which is easily within the tolerance of the equipment described. With care, the error can be cut in half.

In the section on Procedure, a set of approximate tolerances was given on the allowable error in measuring the quantities involved. For the most precise results, more accurate tolerances can be derived by calculus or by simply varying the size of each term in equations for X and Y by small amounts. In either case results close to the following should be obtained: (all quantities in inches)

1. $d_{max} = 5.5\left(\frac{\Delta h}{r}\right)^{\frac{1}{3}} R$ inch

This is the diameter of a spherical zone element whose center of curvature is at the average center of curvature of the actual zonal element under test—the separation of the two surfaces being Δh around the rim of the element.

2. $\Delta x = \frac{2R}{d}\Delta h$ inch

3. $\Delta R = 16m^3\Delta x \qquad \left(m = \frac{\text{focal length}}{\text{mirror diameter}}\right)$

4. $\Delta r = 16m^2\Delta x$

5. $\Delta y = 4m\Delta x$

As a check on what limit can be reasonably reached, it is suggested that the rig be first used to make the best possible sphere, for in this case the errors can be seen with great sensitivity and compared with the test results, right down to the point where the caustic test measurements no longer show up the errors.

Non-paraboloidal Surfaces

The only change required to test other surfaces than the paraboloid is to calculate the proper values of Y and the corresponding values of X. The width of the mask holes may have to be decreased for more strongly aspherical surfaces.

For example, consider the sphere. It has only one center of curvature; for all zones $Y = 0$ and $X = 0$. Therefore the test wire is set at the desired radius of curvature R from the mirror and the values of x measured, all of which will be zero if the mirror is perfect. Caution: In this case some of the cross-over points will probably fall in front of the test wire as was the case for the paraboloid, but some may fall behind it, in which case a minus sign should be placed before the equation for the deviation of a zone in step 9*b*.

For any other curve, whose equation is known, the values of Y and X can be calculated by means of the formulas for the center of curvature given in calculus books. There is an out for those not familiar with calculus, and for those cases where an equation is not known or is too complicated to use if known. In many such cases, for example the Wright telescope in ATMA, the theoretical knife-edge displacements along the axis have been given. The caustic test data can then be handled in a manner similar to that described under 9*c* under the procedure. Since the theoretical values of Y are not known in such a case, the test wire cannot be preset. The trick is to find the center of curvature of the center zone, record the test wire position, and then hunt for the center of curvature of each zone to be measured—*i.e.,* the position of the test wire when the shadow in one of the holes exposing a given zone moves neither to right nor left as the wire cuts across the beam, but rather darkens evenly. The difference in these two positions is recorded as y, and x is measured at this value of y. The equivalent longitudinal displacement of the knife-edge in Foucault's test would then be given by knife-edge displacement $= y - R/2r$ x inch.

The writer was interested to learn that a part of the testing of the 200-inch telescope was carried out by a photographic version of the caustic test. A set of photographs, each like No. 9, Figure 3, was made, one at the center of curvature of each of 13 zones, and the distance x was measured directly from the plates. Some idea of the size of the mirror is given by the largest value of y which was 21.4 inches and of x which was 2.04 inches, approximately. Some workers may wish to try this method on short focus mirrors in place of one of the micrometer heads.

Attention is called to the ingenious test devised by E. Gaviola for testing Cassagrainian secondaries, described in the *Journal of the Optical Society of America,* Volume 29, pages 480–483, November 1939 (the issue that also contains the Platzeck and Gaviola article, as pages 484–500, cited earlier in this chapter) which can be run by the caustic method. A cheap lens is used to

supply a converging beam of light on the convex mirror, the errors of this lens canceling out in the result.

The author has found the caustic test of immense value and hopes it will prove helpful to many others. He wishes to acknowledge the considerable help of John Strong in the project described, as well as the use of the facilities of this laboratory, both of which were freely extended.

—*Applied Physics Laboratory*
The Johns Hopkins University
Silver Spring, Maryland

[Editor's Note: Reproduced here by permission directly from the dusty files of *Popular Astronomy,* 1902 August–September, are four compacted fragments from the classic article by the late Professor F. L. O. Wadsworth, en-

F. L. O. Wadsworth. 341

Under actual conditions of test, however, there will usually be a small difference between the above theoretical value and the actual quantity measured, even when the surface measured is a perfect parabola of revolution. The reason for this is that the point N of intersection of the normals is not the true focal point of the rays from either of the elements A or A' independently. For a radiant point at N the focus of the rays reflected

342 *On the Correction and Testing of Parabolic Mirrors.*

from the element A is at O, for the rays from A' at O' (Fig. 4).

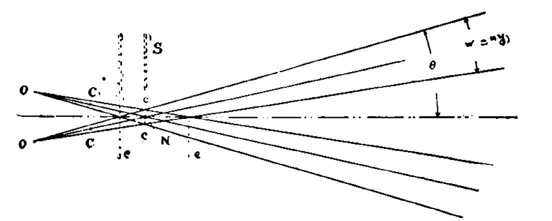


Fig. 4.

titled "Some Notes on the Correction and Testing of Parabolic Mirrors" cited early in the preceding chapter. Only a small part of that 12-page article dealt with the virtually forgotten fact that the c of c of any off axis area of a paraboloid is not on the axis, as most of us have assumed when Foucault testing. The article was buried in the earlier files of the periodical named, and this particular fact was buried within its more general discussions. It remained for Enrique Gaviola of Argentina to disinter this fragment and to prove its worth experimentally. In 1939, November, he, with Ricardo Platzeck, another Argentinian astronomer, described in the *Journal of the Optical So-*

ciety of America their method of surveying optical surfaces, based on Wadsworth's observation. Then, apparently, their own article became similarly buried in the monthly flood of periodicals. A contributing factor may have been the fact that its 17-page treatment was so mathematical that it may have scared away the working optician. Now that it appears in a book it is hoped that the preceding lucid exposition of the caustic test in several applicable forms will result in its use. It is true that it is at its best on short focus mirrors but short focus mirrors are important. The test enjoys an advantage in the matter of visibility; using the eyepiece technic of measuring, a mirror could be examined half a block away since the testing is done on the image. It is also of use on the high f ratio Cassegrainian, a significant advantage. It is an elegant method whereby the lover of high precision and the perfectionist may go about as far as he wishes, also have fun in building the beautiful dingbat and using it.]

Interference of Light *

By Horace H. Selby

The performance of all optical instruments is influenced by the interference of light. Some, such as interferometers and grating spectrographs, could not exist if interference were impossible.

It is the object of this chapter to discuss interference and its relation to the construction, testing and use of astronomical telescopes, avoiding as far as possible theoretical controversy and mathematics. This attempt to explain interference phenomena, especially those caused by diffraction, without critical comparison of theories and without the aid of the calculus, is akin to trying to make whiskey without grain—something is bound to be lacking and the connoisseur will be disappointed.

The true nature of light is probably not known. Certainly no one simple theory is available which will satisfactorily account for all the things which light is known to do. However, the behavior of light has intrigued some of the most brilliant people of history who have, by countless experiments, established many facts. By conjecture and computation, these same men and women have advanced many general and special theories designed to explain the phenomena which they and others have observed. It is fortunate then that one simple theory appears adequate to rationalize all the phenomena associated with the subject of this chapter. This theory is called the wave theory of light and is due largely to Huygens,[1] Young,[2] Fresnel,[3] Fraunhofer,[4] and Sommerfeld.[5] The fact that no wave theory explains the facts associated with the emission and absorption of radiation while certain corpuscular and quantum theories do is unfortunate, but the relative merits of the various theories fall outside the scope of the present discourse. By combining undulatory and corpuscular concepts, as is done in modern wave mechanics, a fairly satisfactory explanation of all optical phenomena is possible.[6]

In general, it is possible to transfer energy from point to point by three methods—a projectile traverses the intervening medium, the medium is forced to flow, or the particles of the medium execute rhythmic movements. In the third method, no particle crosses the space between the points in question. The particles of the medium move only infinitesimal, if any, distances in the direction of propagation of the energy being transferred. The particles of the medium do move to and fro across the axis of propagation at right angles to it, and in all azimuths, except when the light is polarized. This constitutes wave, or simple harmonic, motion. In Figure 1-*a*, a ray of light is represented

* Received 1948, Oct.

1 Christiaan Huygens, "Traité de la Lumière," Leiden, 1690.

2 Thomas Young, On the Theory of Light and Colours. *Phil. Trans.* Roy. Soc. London. Vol. XCII, pp. 12–48, 387–397, 1802. Vol. XCIV, pp. 1–16, 1804.

3 Augustin Fresnel, "Oeuvres Completes," Vol. I, Paris, 1866.

4 Joseph von Fraunhofer, "Collected Writings," Munich, 1888.

5 A. J. W. Sommerfeld, *Math. Annalen,* Vol. 47, pp. 317– 1895.

6 Louis de Broglie, "Matter and Light," trans. by W. H. Johnston, pp. 27–31 (1946).

as moving through the paper at right angles to it and its center is indicated by the dot. At *b*, the same ray is shown moving in the plane of the page from left to right and its center is represented by the line XX'. (Properly the curves depicting light waves should be sinusoids and *a* should be a small fraction of *b*. The curves are distorted for reasons of clarity and ease of preparation.)

For simplicity, only the vertical component of the ray is shown, but it should be clearly understood that other components are present in ordinary

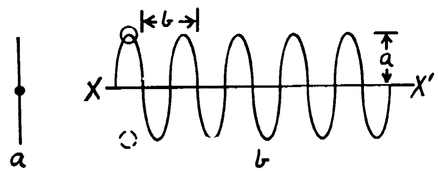


Fig. 1

Drawings and photographs by the author

light, vibrating in all azimuths, as indicated in Figure 2, where one particle vibrates in plane AA', another in plane BB', ets.

In Figure 1-*b*, *a* represents the maximum distance from the axis of propagation which a certain particle moves while vibrating. It is called the amplitude and is proportional to the square root of the intensity of the light. *b* represents the distance along the axis which the light moves while the disturbance

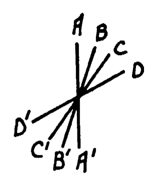


Fig. 2

executes one cycle. It is one wavelength (λ) and is frequently expressed in millimicrons (10^{-6} mm) or angstrom units (10^{-7} mm). A vibrating particle is shown as a circle in Figure 1-*b*. It moves back and forth in a straight line from its indicated to the dotted position. Obviously, many particles representing many azimuths of vibration could not, as Figure 2 suggests, collapse to one dimensionless point λ/4 later than the instant depicted. This absurdity is employed as an artifice to avoid discussion of vectorial resultants which would be difficult without resorting to mathematical complexity.

The number of cycles or wavelengths passing a point of reference in a unit of time is called the frequency. The frequency of light is a constant for any

color and approximates $10^{14.8}$ cycles per second for visible radiations. Velocity, amplitude, and wavelength are not constants for they vary with the medium (vacuum, air, glass) through which the light is passing, all being less in denser media (Figure 3).

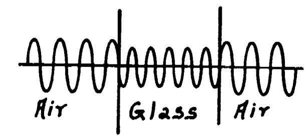


Fig. 3

Often it is more convenient to consider *b* of Figure 1 as an angular quantity equal to 360° rather than as an interval of time or a length. Thus, two disturbances which are out of step by λ/2 are said to be "out of phase" by 180°.

As an illustration of the difference between the geometrical and physical representation of light, consider Figure 4, which represents a beam splitter *ABCD*, composed of two 90° prisms with their hypotenuse faces cemented

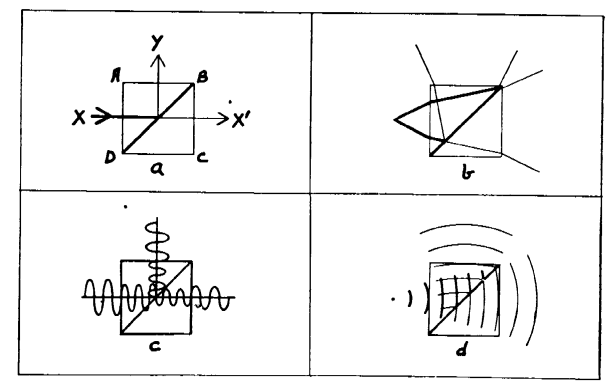


Fig. 4

together. One of the cemented faces is aluminized so that the reflected light equals the transmitted light in intensity.

a and *b* show, respectively, a ray and a fan of rays from *x* as treated in geometric optics by straight lines. *c* and *d* represent the same, illustrated as wave phenomena.

Consideration of a fan of rays proceeding from a point source is facilitated by imagining an infinite number of rows of the curves of *b*, Figure 1, radiating from a common origin or by rotating one curve in a plane around the source.

A corrugated surface is thereby generated about the source and a system of circular waves is the result. By rotating this surface about any of its rays, spherical waves can be generated. Cones of spherical waves are what we deal with in all optical instruments. In the case of the astronomical telescope, a cone of spherical waves of infinite radius of curvature reaches the instrument and is transformed into a cone of waves with a center of curvature at the focus, as in Figure 5.

In explaining optical phenomena in terms of the wave theory, Huygens evolved a brilliant hypothesis which states that every point on a wave front

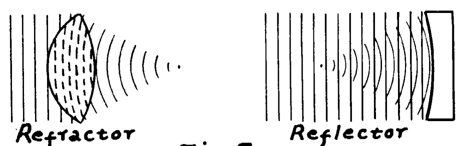


Fig. 5

behaves as if it were a source itself, sending out spherical wavelets ahead of, but not to the rear of, itself. In this way, each wave forms a new one and the light is propagated, for the result of an infinite number of wavelets can be shown mathematically to be a new wave front, that from a point source being spherical, that from a line source, cylindrical. This propagation of light by wavelets from all points in each wave is called "Huygens' Principle."

It would appear that light could be made to destroy itself, if the wave theory were correct, by combining two rays which are precisely 180° out of

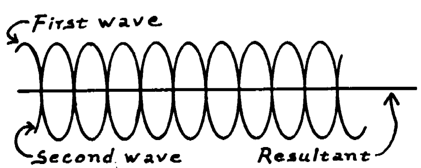
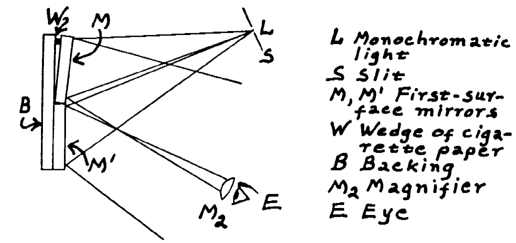


Fig. 6

phase. In other words, if the crests of one wave train were to coincide with the valleys of the other (Figure 6), the sum of the motions would be a constant, no vibration of the medium would occur and therefore no light would be propagated. Experiment proves this to be the case.

If two first-surface mirrors of good quality plate glass, say 2 by 4 inches, are arranged as in Figure 7 and illuminated by a slit, accurately parallel to the line where the mirrors meet, dark areas can be found with a magnifier in the reflected beams, if sodium or other reasonably monochromatic light is used. Between the dark areas will be found bright areas which are much brighter than the same field similarly illuminated by one mirror of any size.

The above shows that, at certain points, the wave trains have paths which differ by odd multiples of $\lambda/2$ and therefore annul each other, producing darkness, while at other points the paths differ by even multiples of $\lambda/2$ and reinforcement occurs, giving increased illumination. Figure 8.



Fresnel's mirrors
Fig. 7

This behavior of wave trains, giving annulment and/or reinforcement, is called interference.

By employing the wave theory, Huygens' Principle, and a knowledge of interference, which have just been discussed, the following phenomena relating to the optics of amateur telescope making can be explained:

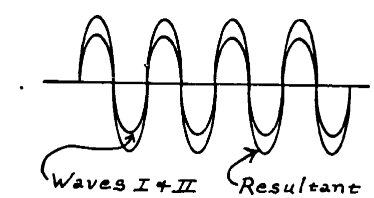


Fig. 8

1. "Newton's rings" or fringes of equal thickness, used in testing flats and lenses for surface contour.
2. Haidinger's fringes, which are fringes of equal angle used in testing plane-parallels for parallelism.
3. Low-reflection coatings on lens and prism surfaces.
4. Diffraction "spikes" radiating from star images.
5. Diffraction patterns at telescope foci.
6. "Edge diffraction," noted when using Foucault's knife-edge test.
7. Loss of definition due to obstacles such as Cassegrain secondaries, etc.

Each phenomenon will now be treated separately.

Newton's Fringes

When a transparent film is bounded by other media of different refractive index, the interfaces can be made to reflect wave trains which differ in path length and thereby produce interference.

In the case of a thin air film between glass surfaces, Newton's fringes are formed as shown in Figure 9.

A ray of monochromatic light from any point in the source S, which may be of any size, passes through the first glass and is partly reflected at the first air film surface to the eye at E. Since this reflection occurs between dense and rare media, there is no phase change. Later, the parent ray is again reflected when it reaches the second air film surface, sending a ray of different

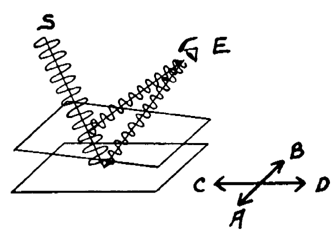


Fig. 9

path length to E. This time, the reflection is at a rare-dense interface and a phase change of practically 180° occurs.

As the film is scanned in the $C—D$ direction, film thicknesses of varying magnitude are encountered. Since the path difference between the two reflected wave trains is thereby changed, the phase difference also changes. The combined phase changes due to varying path length and to the two reflection sequences cause the two trains to interfere in such a way that alternating dark and light areas are seen in the plane of the air film. When the combined phase difference is an odd multiple of 180°, *i.e.*, $\lambda/2 \times 1, 3, 5$, etc., annulment causes darkness. At the next 180°, or $\lambda/2$, reinforcement effects an increase in illumination.

Since there is no thickness change in the $A—B$ direction, constant path differences are found and scanning in this azimuth reveals no change in illumination. Therefore the interference fringes between two surfaces of identical curvature but of opposite sign will be straight lines parallel to AB, regardless of the magnitude or form of curvature (spheres, planes, conics, etc.). If the angle between the surfaces is reduced, the fringes become more widely separated because the eye must then scan a greater distance in the $C—D$ direction in order to reach the next region of half-wave path difference. Therefore, when the surfaces are parallel the fringes are infinitely far apart and the entire film will be uniformly illuminated. Coaxial spherical and aspheric surfaces of revolution which differ in curvature form circular fringe systems because the lines of uniform path difference are obviously circles themselves.

If the curves do not match each other, the fringes will be arcs or will have varying shapes, depending on the relative contours and curvatures of the surfaces. The fringes form accurate contour maps of the air-film thickness. (The reason is that the distance between any two adjacent bright fringes represents one wavelength of path difference but, since the longer path traverses the air film twice, the path difference is double the change in air-film thickness.)

In the mathematical treatment of interference in thin films, the following variables occur and greatly influence the appearance of the fringes and therefore the accuracy of any measurement made with their aid:

1. The wavelength of light.
2. The angle at which a fringe is examined.
3. The thickness of the air film.

When only moderate precision (±4 fringes for flats) is required, it is necessary to consider nothing but the illumination and the cleanliness of the

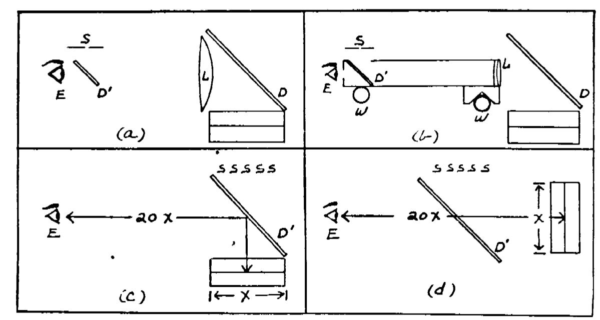


Fig. 10

surfaces. The light must contain but one fairly narrow band of wavelengths, which can be obtained by the use of filters, and the surfaces must be free from large particles which might keep them apart. Wiping with the palm of the hand is usually sufficient. The surface may be illuminated and viewed from any angle up to 20° from the normal and from any distance not closer than two diameters.

When high precision of the order of 0.1 fringe is necessary, extreme precautions must be taken. Each portion of each fringe must be illuminated and viewed from the normal to the surface because only along a normal or perpendicular will one wavelength of film thickness be indicated by two fringes. Arrangements for insuring this condition are shown in Figure 10, where E is the eye, S a monochromatic light source, D' a semi-reflecting diagonal, L a spherically corrected lens, D a diagonal mirror and W parallel sliding ways.

Only diametral fringes should be regarded, or diametral paths across fringe systems. *a* and *b* have the advantage of yielding brighter fringes than *c* or *d*.

If more than one color of light is present, the different fringe systems overlap, giving diffuse fringes which bear no exact relation to film thickness. Also, two or more wavelengths can resonate or "beat," giving maxima and minima which can be many wavelengths apart. Thus, surfaces viewed under mixed colors may appear to match within one fringe under certain conditions, whereas they may be dissimilar by several fringes as proved by examination under monochromatic light (Figure 11).

The light need not be strictly monochromatic in the sense that but one wavelength is emitted. So long as only one dominant, fairly narrow band is

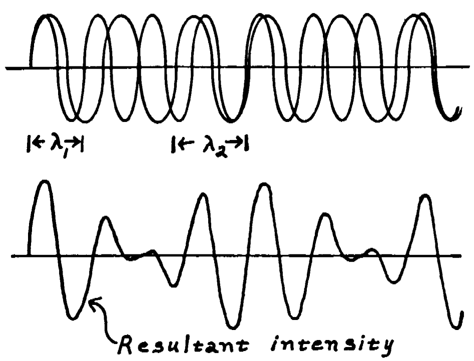


Fig. 11

used, accuracy can be attained. Other colors may be present if they are very weak in comparison with the dominant. If filters are used, they may be small and held before the eye or they may cover the source. If the fringes appear to have very high contrast over the entire surface (jet black and brilliant, pure color) the light is probably satisfactory. One can be positive, however, only by examining the radiation with a spectroscope.

The thicker the air film, the greater will be the various errors due to obliquity, which can be serious. Also, the brilliance of the fringes will be less for thick films. Therefore, separators should not be used. If the surfaces are scrupulously clean, they can be approximated closely enough for possibly all purposes. Cleaning with ethyl alcohol or pure isopropyl alcohol on a lintless cloth, followed by blowing with an infants' syringe, is recommended.

If it is desired to measure the film thickness in order to apply corrections for its magnitude,[7] it can be done as follows: Arrange some form of spectroscope so that the distance between two lines of known wavelength is clearly

[7] ATMA, p. 125, footnote.

indicated in the field of view. Illuminate the air film under consideration brilliantly with incandescent white light and examine the light reflected from it with the spectroscope. Across the spectrum will be seen a number of dark lines which are parallel to the slit. See Figure 12. Since the lines will be narrow if numerous, a narrow slit should be used. The number of lines (n) present between the reference points representing the known wavelengths can

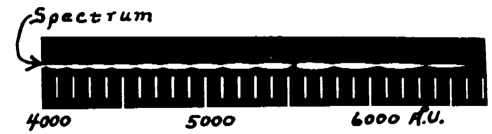


Fig. 12

be counted and entered in the formula given below to find the thickness. α is the angle of incidence of the light.

$$t = \frac{n\lambda_1\lambda_2}{2\sin\alpha(\lambda_1 - \lambda_2)}$$

For example, assume the spectroscope reference marks to be set on $\lambda_1 = 6563$ A.U., the C-line of hydrogen and $\lambda_2 = 4861$ A.U., hydrogen F. Between these marks, if 28 dark lines are counted when the axis of the spectroscope collimator is coincident with the normal to the film at the illuminated point, the thickness of the film at this point will be in angstrom units

$$t = \frac{28 \times 6563 \times 4861}{2(6563 - 4861)} = 260{,}000.$$

If the result is wanted in millimeters

$$t = \frac{28 \times 0.0006563 \times 0.0004861}{2(0.0006563 - 0.0004861)} = 0.026 \text{ mm}$$

(It will be noted that, for the same units, the thickness is a linear function of n and extremely easy to calculate.)

The reason that this method of thickness computation is valid is that any moderately thick film will be correct for the production of a maximum of illumination through interference for a number of different wavelengths and therefore will transmit only this number of wavelengths, holding back by annulment an equal number, which are therefore absent from the spectrum transmitted, appearing as dark lines in the spectroscope. This method is strictly correct only for thicknesses of several wavelengths, but is entirely adequate for the correction of fringes between flats. A more complicated but exact method is described by Peters and Boyd.[8]

[8] *Bur. Stds. Sci. Papers*, Vol. 17, pp. 693–704.

Haidinger's Fringes

A different system of interference fringes—Haidinger's rings—is extremely useful for determining the degree of parallelism of the surfaces of plane-parallels.[9]

These fringes may be seen at infinity either by looking through the glass or preferably by reflection, as shown in Figure 13. Some ray from every point x in the illuminant will strike the glass perpendicularly. Each such ray will be partially reflected back upon itself to M and will then be partially reflected through the lens L to its axial focus F. Some of the light will proceed simultaneously downward from A to B and be reflected upward from B to M through L to F. Due to the difference in path length of these two rays, they will reach F under conditions of interference, the out-of-phase relationship between them governing the amount of annulment or reinforcement at F. All such rays from all points, being perpendicular to the glass, are parallel and therefore contribute to the illumination at F.

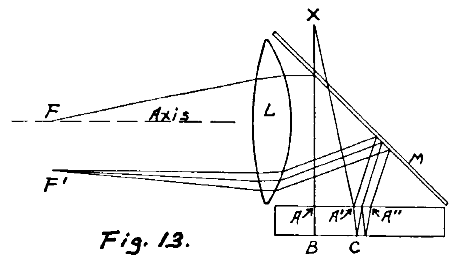


Fig. 13.

X A point in the monochromatic source.
L Lens, focussed on infinity.
M Semi-reflective mirror.

Consider a ray from the first or any other point which strikes the glass at an angle to the normal. It, too, will undergo multiple reflection within the plate, sending many portions of itself (only three are shown) over different path lengths to F', where interference occurs again. By rotating the angular ray $XA'C$ around XAB, keeping angle AXA' constant, it can be shown that the point F' will form a circle about F, with the radius FF'. At greater angles, other, larger circles are formed around F. Therefore, a system of interference rings, centered in the field of view, is seen when looking through the plate with a telescope which is focused on infinity. The reason that the fringes are seen only at infinity is that the rays causing the interference (such as $A'M$ and $A''M$) leave the plate mutually parallel and therefore have the effect of coming from an infinitely distant source.

By transmitted light, the fringe system has very low contrast because wave trains of very small amplitude are interfering with directly transmitted ones of high amplitude. The minima are therefore nearly as bright as the maxima. By coating one or both surfaces with a semi-reflecting film of silver or aluminum, the contrast can be improved by making the interfering rays more nearly of equal brightness. With no treatment, the two rays have an approximate brightness ratio of 100:1, even with dense flint. By making one surface semi-reflective a 20:1 ratio is possible, while treatment of both surfaces yields 4:1. It is therefore wiser to employ the method using reflected light, for a ratio of 1.1:1 is obtained without special treatment. In fact, a semi-reflecting coating on one or both surfaces will give the following ratios in reflected light: Upper only, 80:1. Lower only, 8:1. Both, 11:1.

[9] ATMA, p. 127.

If, for some reason, transmitted illumination must be used, the phase changes of reflection at the high-index surfaces of the silver or aluminum coating need cause no concern. The only effect will be to change the fringe spacing, not the number appearing per unit of distance.

The formula expressing the path difference in films is $\Delta = 2Nt \cos(\alpha - \theta)$ where N = ref. ind. of film, t = film thickness, α = angle between internal ray and normal to first surface and θ = angle between the surfaces of the film.

In good plane-parallels, N and t are practically constant and θ is insignificant in comparison with α. Therefore, Δ depends largely on α. Since α can only be constant in a circle around a normal, the fringes must be circular.

When t is not absolutely constant, the path differences will change as the plate is moved across the field of view, causing the central fringe to collapse and disappear as less thickness is encountered or to expand and make room for new ones, as greater thickness is found.

The difference in thickness between any two points is $n\lambda/2N$ where n is the number of fringes lost or gained, λ the wavelength of the monochromatic light used and N the refractive index of the glass for λ.

For example, assume that a disk of BSC-2 has been examined, using sodium light and that the greatest number of rings seen to disappear while moving the disk across many diameters was 11. Then the disk is lacking in parallelism by $(11 \times 0.000589)/(2 \times 1.517) = 0.0021$ mm.

Low-reflection Coatings

The third phenomenon of telescope interest caused by interference is that of reduction of reflection at glass-air surfaces by coatings.

The entrant and emergent faces of right-angle prisms, the faces of the correcting lenses of Schmidt-type cameras and the lens surfaces of oculars and objectives all reflect some of the light which passes through them. This reflected light does not properly illuminate the image. The light that is reflected away from the image may be lost or it may, by other reflections, reach the image field with whatever light has been reflected toward the image and cause lowered contrast, flare, ghosts and other spurious images, especially when Venus or other bright objects are close to or within the field of view.

By changing the refractive index of the glass surface, the amount of reflection can be altered, for the amount of reflected light is a function only of the refractive index of the glass and of the angle of incidence. If it were possible to coat a lens with a layer of a transparent material the refractive index of which changed continuously from that of air to that of glass where it touched the lens, no reflection could occur. Since no such substance is known, a compromise is adopted and a substance with an index intermediate between air and glass is employed. The best index would be $\sqrt{N}$, where N is the index of the glass.

One popular method is to evaporate magnesium or other fluoride in a high vacuum and permit it to condense on the glass, forming a film. Another method

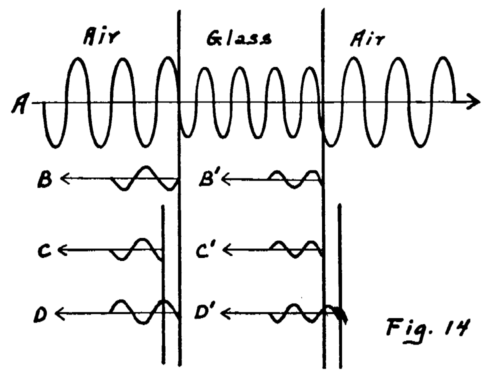


Fig. 14

removes the components of the glass which raise its refractive index—such as lead, barium, sodium and potassium—by leaching with water, nitric acid, etc. Still another etches the surface with fluorine compounds in such a way that the pits formed are small in comparison with the wavelength of light. This has the effect of "diluting" the surface with air without impairing its ability to properly refract light. Organic compounds have been developed which can be applied to glass surfaces at atmospheric pressure and which can be made to decrease as well as increase reflectivity with negligible absorption.[10]

Without a knowledge of interference we should be able to reduce the reflecting power of glass but little by the above methods. By taking full advantage of this property of light, however, we can practically eliminate reflection of one wavelength at normal incidence and greatly reduce it over the remainder of the visible spectrum and over useful angles.

Consider the effects of two properly formed films, as shown in Figure 14.

Imagine a wave train traversing a glass plate, as at A. Some will be reflected, as at B and B' and be lost or contribute to image faults. If, now, the glass is properly coated with a quarter-wave film, the first reflections at each face will occur as shown at C and C'. After $\lambda/4$, in terms of time, the second

[10] American Optical Co., Southbridge, Mass.

reflected waves D and D' will start back, being propagated out of phase with C and C', respectively and annulling them. (Although all trains are coaxial, they have been separated for clarity.) After the first half-cycle, A will be reinforced by the amount of energy possessed by C, C', D and D' in their first cycle and the particles transmitting A will vibrate with increased amplitude. The fact that the reflections of C and D are at denser surfaces means that each has changed phase 180° and they are "in step" as soon as they reach the air, if their path lengths are equal. However, D has traversed $\lambda/4$ twice and is therefore $\lambda/2$ behind C or 180° out of phase, making annulment possible. C' and D', being reflected at rarer media, suffer no phase change. Otherwise, they do not differ from C and D. It has been argued that, when a ray passes from a dense to a rare medium, no coating is necessary because no phase change occurs and that the reflected ray would be annulled by a portion of the parent ray. That this is incorrect is shown by the fact that wave trains must be moving toward a common point, as are C and C', above, before interference can be utilized, quite apart from any phase changes.

It is obvious that a coating can be $\lambda/4$ thick for only one wavelength and that any odd multiple of $\lambda/4$ will do well for this color. However, the thinner a coating, the better it will perform with widely-separated colors and it is therefore wise to have a coating no thicker than one one quarter wavelength. This can be assured in the high-vacuum process by turning off the filament as soon as the first reflection minimum is reached for the chosen color. Another possible advantage of the $\lambda/4$ thickness is that it usually gives greater durability than does a thicker film. For visual instruments, it is best to coat all surfaces for the maximum transmission of 5500 to 5600 A.U. unless the instrument is to be used for critical colorimetry. (In this case, color distortion can be avoided by coating each surface for maximum transmission of a different color, as recommended by Jacobs.[11]) When such a coating is examined in white light, it will appear to be faintly reddish-violet (purple). A brilliant, deep purple indicates a thickness of $\frac{3}{4}\lambda$, $\frac{5}{4}\lambda$, etc. A color differing from purple indicates a minimum reflectance differing from the visually brightest yellow-green.

Whether or not surfaces should be coated must be left to the owner's judgment. Properly done, coating improves instruments used under threshold illumination, especially if many glass-air surfaces exist. Some cases of ghost and flare-spot can be completely cured. However, injudicious baking of the film may strain or break a large prism or lens (the durability of some fluoride and organic films is enhanced by heating to 200–450°F) and there are the usual hazards which accompany handling, transportation, etc. Certainly, an instrument which is perfectly satisfactory as it is should not be changed.

Diffraction

A particularly interesting type of interference occurs when a beam of light rays is limited in any way, as it is in telescopes by the edges of mirrors, lenses,

[11] "Fundamentals of Optical Engineering," p. 121, 1943.

supports, etc. This type of interference is called diffraction and is the cause of the spikes often seen extending radially from star images formed by reflectors. It also makes it impossible to form a true point image of an object; it causes the edge of a mirror under test by Foucault's method to appear brightly illuminated and it causes reflecting telescopes to give images of lower contrast and slightly poorer definition than those of high-quality refractors.

Image Spikes: Consider the train of waves shown in Figure 15. The light is being propagated in the conventional left-to-right direction from a distant small source to the opaque knife-edge K, where a portion of the wave front is obstructed.

According to Huygens' Principle, every point on every wave is sending out wavelets into the hemisphere ahead of it, the sum of all these wavelets at any instant constituting a new wave, the repetition of this wave formation, resulting in a smooth flow of waves. When K is reached, this smooth flow is interrupted and the wave existing along the edge of K now radiates wavelets which cannot combine their energy with other wavelets on both sides to form the customary new wave front, since the medium on one side is devoid of wavelets, being shielded.

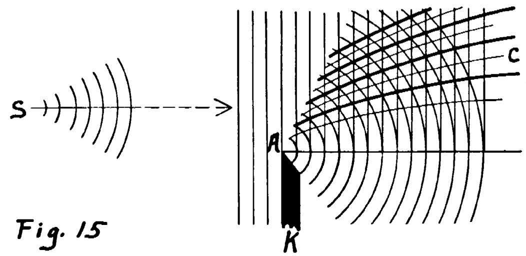


Fig. 15

The wavelets along K therefore begin the propagation of an entirely new wave and the edge of K consequently behaves exactly as if it were an independent source of light of precisely the same character (frequency, constancy, etc.) as S, save that the wave-front is cylindrical instead of spherical. As we have found earlier, waves from two sources of the same character proceeding toward a common point can and do cause interference where they meet, depending on their relative path differences. So it is with the waves from the edge of K and from S. Along the parabola AB, for example, the waves have path differences of even multiples of $\lambda/2$ and reinforcement causes a maximum of illumination while, along AC, the difference is an odd multiple of $\lambda/2$ and a minimum is encountered. Into the shadow of K, the obstructed wave front also sends light, but since there are no other waves in this area in proper condition for interference, the illumination merely decreases smoothly and rapidly, without exhibiting maxima and minima. With a very narrow monochromatic source, the fringes show good contrast, as in Figure 16-*a*, which was made with a slit source.

When a straightedge diffracts white light, a series of colored fringes which are, in fact, spectra are formed. The lines forming these spectra will be parallel with the straightedge and the spectra themselves will extend at right angles to the straightedge into the unobstructed beam. If the light, after passing the obstruction, is brought to a focus, the spectra will be focused also and will be composed of lines which are short for small sources, such as pinholes, and long for large or extended sources.

Consider now, the support EA in Figure 16-*b*, which represents the diagonal-supporting mechanism of a typical Newtonian telescope. EA acts as a double straightedge. The diffraction pattern caused by one edge will form a series of spectra in the field of view extending horizontally to one side of the image, making one spike of the artificial star image of *c*. The other edge will form the spike on the opposite side.

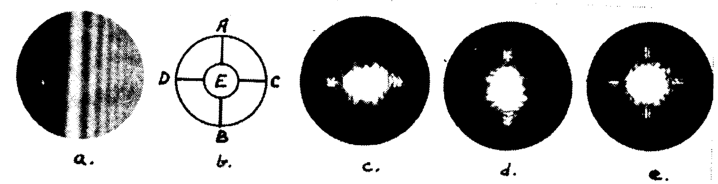


Fig. 16.

Simultaneously, the two edges of support ED will form *d*. Supports EB and EC will merely form patterns identical with those from EA and ED, which will merge precisely at the focus, intensifying the spike pattern *e*. Therefore, it is obvious why a vertical support forms a horizontal spike and why every arm of a support causes two opposing spikes.

This also shows why bending the supports [12] and the use of curved masks [13] causes elimination of the spike phenomenon—they multiply the spectra, forming them in many azimuths over such an area that they become too faint and too broad to see.

The image of a point formed by a telescope, as will be shown later, is a system of rings surrounding a central disk. These rings extend into the field, but rapidly diminish in brightness away from the center.

The energy contained in the spikes mentioned above and illustrated in Figure 16-*c* partially combines with the feeble energy present in the rings of the image pattern to give reinforcement at an angle of 45° to the spikes, Figure 17-*a*.

As in the case of the prominent 90° primary spikes previously described, the secondary 45° spikes from the vertical supports of Figure 16-*b* are superimposed on those of the horizontal supports, giving the pattern shown in Figure 17-*b*. The secondary spikes are rarely found on astronomical negatives

[12] *Sci. Am.*, June, 1945, pp. 381, 382.
[13] ATMA, p. 621.

because of their faintness and because the mechanical constants of the telescope must be rather critically arranged in order to produce them most efficiently.

By deliberately altering the dimensions of diffracting obstacles and the intervals between them, diffraction can be made to do certain things which demonstrate and prove the "bending" of light. Figure 18-*a* shows a slit image formed by a lens. By placing a second slit immediately in front of the lens the image is changed by diffraction into a band, as at *b*. If a double slit of proper dimensions for the wavelength and distances concerned is substituted for the single lens slit, secondary interference, as at *c*, is produced. If an opaque disk, which Editor Ingalls aptly calls a curled-up straightedge, is used to cast a shadow in a parallel beam, the bending of light can be conclusively proved, for, at the proper distance from the disk, the shadow will have a bright center, as in 18-*d*. Also, by photographing a disk, while backlighted, with a lens of smaller aperture than the disk diameter, so that no direct light enters the lens, the edge diffraction phenomenon seen when testing by Foucault's method can

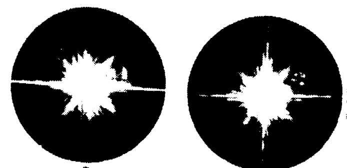


Fig. 17.

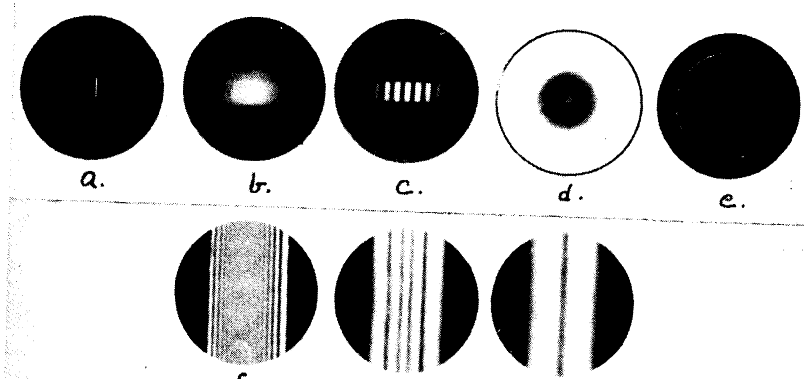


Fig. 18.

be demonstrated. See *e*. Another refutation of the ancient idea that light travels only in straight lines can be obtained by photographing the light distribution within an illuminated slit and at various distances back of it, as in *f*, *g* and *h*.

The reason for the formation of a bright line at the edge of a mirror, when it is tested by Foucault's method at its center of curvature, is similar to that outlined above for image spike diffraction. (Mathematical treatment is different, however, for the former case is considered to belong to the class of Fraunhofer diffraction phenomena since the diffracting obstacle is in parallel light, while it is in non-parallel light in this instance and therefore is classed under Fresnel diffraction.) It is allied, too, with the Airy disk and rings which are formed at the focus of a telescope, instead of a geometric point. In keeping, then, with the time-tested policy of the editor of this compilation †, let us treat the latter case first.

Focal Diffraction: When a telescope forms an image of a point object, this image is never a geometric point. Instead, it is a small disk, containing some 80 percent of the illumination and surrounded by alternate circles of interference maxima and minima which contain the remaining 20 percent, approximately, of the light. The diameter of the central disk is an inverse function of the aperture ratio and approximates $2\lambda f/D$ for an aberrationless instrument. Imagine the aperture of a telescope, refractor or reflector, filled with parallel rays, which are brought to a focus, Figure 19-*a*.

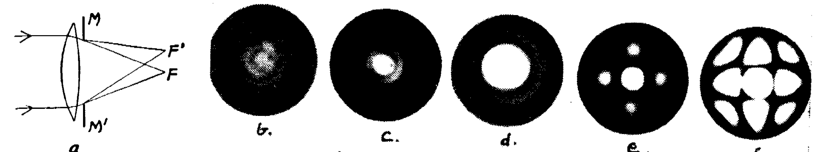


Fig. 19.

Since the path lengths of all the refracted rays are equal in a perfect telescope, the wave trains which they represent all reach F in phase and F is always bright. From the distant axial point source, no refracted light reaches the area outside F, and it is black. The diffracted light from the stop MM' does reach the area surrounding F, however, producing minima at places where the path length difference between MF' and $M'F'$ is $\lambda/2$ or odd multiples thereof and maxima at others where the difference is zero or an even multiple of $\lambda/2$. F is therefore surrounded by concentric circles of comparatively low luminosity, becoming fainter as the angle $MM'F'$ increases. At F, the light from all parts of MM' arrives along the same path length, which may differ from the path length of the refracted rays reaching F. The resulting interference effect is unimportant from the standpoint of the present paper. Figure 19 shows the effects of focal diffraction. *b*, *c* and *d* were made at $f/1.5$, $f/3$ and $f/6$, re-

† ATMA, p. 26. [Greetings!—*Ed.*]

spectively. *e* and *f* show how the supports of Figure 16-*b* alter the diffraction pattern.

Edge Diffraction: When the objective of Figure 19-*a* is tested by autocollimation or when a concave mirror is tested at its center of curvature, using Foucault's method, and the surface is darkened by cutting off the image of the light source, a line of diffracted light can be seen on certain portions of the periphery and bordering some objects near the surface which obstruct parts of the beam, such as dust, scratches, supports and edges of many kinds.

The mechanism causing this edge diffraction can be explained by reference to Figure 20 where R is a reflecting surface, MM' represents a circular mask,

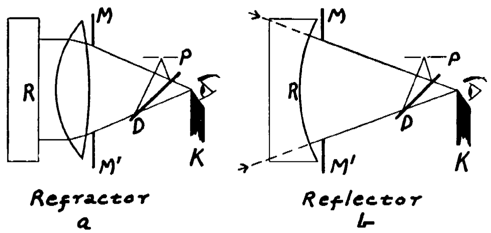


Fig. 20

P indicates a pinhole and D is a semi-reflecting diagonal. K represents an obstruction, such as a knife-edge.

Light proceeding from P is limited by MM', which diffracts light according to Huygens' Principle. This diffracted light is not visible from the vicinity of K, however, until it has reached R and has been reflected back toward K; for, as was mentioned earlier, points on a wave front send out wavelets ahead of but not to the rear of themselves.

When the distances from P and K to R are equal, as well as when P is farther from R than is K, the above statement holds. When K is farther from R than is P, however, the situation changes and MM' does not limit the cone of rays until after reflection has occurred at R. In this case, the diffracted light from MM' is propagated in the direction of K and the luminosity is viewed directly.

When P is not on the axis, one side of MM' gives diffracted light which is seen directly while the illumination from the other is viewed by reflection. The reflected light will appear slightly dimmer and narrower than that directly viewed when the distance from MM' to R is great, due to physiological factors and greater path length.

When MM' coincides with R, *i.e.*, when no mask is used, the edge of the mirror itself functions precisely as a mask for the virtual rays (dashed lines, Figure 20-*b*). The edge of the mirror does in fact limit the cone of actual rays going from P to K and the *limitation* of waves, whether performed by a physical obstruction or by a discontinuity of surface is the fundamental cause of diffraction.

If a pinhole is used in the arrangement shown in Figure 20-*b*, and if an opaque, circular screen (such as an ink spot on a microscope cover glass) is employed instead of a knife-edge at the focus to mask the image of the pinhole, a line of light of uniform intensity will be found encircling the aperture. The light will be uniform (Figure 21-a) because path differences and amplitudes are equal in all azimuths around the axis and because all the RYY' planes of Figure 22-*a* are obstructed equally. Note also that both horizontal and vertical obstructions show uniform edge illumination.

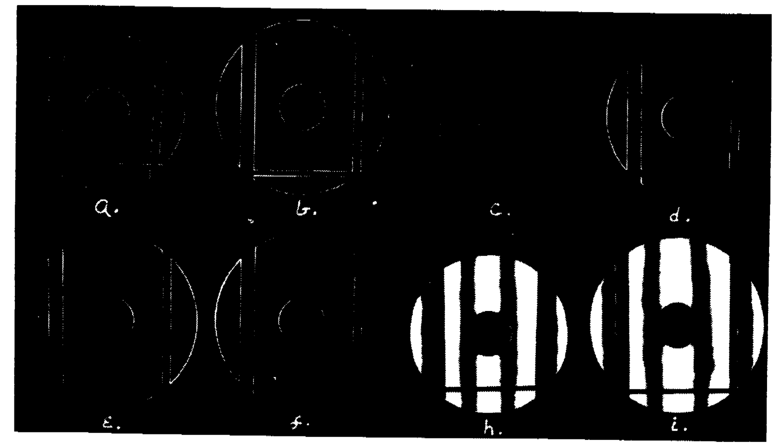


FIGURE 21

When the symmetry of the path system is destroyed, as it is when the spot is replaced by a knife-edge or a wire or when the pinhole is replaced by a slit, the appearance of the mirror edge and of some obstructions is changed. Use of a vertical knife-edge or wire with a pinhole or a vertical slit causes the top and the bottom of the mirror and any horizontal obstacle to lose their illumination. (Figure 21-*c*.)

The reason for this phenomenon is that light is diffracted by any given point on an edge in a two-dimensional, not a three-dimensional, angle, for the wave front originating at a line is cylindrical except at the ends. The plane of this angle contains the ray which just grazes but passes the point. The angle plane is also perpendicular to the diffracting edge. (See Figure 22-*a*, where the diffracted light from R is thrown forward only in the RYY' plane, not in other planes, such as RXX'.)

When the mirror is darkened by covering the center of the focal diffraction pattern, as in Figure 22-*b*, all the YY' planes from all horizontal obstructions are also covered and their diffracted light cannot be seen.

Further, more than half of the diffraction system at the image is occulted and, though the eye may still receive equal amounts of light directly from both sides of the mirror, the interfering beams from various edge points enter the relatively large aperture of the eye dissimilarly, causing one side, that opposite to the knife-edge, to be somewhat the brighter (Figure 21-*b*). If a large pinhole is used and the mirror edge is perfect, the diffracted light will be

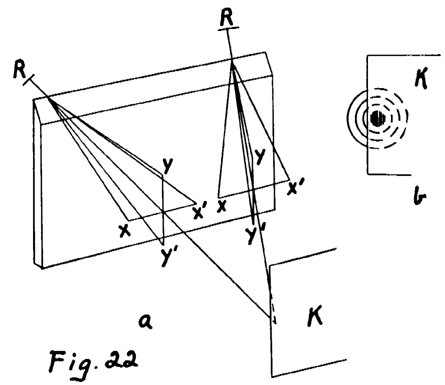


Fig. 22

relatively fainter because each point in the pinhole produces its own diffraction system and appreciable angular separation of the systems tends to blur the visual picture. If the mirror edge is badly turned, however, a large pinhole causes the extreme edge to diffract more light to the eye.

The use of both a knife-edge and a slit will cause a further blurring in a direction parallel to the slit, for a slit represents a series of pinholes, each of

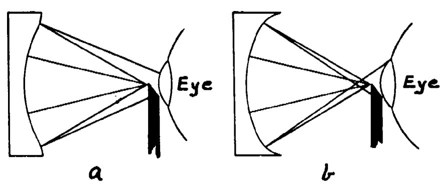


Fig. 23.

which contributes its own little family of diffraction gremlins. The result—Figure 21-*d*—is a complete lack of light at the top and the bottom of the mirror with bright, though slightly unequal illumination at the sides. (Figure 21 was made using a mirror having a perfect outer edge and a very slightly turned-down edge around the central perforation. See ronchigrams *h* and *i*, photographed with and without a mask, respectively.)

If turned down edge is present, the illumination from the edge of the mirror opposite to the knife-edge will be increased and that from the other edge decreased due to reflection, as in Figure 23-*a*. Turned up edge will give the opposite effect, as in Figure 23-*b*.

From the above it is clear that, when the focus of a mirror or lens is in the plane of the knife-edge or of the opaque spot and the aperture is darkened by

TABLE 3

Equipment		Perfect edge (A)	Turned down (B)	Turned up (C)
Pinhole and spot both on axis	(1)	All azimuths uniform, very narrow and bright. (Fig. 21-*a*, mirror edge)	All azimuths uniform, broader and dimmer than 1A. (Fig. 21-*a*, edge of hole.)	Same as 1B
Pinhole and spot separated off axis	(2)	All azimuths bright and narrow. Side illumination very slightly unequal. (Fig. 21-*b*)	Broader than 2A. Otherwise same. (Fig. 21-*b*, edge of hole)	Same as 2B.
Pinhole and knife on axis	(3)	Top and bottom dark. Sides very slightly unequal, narrow. (Fig. 21-*c*, edge of mirror)	Knife edge dimmer, more narrow. Top and bottom dark. (Fig. 21-*c*, edge of hole)	Knife side brighter, broader. Top and bottom dark.
Pinhole and knife off axis	(4)	Ditto. Side inequality slightly less or greater—varies with right or left cut-off.	Same as 3B.	Same as 3C.
Slit and knife on axis	(5)	Same as 3A with very slightly greater inequality. (Fig. 21-*d*, mirror edge.)	Same as 3B. (Fig. 21-*d*, edge of hold.)	Same as 3C.
Slit and knife off axis	(6)	Same as 4A. (Fig. 21-*e* and *f*.)	Same as 3B.	Same as 3C.

proper cut-off, the extreme edge of the aperture will have the appearance indicated in Table 3 when viewed with the eye precisely on the axis.

Caution concerning inequality of side illumination is advisable, for such illumination is a function of the position of the eye as well as of the factors just discussed. By attempting to peer around a knife-edge, instead of holding his eye precisely on the axis, a TN can unconsciously distort the appearance of the edge of his mirror. Practice and mental discipline probably make the warning unnecessary in the case of the experienced mirror maker.

Refractor vs. Reflector: For many years it has been asserted by some that the refractor is superior to the reflector as regards sharpness of definition and contrast. Pickering [14] in particular has stated the case against the reflector quite well from the practical standpoint.

A qualitative consideration of diffraction effects indicates that reflectors do suffer from more scattered light than do refractors, for, with the exception of Herschelian and other off-axis telescopes, all reflectors have supports, diagonals, plateholders or similar diffracting obstructions in the light beam.

The sum of the lengths of all diffracting edges in the light path of a telescope is an approximate measure of the amount of light which can improperly illuminate the image field to lower contrast and alter the size of the diffraction disk, while the area of the free aperture is a measure of the quantity of light which can properly form the image. In Table 4 three telescopes are compared. In earlier parts of this chapter, it has been shown that diffraction greatly limits the performance even of refractors. It is probable, therefore, that the additional effects given in Table 4 are significant, indicating over twice the diffraction effect in the case of the reflector.

TABLE 4

Telescope	Area of free aperture	Circumference of free aperture	Support length (2 edges each)	Circumference of center obstacle	Ratio of free area to diffracting edges
10 inch refractor	78.6 in.²	31.4 in.	0.0 in.	0.0 in.	2.50
10 inch Newtonian, +2 inch diagonal, +4 supports.	75.5	31.4 in.	32.0	6.3	1.08
10 inch Cassegrain, +3 inch secondary +4 supports	71.5	31.4 in.	28.0	9.4	1.04

Table 4 is valid only if the aperture ratio of the refractor is such that chromatic residuals do not limit its performance.

REFERENCES

Mathematical treatment of some aspects of interference can be found in the references given below:

CORNU, *Jour. de Phys.*, Vol. 3, p. 1, 1874.
STOKES, *Camb. Trans.* Vol. IX, 1850.
GLAZEBROOK, "Dictionary of Applied Physics," Vol. IV, pp. 172, 181–188, 1923.
PAGE, "Introduction to Theoretical Physics," pp. 515–531, 1929.
RAYLEIGH, "Encyclopedia Britannica," Vol. VIII, pp. 238–255, 1910.
NIJBOER, *Physica,* Vol. X, No. 8, pp. 679–692, 1943.

[14] ATMA, pp. 606–615, 1937.

Telescope Eyepieces

BY HORACE H. SELBY

Comparatively few of us have seen the splendid spectacle which a perfect telescope is capable of revealing when directed toward the sky on a fine night. One of the major reasons for this situation is that the eyepiece is more frequently than not of inferior quality or improperly matched with the objective or mirror with which it is used. The objects of this chapter are to attempt to show the importance of the eyepiece or ocular, to present a survey of the types available and to describe the faults which affect eyepieces for astronomical use.

Eyepieces may be considered to have but two functions in visual optical instruments—to magnify the primary image formed by the objective or mirror and to render the enlarged image acceptable to the observer.

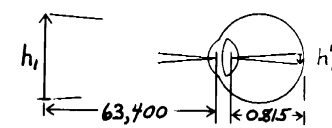


Fig. 1

Magnification can be easily imagined as the ratio of the size of the retinal image formed with the aid of an eyepiece to the size of the retinal image of the same object formed without the eyepiece. This is illustrated in Figures 1–3, which are diagrammatic only—not drawn to scale.

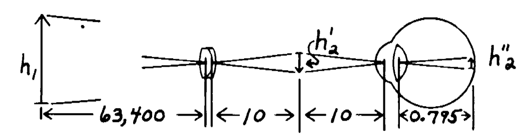


Fig. 2

In Figure 1, an object 300 inches high, one mile from the first principal point of the eye is shown imaged on the retina. Since the average normal eye, accommodating on the object, is shown, its focal length is 0.815 inch (1) [1] and the image height, h_1', equals

$$(300 \times 0.815)/63{,}400 = 0.00386 \text{ inch.}$$

Figure 2 illustrates the effect of a telescope objective without an eyepiece. Here, the image formed by an objective of 10-inch focal length is shown to have a height, h_2', of

$$(300 \times 10)/63{,}400 \text{ or } 0.0474 \text{ inch.}$$

[1] Numbers in parentheses refer to references at end of chapter.

If now the eye views this primary image from a distance of 10 inches, which is the conventionally accepted distance of most distinct vision, the height of the retinal image will be h_2'', which equals

$$(0.0474 \times 0.795)/10 = 0.00377 \text{ inch.}$$

The reason 0.0795 is used instead of the former 0.815 is that its focal length shortens as the eye accommodates for shorter distances and its principal points change position.

When an eyepiece of 1-inch efl is introduced, as shown in Figure 3, and the image is examined with the eye accommodated for ∞, magnification occurs, for the retinal image is enlarged. In this case,

$$h''' = (0.0474 \times 0.815)/1 = 0.0386 \text{ inch.}$$

By comparing 2 with 3, the absolute magnification of a 1-inch eyepiece is shown to be 0.0386/0.00377 or 10.2× under the given conditions.

A comparison of 1 with 2 indicates that the magnification of an objective of 10-inch focal length is 0.00377/0.00386 or 0.976×.

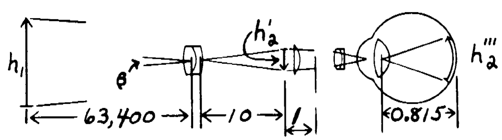


Fig 3

1 and 3 together show that a 10-inch objective plus a 1-inch eyepiece afford a total magnification of 0.0386/0.00386 or 10×.

In the early days of the compound microscope, each maker attempted to state the magnifying power of his instrument in the absolute sense, which was very commendable. Optical magnification is influenced by so many variables, however, and the treatment of and interpretation of the effects of these variables by the designers was so different that, for a time, some manufacturers did not even mention magnification, stating instead the equivalent focal lengths (efl) of their objectives and assigning arbitrary numbers to their eyepieces.

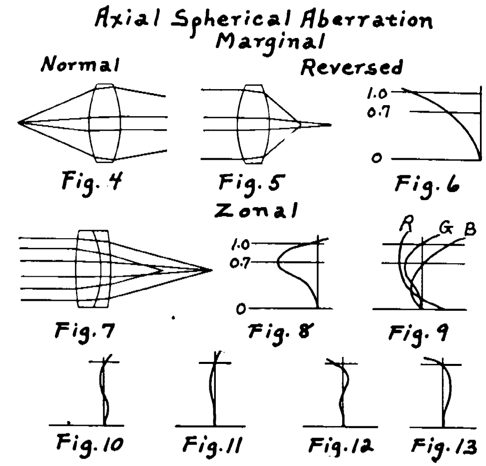
Modern optical convention dismisses absolute magnification in telescopes and deals instead with relative magnification which is very simply calculated and imagined by making a few assumptions which, though only approximately correct, are valid. The eye-to-object distance of most distinct vision is assumed to be 250 mm (10 inches) although it varies, being affected by brightness, area, age, training, wavelength, adaptation, time and fatigue. When using an eyepiece, the observer is assumed to have accommodated for ∞. Also, the virtual image is postulated plane and 250 mm from the eye. Under the stated conditions, the magnifying power of any ocular will be 250/efl in mm or 10/efl in inches, and the magnification due to any objective is efl/10 (in inches), and the magnification of a complete telescope is

efl objective/efl eyepiece.

The acceptability of the image formed with the aid of any instrument is a function of the degrees to which the corrections of the various aberrations of

the eye and the instrument as a whole have been carried. The aberrations which are of importance in eyepiece imagery are illustrated in Figures 4–29, in a purposely exaggerated manner. For simplicity and clarity, the eyepiece is represented by a single element and, instead of rendering divergent pencils parallel for acceptance by the eye, parallel rays are rendered convergent. This reversed direction is necessary for clear exposition of aberration effects. (Compare Figure 4 with Figure 5.)

Axial spherical aberration, Figure 5, is present when various zones of a lens focus at various axial points, and it reduces the sharpness of the central image by forming a symmetrical patch image of a point object. If corrected



for one object distance, it is usually uncorrected noticeably for others. When corrected for two object distances, the Herschel Condition is satisfied. When corrected for objects on both sides of a system, the König Condition obtains. The Gauss Condition is fulfilled when correction for two colors is accomplished. Spherical aberration of simple lenses varies as the square of the height at which the ray in question enters a lens surface (y in Figure 30). The aberration is frequently plotted as a graph for more compact presentation and clarity, as in Figures 8–13. Uncorrected or positive spherical aberration is indicated in Figure 6, where horizontal distances represent axial foci and vertical distances represent the y-values of the zones. The intersection of the two coordinate lines represents the focus of the paraxial or center zone. Spherical aberration is said to be corrected when the marginal and paraxial foci coincide, as in Figures 11 and 13. Spherical aberration is not constant for all colors and, when corrected for one, it is usually not corrected for others, as shown in Figure 9, where red light is undercorrected and blue is overcorrected when green is corrected. In good designs, however, this chromatic variation of spherical aberration is not excessive. In general, the brightest portion of the spectrum (555 mμ) is chosen for the correction of spherical and the other monochromatic aberrations in visual instruments. Dim light and other specialized conditions do require other points to be chosen, however.

Axial zonal aberration, Figure 7, remains after marginal spherical aberration is corrected. Its effect on the image is similar to that of marginal spherical aberration and it, too, increases with the aperture, as shown in Figures 8 and 11, which represent $f/4$ and $f/8$ systems, respectively. If sufficient degrees of freedom are available to him, the designer can reduce zonal effects markedly, as in Figure 10, which represents an $f/3$ triplet designed by the writer. In simple doublets, zonal error is usually at a maximum for the 0.7071 zone for green light when spherical surfaces are used.

Axial chromatic aberration, axial chromatism or central color causes light of different wavelengths to be refracted at different angles and therefore to be

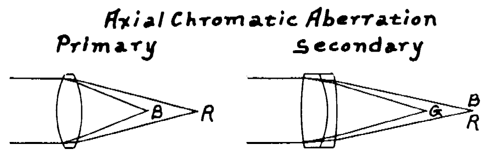
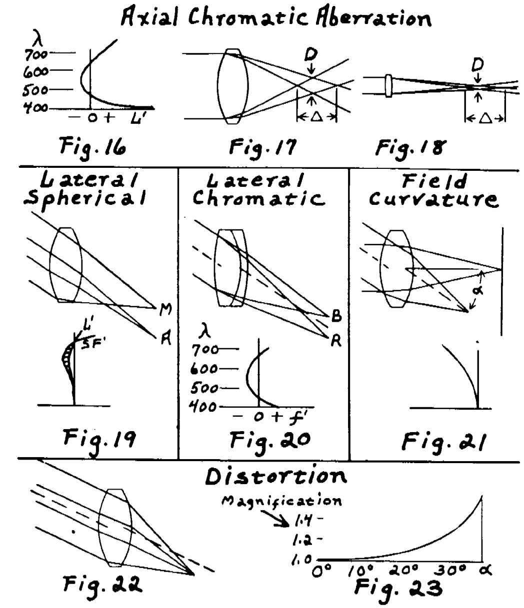


Fig. 14 Fig. 15

focused at different axial positions (Figures 14 and 15). It causes the image of a white object to be colored and diffuse. Primary chromatic aberration is said to be corrected when two wavelengths near opposite ends of the visible spectrum are made to coincide. The two are usually red and blue and their wavelengths are in the general neighborhood of 656 mμ and 486 mμ—the C and F lines of the hydrogen spectrum. For large exit pupils, 680 mμ and 486 mμ are often better. An instrument corrected in this manner is called achromatic. The fact that two wavelengths are cofocal does not mean that others are also brought to the same point. In the great majority of cases, wavelengths between the two chosen for achromatization fall inside, and those beyond, outside the red-blue focus as shown in Figures 14 and 15. The resulting image defect is called the secondary spectrum. When three colors are brought to a common focus, as is done in apochromats, those remaining form the tertiary spectrum, which can be as troublesome as the average secondary spectrum in some certain cases.

It is usual to express axial chromatism as a longitudinal distance (Δ_{chr} in Figure 17), which is independent of y. For this reason, many users of telescopes feel that a good $f/4$ instrument should perform as well, chromatically, as a good one of $f/16$. However, the diameter of the blur caused by Δ_{chr} is the important factor in such comparisons. As shown at D in Figures 17 and 18, the same Δ_{chr} does not insure a constant chromatic blur diameter. This is one reason for the use of large telescope f numbers when good chromatic results

are necessary. In the case of single lenses, of low dispersion, the primary spectrum becomes evident when the aperture exceeds the value $\sqrt{f'/10}$ (in inches). If the normal type of achromatism is considered, the secondary spectrum is noticeable at apertures greater than $\sqrt{f'/2.2}$ inches. This applies to objectives as well as to oculars. For examples, consider four situations:



A. A single plano-convex ocular of crown used on faint objects.
B. A similar ocular used to view the full moon—a very bright object.
C and D. Ordinary achromatic doublets on dim and bright objects, respectively.

At high brightness levels, the pupil of the eye may have a diameter of less than 2 mm (0.08 inch). Dark-adapted pupils usually exceed 5 mm (0.2 inch). Since the entrance pupil of the eye limits the effective aperture of the eyepiece, it is evident that the shortest f' (highest power) eyepieces which can give colorless central images in the four cases in question are, conservatively:

A. $0.04 \times 100 = 4$ inches (2.5×) B. $0.0064 \times 100 = 0.64$ inch (16×)
C. $0.04 \times 5 = 0.2$ inch (50×) D. $0.0064 \times 5 = 0.032$ inch (310×)

Although this chapter does not properly concern itself with objectives, it is of sufficient interest to justify mention that the above relations apply to objectives with complete validity as in Table 1.

It is obvious why the telescopes of Huygens' day were so inordinately long (some over 200 feet), for the immense f nos. tended to minimize the effects of spherical and chromatic aberrations.

Leaving the simpler aberrations affecting only the axial image, we proceed to those which affect the field away from the center. These are very much more important in eyepieces than in objectives and mirrors, for the former cover fields as large as 70°, while the latter usually cover very small angles. (The popular 6-inch, $f/8$ Newtonian with an eyepiece tube of 1¼-inch diameter has approximately a 0.75 field and a 3 inch, $f/15$ refractor has a similar coverage in normal use.)

Lateral spherical aberration, also called transverse spherical aberration, comatic aberration, sinical error, offence against the sine condition, etc., gives rise to the image defect known as coma. In Figure 19 it is shown that a comatic image is formed when the rays from different zones focus at different distances from the axis, M representing the marginal and A the axial focus.

TABLE 1

Single crowns			Conventional achromats		
diam.	min. f'	f/no.	diam.	min. f'	f/no.
1 in.	100 in.	$f/100$	1 in.	5 in.	$f/5$
2 in.	400	$f/200$	2 in.	20	$f/10$
4 in.	1600	$f/400$	4 in.	80	$f/20$

The comatic image itself is a roughly triangular flare, bright at the apex and rapidly diffusing and becoming dimmer toward the base. It is frequently described as comet- or pear-shaped. The effect increases directly with the distance from the axis and with the square of the aperture and is therefore most troublesome in wide-field oculars used with objectives of small f no. on dim objects. This aberration is difficult to illustrate directly in a graphic form. However, it is proportional to the difference between the distances $P'F'$ and SF' in Figure 30 when axial spherical aberration is corrected. Therefore, if the F' positions for the various zones are plotted to give the spherical aberration curve as before (Figures 6 and 13) and, simultaneously, the change in SF' is plotted, the difference between the two curves obtained will be a measure of the aberration. See Figure 19, where the shaded portion represents the aberration. It will be noted that coma is also zonal.

Lateral chromatic aberration (chromatic variation of focal length, chromatic difference of magnification, lateral chromatism, edge color, etc.) is a defect frequently present when axial chromatism has been corrected. (Figure 20). Although the axial C and F foci may coincide, the equivalent focal lengths, efl, for the colors may be different. If so, the longer efl will produce the larger image and, since the two images are of different size, they overlap, giving colored edges to images of extended objects and giving spectra, instead of normal images of distant point objects. Lateral chromatism varies directly as the distance from the axis and is constant over the aperture. Lateral chromatism can be plotted (Figure 20) in a manner similar to that used for axial chromatism, substituting the efl for the focal intercepts of Figure 16.

Curvature of field, Figure 21, occurs when the image surface is not plane. Eyepiece field curvature of the proper amount is usually desirable in order to match the curvature of the field of the image which is being magnified. Exact matching is rarely necessary, however, for the eye's ability to accommodate gives some leeway in one direction. The untrained eye cannot accommodate for convergent rays, so any mis-match should therefore be in the direction of overcorrection. In the absence of astigmatism, the curvature of field is fixed by the Petzval sum, which is the sum of all the products of the refractive indices and the focal lengths of the lenses of a system. Unless this sum is small, a flat, anastigmatic field is impossible. On the basis of thin-lens theory, the sum would have to be zero.

Field curvature can be altered at will within limits by permitting astigmatism and coma of varying degrees in the image. When astigmatism is absent, the field curvature varies as the square of the distance of the image from the axis.

Distortion is the aberration which causes the magnification of the image to vary over the field. Due to this, straight lines away from the axis will appear to be curved, the curvature becoming greater the farther they lie from the center. Figures 22 and 23 show distortion and its graphic plot. Negative distortion is shown. It is usually called pincushion distortion. The converse, positive distortion, is termed barrel distortion, due to the shape of the image of a rectangular object. Distortion varies as the cube of the distance of the principal ray from the axis. Eyepiece distortion is rather unimportant in even terrestrial telescopes and binocular field glasses, where a fairly large amount is tolerable. In rangefinders and in several other military instruments it is corrected. For these applications, orthoscopic oculars which are corrected for distortion are employed.

Astigmatism causes the extra-axial image of a point to be a symmetrical patch at its best focus and to collapse to a short line inside focus. Outside focus, a similar line is formed which is perpendicular to the first one. This behavior is shown in Figure 24, where fans of rays are shown passing through two meridians of a lens from a distant point source to the astigmatic foci. Uncorrected positive astigmatism can be graphically depicted as in Figure 25 where OY is a plane passing through the axial focus and OT and OR represent the surfaces containing the T and R images. The T focal lines are called tangential, meridional or primary astigmatic images. They are tangent to centered circles in the field. The R lines are termed radial, saggital or secondary. They are perpendicular to the tangential lines, just as wheel spokes are perpendicular to the wheel rim.

Astigmatism varies with the square of the distance of the image from the axis and directly as the aperture. Although the distance between the T and R foci does not change with the aperture, the length of each focal line (a, Figure 24) does.

Astigmatism is usually permitted in eyepieces in order to obtain suitable field curvature. Various types of astigmatic correction are shown in Figures 26 to 29. Figure 26 represents complete astigmatic correction, with the T and R surfaces coincident. The focal surface is therefore the Petzval surface, since it is controlled by the Petzval sum. In 27, the tangential surface is plane and the surface of least confusion is shown as a dotted line. By introducing more negative astigmatism, the astigmatic surfaces can be brought to opposite sides

Astigmatism

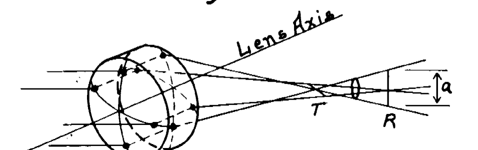


Fig. 24

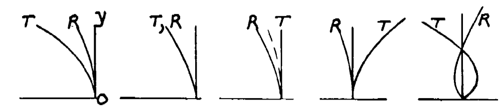


Fig. 25 Fig. 26 Fig. 27 Fig. 28 Fig. 29

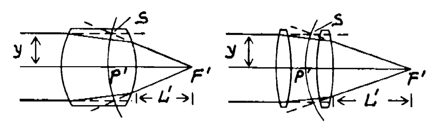


Fig. 30

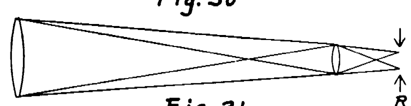


Fig. 31

of a plane, as in 28. This, however, usually results in poorer imagery than in 27. The field correction of an ocular adaptation of a photographic "anastigmat" is shown at 29.

Fundamentally, astigmatism, axial spherical aberration, zonal aberration and lateral spherical aberration are components of one aberration. However, it is tremendously easier to deal with the parts in turn, rather than with the whole.

One type of spherical aberration remains to be mentioned before we are finished with important eyepiece faults. This is spherical and zonal aberration of the exit pupil and makes it desirable that eyepieces be spherically corrected in such a way that a reasonably sharp, uniformly illuminated image of the objective or mirror is formed at the eyepoint (R, Figure 31). This requires that

the eyepiece be spherically corrected in both directions within limits and that zonal aberration be not excessive.

If the exit pupil spherical correction is poor, the eye, on its natural slight to-and-fro movements, will get an impression of shadows moving across the field. This is particularly important in the cases of riflescopes and military instruments with large eyepoint diameters, where freedom of eye movement is essential.

The aberrations outlined above are not invariants, even in one particular eyepiece. If a prism diagonal or a prismatic erector is used, all the aberrations will be affected—some markedly.[2] Generally, the extra-axial aberrations are seriously changed only above $f/15$ and beyond 10° from the axis. Field curvature is correct for only one eyepiece efl of a given class when used with a particular objective. Unfortunately, all the extra-axial aberrations except radius of Petzval surface are functions of the efl of the objective or mirror with which an eyepiece is used, for the efl is a measure of the stop distance and this distance enters into the equations of the separate errors. Astigmatism, distortion, coma and field curvature are more seriously affected by the stop distance than is lateral chromatism, particularly if any axial spherical aberration exists. The effect on lateral chromatism may be far from insignificant, however (20).

Eyepiece Terminology

In discussions involving eyepieces, as in those involving other specialized groups of things, certain words are used with highly restricted meanings. Unfortunately unanimity is not encountered throughout the literature; so the convention used in this chapter is outlined below, combined with an abridged glossary of names associated at times with eyepieces in general.

Abbe, Ernst: German designer of original orthoscopic eyepiece and many other systems.

achromatic: Coined by Bevis in 1760 to indicate a system producing color-free images. In modern usage, it means that two widely-separated colors are brought to a common focus. Greek: without + color.

Airy, Sir George: English astronomer. Improver of Huygenian and terrestrial oculars. (See Eyepiece Constructions Nos. 18, 20 and 63)

Ampliplane: Trade name for a well corrected photomicrographic amplifier similar to Zeiss' Homal. Mfd. by Bausch & Lomb (Rochester, N. Y.), occasionally misused as a Barlow lens. Latin: large + flat.

anastigmatic: Loosely applied to photographic objectives and to eyepieces to imply freedom from astigmatism. Greek: throughout + point.

aperture: The free opening of a lens or a system, as distinguished from its diameter.

aperture, critical: The f number of a system at which definition deteriorates beyond a given tolerance.

---

[2] See appendix on "Prism Diagonals," at end of chapter.

aperture ratio: Frequently called f number. The ratio of aperture to equivalent focal length. 1:4.5 indicates an aperture 1/4.5 of the focal length, or, $f/4.5$.

aplanatic: A system corrected simultaneously for comatic and axial spherical aberrations. Usually but not necessarily achromatic. Widely misused. Greek: without + planets, *i.e.*, blurs.

apochromatic: Introduced by Abbe circa 1885 to describe his new microscope objectives. Modern meaning: three wavelengths joined axially at a common focus. Greek: from + without + color, "free from even traces of color."

astigmatic: Afflicted with astigmatism. Greek: not + point.

compensating: Originally applied by Abbe to eyepieces computed to compensate and neutralize the heavy lateral chromatism of his apochromats. Strictly speaking, any ocular which compensates one or more aberrations outstanding elsewhere in an instrument.

Davidson: Early Scottish optician. Popularizer of the compound eyepiece (No. 62) as the Davon Super Micro-telescope.

diopter: Unit of lens power. Power in diopters = 1/efl in meters. Infrequently used in U. S. A. outside ophthalmic field. Greek: by means of seeing.

disk, Airy: The spot of light forming the center of the diffraction image of a point object. Diameter = $1.85\lambda f'/A$, approximately, where λ = wavelength, f' = focal length, and A = aperture.

disk, Ramsden: The exit pupil of an instrument. The image, formed by an eyepiece, of the entrance stop of a system, such as R, Figure 31. The eyepoint is at the center of the Ramsden disk. Diameter = Af_2'/f_1', where A = aperture of system, f_2' = focal length of eyepiece and f_1' = focal length of objective or mirror.

Erfle, Heinrich: Optical designer of Jena, Germany. Eyepieces (Nos. 32, 33, 37) and military, particularly binocular, instruments.

Euryscopic: Trade name for wide-field oculars mfd. by Ferson Optical Co. (Biloxi, Miss.). Greek: wide – to see.

Euryskop: Trade name of photographic objectives, now obsolete, mfd. by Voigtlander.

eyepoint distance (e.p.d.), eye relief: Distance from back surface of eyepiece to entrance pupil of the eye. Varies with focal length of objective and with focal length and magnification of erector, if used. Without erector, e.p.d. = b.f.l. × f_2^2/f_1 where b.f.l. = back focal length of eyepiece, f_1 = focal length of objective and f_2 = focal length of eyepiece. With erector

$$\text{e.p.d.} = \text{b.f.l.} \quad \frac{f_2^2(Mf_1 - f_3)}{M^2 f_3 f_1}$$

approximately, where M = magnification of erector, f_3 = focal length of erector. Examples:

	f_1	f_2	b.f.l.	f_3	M	e.p.d.
a.	100,	2	0.5			0.54
b.	10	2	0.5			0.9
c.	10	2	0.5	2	1	3.

approx.

Field of view, apparent: 2α in Figure 21. Not a constant for any one eyepiece, for it varies with e.p.d., decreasing as e.p.d. increases field of view, real. The angular field in the object space. β in Figure 3. Equal to apparent field of view ÷ magnification of entire instrument.

focal length, back: (b.f.l.) Distance from last surface of a lens or a system to the focus of parallel incident rays. L' in Figure 30. Paraxial focus is the one usually employed.

focal length, equivalent: (e.f.l. or efl) The focal length of a simple lens equivalent in power to the system in question. $P''F'$ in Figure 30. Frequently shortened to "focal length."

focal length, flange: (f.f.l.) The distance between the focus and some physical stop, shoulder or flange. If the f.f.l. is the same throughout a series of eyepieces, the eyepieces are said to be parfocal, for each can be substituted for any other without the need for refocusing.

f *number, f/number:* (f/No.) A measure of the potential brightness of the image. See aperture ratio.

fovea centralis: Small depression in retina of the eye, where vision is most acute. Latin: small pit.

Gauss, Karl: German mathematician and designer. Inventor of auto-collimating eyepiece (No. 74).

Holoscopic: Trade name for eyepieces, etc., largely microscope and photographic. Mfd. by W. Watson and Sons (London). Greek: entire + to see.

Hastings, Charles: American professor and designer. (Nos. 23, 25, 27).

Hyperplane: Trade name for oculars, largely microscope. Mfd. by Bausch & Lomb. Hybridized: Greek overly + Latin flat.

isokumatic: Coined by Hastings to indicate axial and lateral apochromatism. Greek: equal + wave. (11)

Kalliscopic: Trade name for oculars and objectives. Mfd. by Ferson Optical Co. Greek: beautiful + to see.

Kellner, C.: German optician. Inventor of ocular No. 21.

König, Albert: German designer of eyepieces, objectives, etc. Prolific. See Nos. 35, 36, 41.

Lamont-Abbe: Type of especially good, prism-illuminated auto-collimating eyepiece, No. 75. Mfd. by Gaertner Scientific Corp. (Chicago).

Lens, Barlow: Negative element placed between entrance stop and primary image to increase efl.

Lens, Bertrand. Positive element placed between entrance stop and primary image. Converts eyepiece to microscope, which can be used to examine principal surfaces of the objective. Used in petrographic microscopes to examine interference figures of specimens. Not used in telescopes. Frequently confused with Barlow lens.

monocentric: Type of eyepiece with all radii struck from a common center. First made by Steinheil.

orthokumatic: Coined by Hastings to indicate axial apochromatism with lateral chromatism. Greek: true + wave. (11)

orthoscopic: Any eyepiece corrected for distortion. Originated by Abbe about

1880. First made by Zeiss. Name now used by many makers. Greek: true + to see.

pancratic: Term signifying variable power. Pancratic oculars have elements movable simultaneously at rates proper to change magnification without alteration in image sharpness. (Nos. 65–67) Greek: all + power.

parfocal: See focal length, flange.

Periplan, Periplanatic: Trade names for eyepieces, largely microscope. Mfd. by E. Leitz (Wetzlar, Germany and New York, N. Y.). Hybridized: Greek around + Latin flat.

platyscopic: British term used to imply good lateral correction in oculars, etc. Similar to American misuse of aplanatic to denote flat field. Greek: flat + to see.

Ramsden, Jesse: English optician. Inventor of early eyepiece, etc.

Selsi: Trade name for eyepieces and telescopes. Mfd. by Busch.

stigmatic: Sharp. Free from astigmatism. Anastigmatic. Greek: point or dot. Used by Dallmeyer as trade name for old photographic objective.

Telaugic: Trade name for wide-field oculars. Mfd. by James Swift & Son, Ltd. (London). Greek: distant + luster.

Tolles, R. B.: American maker, but possibly not inventor, of solid ocular.

working distance: Free space between field lens or its mount and the primary image.

Eyepiece Design (10), (20), (21), (24)

The human eye, as a part of any visual instrument, should be considered in the eyepiece designer's computations. As practically an air-water lens system, the eye is chromatically undercorrected by approximately ¼ diopter at both *C* and *F* wavelengths. It is, in general, spherically undercorrected for pupil apertures up to 3 mm. Above 3 mm, however, eyes vary markedly in spherical correction, all the way from marked undercorrection to serious overcorrection. This view is not universally held (2). Fortunately, each eye is accustomed to seeing all objects improperly corrected spherically, within fairly wide limits; so deliberate compensation is not needed. Strangely enough, the eye is able to perform noticeably better when its inherent chromatism is corrected. This has been recognized for decades and proper chromatic overcorrection has been deliberately introduced in the designs of the best makers of optical instruments. Direct confirmation of such improvement by hypochromatisation has been published (2).

The extra-axial aberrations of the eye are large, but can be neglected completely in designing all the optical systems of interest to TNs, because the eye automatically turns to present the image of interest to the fovea. (In instruments designed for certain opthalmological uses, the lateral ocular aberrations are of importance.)

The eye is accustomed to accepting a point object as sharp if it subtends 1 minute of arc or less in the object space. Therefore, any axial aberration which gives a blur subtending decidedly less than this can be considered as corrected. The extra-axial aberration tolerances can be somewhat more liberal for good performance, going up to 5 minutes at the edge of a wide field when a large field is of primary importance.

A description of the optical characteristics of the average normal eye can be found in many publications (1), (3), (4).

When an optical designer is called upon to develop a new ocular design, it may be because the many specifications in the literature do not offer a suitable eyepiece for some particular instrument, or the request may be for a particular improvement in some existing system. Whatever the reason, the designer will probably proceed as follows:

1. Ascertain the amounts of the aberrations which are present in the image which the ocular is to magnify.
2. Find the effective distance from the eyepiece and diameter of the objective which is available. These can profoundly affect the extra-axial performance, and may be greatly altered by the erecting system, if one is used.
3. Set up the performance tolerances for the instrument as a whole. If inconsistencies are found, compromises or additions are made at this point. For example, should a mesh or grid type reticle be required, this would normally call for a flat tangential field in the ocular, but the available objective-erector might have a strongly curved focal surface. To surmount this difficulty either a curved reticle, a supplementary field flattener or redesign of the system would probably be necessary.
4. Select the simplest existing available eyepiece design which he feels from experience to be most nearly suitable.
5. Arithmetically scale this design to the proper focal length and algebraically determine whether or not the aberrations of the ocular match those of the rest of the instrument within the necessary tolerances. If not, he will now make changes in radii, powers, glasses, etc., which he thinks will improve the picture and repeat his algebraic work. Perhaps but one aberration is far afield. Then, the worker will pick the surface or the medium which contributes most strongly to this one error, set the equation dealing with the aberration equal to zero and solve, if possible, for the power or glass necessary. If the change proves not to have brought the remaining faults outside the tolerances set for them, the algebraic work is done.
6. If no satisfactory solution can be found or if analytic methods indicate the futility of making the changes which are possible, another type of design with more degrees of freedom (number of elements, types of glass, etc.) is taken and the investigation begun again.
7. When a suitable compromise is found, the rapid but relatively inaccurate algebraic methods are dropped and a number of properly chosen rays is traced trigonometrically through the system to rigorously test the work. Almost inevitably, violations of the tolerances will be found.
8. A few likely adjustments are made and checked algebraically or by very rapid graphic methods (8), (19) to find whether the errors are being reduced. If not, the changes are repeated in the proper direction until the rapid methods indicate the desired reduction.
9. The designer, whose hair is now rumpled, whose eyes are red and whose

fingernails no longer exist, now repeats the trig tracings. Very probably, the tolerances are met satisfactorily. If not, 8 and 9 are repeated until (a) the design is perfected, (b) it is proved that a more complex system is needed or (c) the designer is taken away for psychiatric observation.

10. Strict scale drawings are now made and sufficient rays are traced graphically to be sure that nothing physical has gone awry which might cause trouble, such as a bending which gave negative edge or center thickness to an element or an increase in eyepoint distance which caused a stop to cut the field angle. Finally, if the design is a radically new one, the ultra-conservative designer will carefully check and repeat all computations and have a pre-production specimen manufactured for testing, especially if he has relied heavily on algebraic methods for wide field computations, for he knows that higher order aberrations (5), (6) which are not subject to analytical treatment may possibly have some adverse effect. On the other hand, if his main reliance has been on trigonometric solutions, he has traced only four or five skew rays, because the average human life is not interminable, seem what it may at times; so he is sure that he doesn't know exactly what every ray will do, hence the test specimen will be made in any event. On non-radical systems, however, only routine rechecking is needed for the general performance of the customary types is known beforehand.

As outlined above, the accurate design of eyepieces appears difficult. It is, at first, and it is always tedious in comparison with the design of objectives. Five-place accuracy is required. Expensive and impermanent surfaces, *e.g.*, very steep curves, or similar but not identical radii, and elements of soft and hygroscopic glasses not protected by cement, must be avoided. However, the mathematics necessary is not so involved that the average enthusiastic TN cannot learn it from texts or in night school. The equipment is not too costly and, if one has a natural aptitude for figures, he should find genuine pleasure and satisfaction in designing an occasional system for his own use. Unless he has unusual persistence and tenacity of purpose, however, and an inquisitive but plodding temperament, the hobbyist should avoid optical computation and design.

He who yearns to compute optical systems can be well advised to first study and understand **ONE** good text on elementary optics, such as Valasek (9), then to master the first 71 pages of Conrady (10), before computing anything. He can then compute a doublet objective or two. After the doublets, a good exercise would be an achromatized Ramsden eyepiece to exactly match one of the objectives, investigating the entire field in *C*, *D* and *F* colors at 2° intervals, while finishing Conrady. After Conrady has been assimilated, the enthusiast will be able to pick from the literature the proper tools to allow him to work on any chosen system—the alegbraic methods of T. Smith (7) and Herzberger (18), for examples.

Notwithstanding the fact that many eyepieces are difficult to design and are complex, extremely simple ones can serve well for certain purposes. Galilei discovered much with a telescope which used the simplest type of negative ocular—a single biconcave lens.

To show that eyepieces need not be elaborate, Mr. John M. Holeman has made several of Coca-Cola bottle glass, Lucite and ordinary plate glass, many of which performed fairly well, as judged by the comments of TNs to whom he submitted them. It is quite true that a 2-inch eyepiece used with any fairly good telescope to examine the moon during its brighter phases will give a good impression regardless of its construction. This is because the iris of the eye contracts so strongly under high illumination that the effective *f* number of the objective-ocular combination rises to such a figure that most aberrations have little effect on the sharpness of the image. After thus viewing the full moon for one minute, the pupil of a friend's eye had contracted to approximately 1.5 mm, when I examined it a fraction of a second after he had removed his eye from the ocular. At this opening, the eye was perceiving the image formed at $f/33$ (50 mm ocular efl ÷ 1.5 mm aperture).

Under conditions favoring maximum resolution, a properly designed and constructed eyepiece is essential. On nebulae, clusters, planets, and double stars a telescope with high grade doublet objective or mirror and the best possible eyepiece will easily outperform another telescope with the most costly apochromatic objective if equipped with an indifferent ocular.

When used in the neighborhood of $f/4$ to $f/8$, especially if a wide angle is covered, the differences among eyepieces become glaringly evident. It is only with narrow fields and apertures of $f/20$ to $f/50$ that run-of-the-mill oculars can be used indiscriminately.

Microscope Oculars

In general, microscope eyepieces are not particularly suitable for use in astronomical telescopes because of the following factors.

1. Their outer diameter is usually 23.2 mm (0.91 inch) which is too small for low and medium powers and inconvenient.

2. They are designed for a tube length of 160 to 180 mm (6.3 to 7.1 inches), which makes their already short e.p.d. shorter when used with telescopes of the usual length of 1 to 3 meters (40 to 120 inches) and upsets certain corrections.

3. The average microscope ocular works at $f/27$ to $f/60$; so it is uncommon to find one with a good critical aperture number.

4. The image fields of most microscope objectives are much more strongly curved than those of telescope objectives. Therefore, good microscope eyepieces are heavily overcorrected for field curvature from the astronomical standpoint. This gives rise to adverse astigmatic and comatic conditions.

The above remarks should not discourage the trial use of microscope eyepieces. For non-critical applications, an occasional one is found which will be satisfactory. In fact, an instrument synthesized from odds and ends might possess faults which the average microscope ocular would tend to correct.

Custom-built Eyepieces: On special order, some firms will incorporate certain features in an ocular which are especially useful to the critical user. These features may be one or more of the following:

a. Toroidal or cylindrical eyelens surface to compensate for the user's astigmatism.

b. Modified eyelens radius for correction of extreme myopia or hypermetropia.

c. Illuminated micrometer reticle, graduated in minutes of arc, to be used on a telescope of stated efl.

d. Adjustable mount, permitting a variable separation of components. This enables the user to obtain the best possible compromise performance under varying conditions of use.

War Surplus Eyepieces: Soon after the close of World War II, obsolete, used and otherwise surplus military instruments became available for public purchase in large numbers and at small fractions of their cost. The eyepieces of these instruments are of such varied types that no general comment can be made regarding them, save to say that few of them are proper for critical, high-resolution use in conventional astronomical telescopes. Practically all of them, however, give fair performance at $f/30$ to $f/15$ and, since most fire control instruments use wide field oculars, a large proportion of the long-focal-length systems can be used for superb finder oculars.

Aside from the above, no advice can be given other than, "Try them. If they satisfy, use them."

A few of the eyepieces available on the surplus market are:

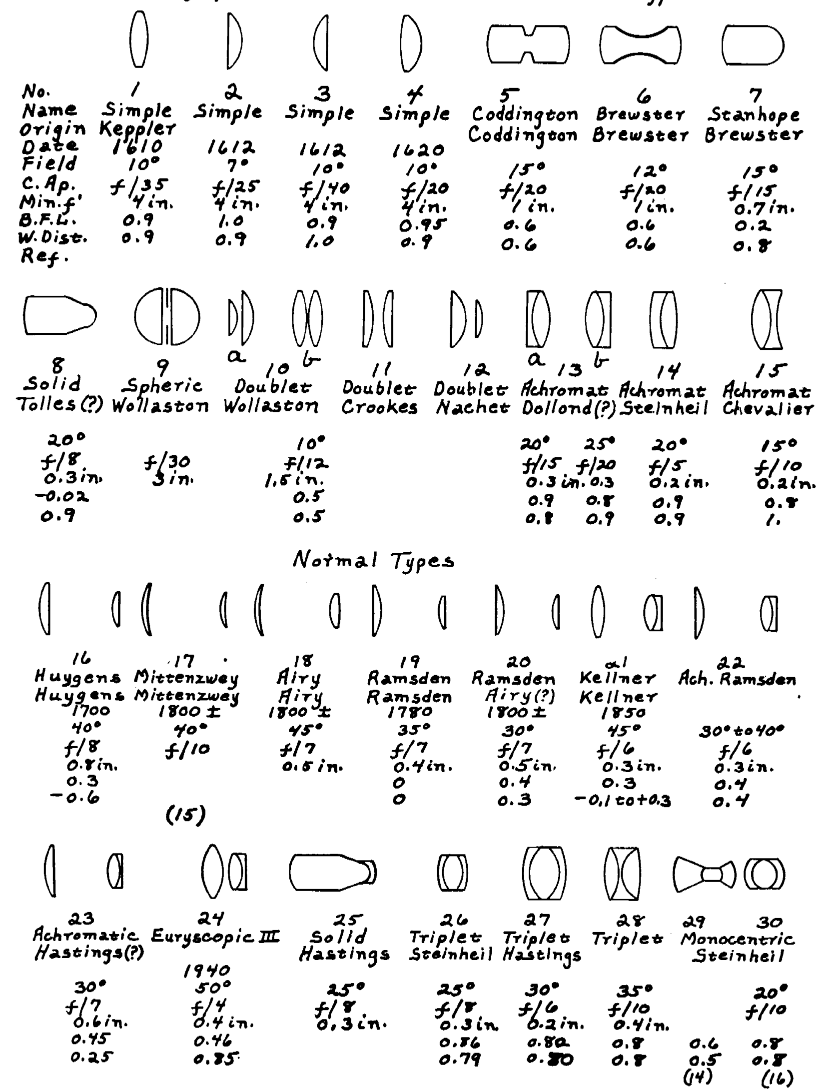
No. 21	0.75	inch and 1.1 inch efl.
22	1.4	
33	0.625	and 1.00
34	1.5	
42	1.0	and 2.3

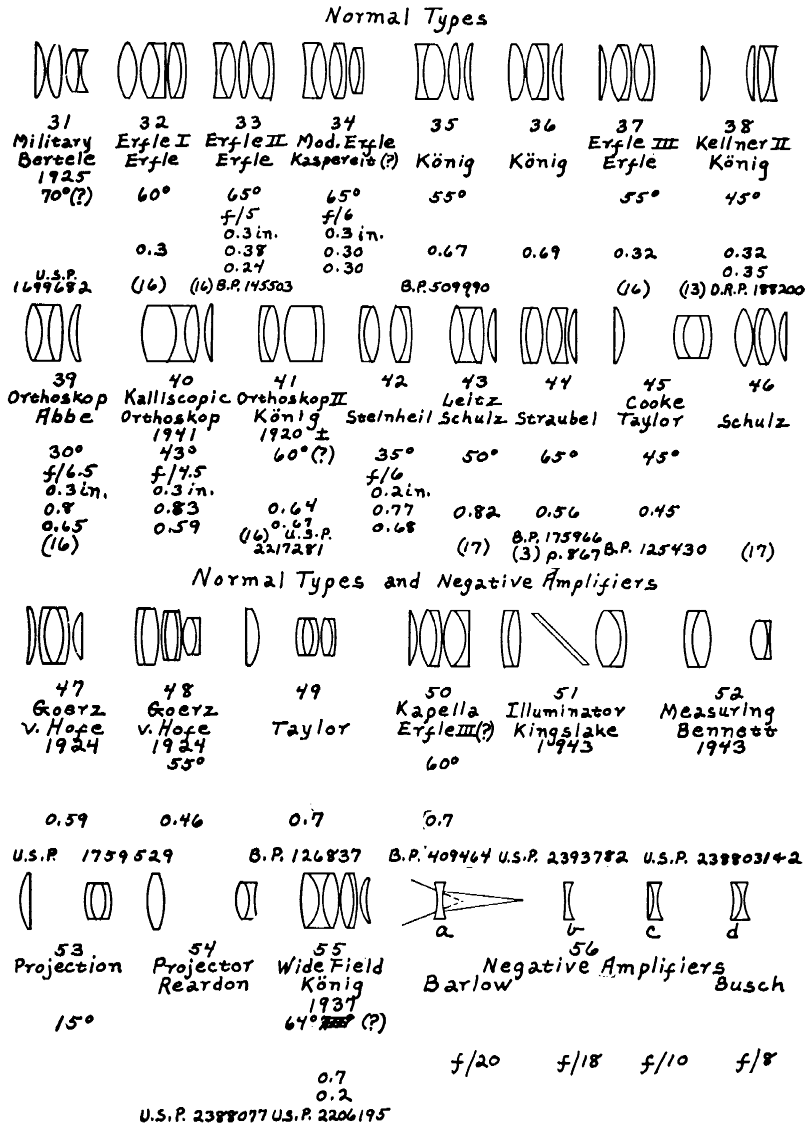
Synthesis of Eyepieces: For some special uses, the cost of an especially designed ocular would be prohibitive. In such cases, an eyepiece can frequently be synthesized from odds and ends such as war surplus elements. Using what is at hand, the TN should throw caution and theory out the window and start with two, then three and later four simple lenses or achromats and should systematically vary the separations and orientations of his stock, using the objective or mirror which he wishes to furnish the primary image as the constant part of his system. In some cases, acceptable results can be obtained in a short time—especially if an optical bench is available and the TN knows exactly what he desires beforehand.

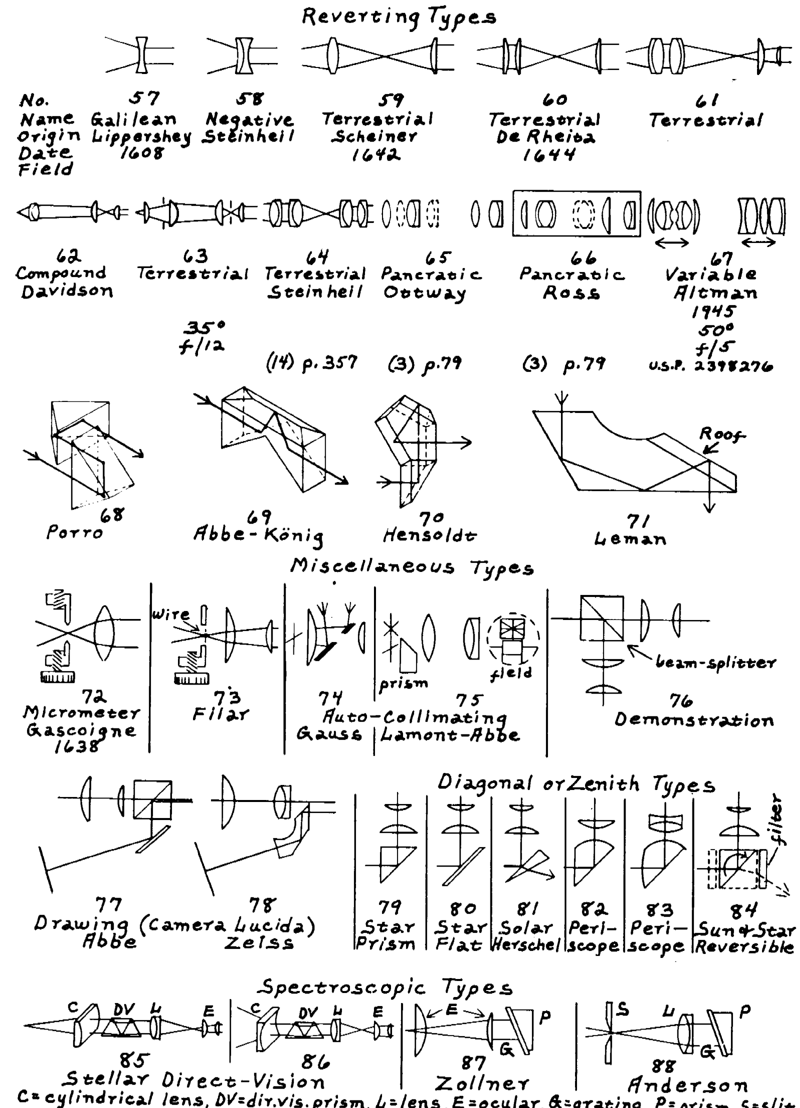
Eyepiece Constructions

On the following pages are illustrated various types of lenses and optical systems which have been used as eyepieces from time to time prior to mid-century. For the purposes of this chapter, the entire optical system past the objective is considered to magnify the primary image and therefore to be an eyepiece. In each case, the object is to the left of and the eye is to the right of the specimen.

Eyepiece Constructions — Normal Types




Normal Types
31 Military Bertele 1925 70°(?) U.S.P. 1699682
32 Erfle I Erfle 60° 0.3 (16)
33 Erfle II Erfle 65° f/5 0.3 in. 0.38 0.24 (16) B.P. 145503
34 Mod. Erfle Kaspereit(?) 65° f/6 0.3 in. 0.30 0.30
35 König 55° 0.67 B.P. 509990
36 König 0.69
37 Erfle III Erfle 55° 0.32 (16)
38 Kellner II König 45° 0.32 0.35 (13) D.R.P. 188200
39 Orthoskop Abbe 30° f/6.5 0.3 in. 0.8 0.65 (16)
40 Kalliscopic Orthoskop 1941 43° f/4.5 0.3 in. 0.83 0.59
41 Orthoskop II König 1920± 60°(?) 0.64 0.67 (16) U.S.P. 2217281
42 Steinheil 35° f/6 0.2 in. 0.77 0.68
43 Leitz Schulz 50° 0.82 (17)
44 Straubel 65° 0.56 B.P. 175966 (3) p. 867
45 Cooke Taylor 45° 0.45 B.P. 125430
46 Schulz (17)
Normal Types and Negative Amplifiers
47 Goerz v. Hofe 1924 0.59 U.S.P. 1759529
48 Goerz v. Hofe 1924 55° 0.46
49 Taylor 0.7 B.P. 126837
50 Kapella Erfle III(?) 60° 0.7 B.P. 409464
51 Illuminator Kingslake 1943 U.S.P. 2393782
52 Measuring Bennett 1943 U.S.P. 2388031+2
53 Projection 15°
54 Projector Reardon
55 Wide Field König 1937 64° (?) 0.7 0.2 U.S.P. 2388077 U.S.P. 2206195
a b c d
56 Negative Amplifiers
Barlow f/20 f/18 f/10 Busch f/8


Reverting Types
No. Name Origin Date Field
57 Galilean Lippershey 1608
58 Negative Steinheil
59 Terrestrial Scheiner 1642
60 Terrestrial De Rheita 1644
61 Terrestrial
62 Compound Davidson 35° f/12
63 Terrestrial
64 Terrestrial Steinheil (14) p. 357
65 Pancratic Ottway (3) p. 79
66 Pancratic Ross (3) p. 79
67 Variable Altman 1945 50° f/5 U.S.P. 2398276
68 Porro
69 Abbe-König
70 Hensoldt
71 Leman
Roof
Miscellaneous Types
72 Micrometer Gascoigne 1638
wire
73 Filar
prism
field
74 Auto-Collimating Gauss
75 Lamont-Abbe
beam-splitter
76 Demonstration
Diagonal or Zenith Types
77 Drawing Abbe
78 (Camera Lucida) Zeiss
79 Star Prism
80 Star Flat
81 Solar Herschel
82 Peri-scope
83 Peri-scope
84 Sun+Star Reversible
filter
Spectroscopic Types
C DV L E
85 Stellar
86 Direct-Vision
E G P
87 Zollner
S L G P
88 Anderson
C=cylindrical lens, DV=dir.vis.prism, L=lens, E=ocular, G=grating, P=prism, S=slit.

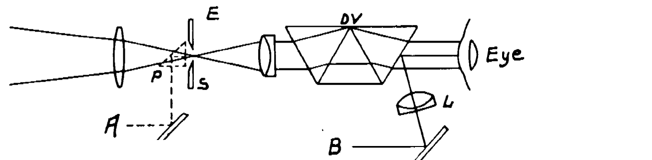
The specimens are grouped as follows: Normal eyepieces which do not reorient the normal, inverted primary image; reverting eyepieces which erect the image; instrument oculars, used for measurement, demonstration and sketching; diagonal eyepieces for deviation of the axis and spectroscopic eyepieces, with which the spectra of images can be studied.

Beneath each illustration are tabulated the following data, when available: (In case both literature and actually determined values are available, the actual value of illustration is reported.)

Serial number in this chapter.

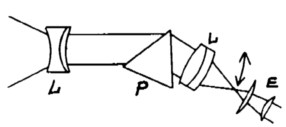
Common name in U. S. A.

Spectroscopic Types

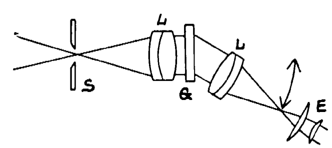


89 Abbe

Comparison spectra (½ slit) via A. Reference scale via B.



90
Stellar Prism



91
Prominence Grating

Origin: Inventor, designer, first user or first manufacturer.
Apparent date of first use.
Apparent image field (2a Figure 21).
Critical Aperture: f No. at which image deteriorates noticeably.
Minimum efl which can be employed without excessive chromatism.
Back focal length or eye relief for an objective of $f' = \infty$ (L' Figure 30).
Working distance or clearance between primary image and ocular.
Reference in the literature, including patents, to the specimen type.

An effort has been made to compile strictly comparable performance data for the eyepiece types described. Discrepancies will be noticed, however, which make some introductory remarks desirable.

Field of view, when taken from patent specifications, advertising literature or other questionable sources is followed by a question mark. Otherwise, it represents the actually determined value obtained from examination of one or more specimens. The angle given is the extent of fairly good definition when the specimen is used at its critical aperture. At smaller apertures, the

Eyepiece Prescriptions

No.	1	2	3	4	5	6
r_1	0.977	∞	0.517	3.22	0.689	0.689
d	0.326	0.21	0.21	0.188	1.378	1.378
D	0.5	0.5	0.5	0.5	0.75	0.75
G	517/645	517/645	517/645	517/645	525/590	525/590
r_2	−0.977	−0.517	∞	−0.537	−0.689	−0.689
A					0.25	0.20
Source	Comp.	Comp.	Comp.	Comp.	Anal.	Comp.

No.	7	8	8	9	10a	14
r_1	1.158	0.675	0.576	0.683	∞	0.745
d_1	1.26	1.600	1.554	0.680	0.10	0.032
D_1	0.75	0.75	0.80	1.35	0.50	0.30
G_1	525/590	514/650	512/636	525/590	525/590	604/381
r_2	−0.556	−0.421	−0.401	∞	−0.50	0.258
S_1				0.06	Var.	0
A				0.30		
r_3				∞	∞	0.258
d_2				0.680	0.20	0.143
D_2				1.35	1.10	0.30
G_2				525/590	525/590	517/645
r_4				−0.683	−1.333	−0.926
Source	(11)	(12)	Anal.	Comp.	Anal.	Comp.

No.	16	18	19	20	20	21
r_1	1.13	0.952	∞	∞	∞	2.64
d_1	0.19	0.238	0.28	0.35	0.20	0.202
D_1	1.10	1.43	0.90	1.22	1.00	0.98
G_1	514/636	525/590	523/590	525/595	514/64	517/645
r_2	∞	2.62	−0.559	−0.817	−0.801	−1.263
S_1	1.23	2.00	0.80	0.735	0.77	0.71
r_3	0.397	0.594	0.559	0.743	0.727	0.718
d_2	0.085	0.386	0.15	0.18	0.10	0.218
D_2	0.40	1.07	0.38	0.72	0.6	0.637
G_2	514/636	525/590	523/590	525/595	514/64	541/600
r_4	∞	−3.56	∞	∞	∞	−0.550
S_2						0
r_5						−0.550
d_3						0.023
D_3						0.637
G_3						621/362
r_6						−4.08
Source	(12)	Comp.	Anal.	Anal.	(12)	Anal.

field may be larger and, if excellent edge definition is demanded, it will be drastically reduced in many cases. The performance of eyepieces is discussed in general terms throughout the literature. (3) pp. 74–80, (12), (13), (14), (15), (16), (22), (23), (25).

Critical apertures, b.f.l. and working distances were determined especially for this chapter on 28 specimens, representing 19 types of the first 55 described. The remaining entries were obtained from analyses made as long ago as 1923 and from the literature. Being uncertain, these values are reported to but one significant figure.

No.	21	21	22	23	25	27
r_1	1.61	∞	∞	1.033	0.871	0.811
d_1	0.28	0.22	0.184	0.091	1.16	0.096
D_1	1.00	0.90	0.974	0.55	0.75	0.534
G_1	523/586	510/634	511/635	523/586	514/650	617/364
r_2	−1.61	−0.881	−0.968	−6.36	−0.240	0.404
S_1	0.91	0.783	0.649	0.762	0	0
r_3	0.685	0.734	0.852	0.529	−0.240	0.404
d_2	0.230	0.23	0.368	0.07	0.07	0.216
D_2	0.70	0.63	0.80	0.344	0.45	0.534
G_2	540/600	592/582	611/572	511/635	615/337	524/594
r_4	−0.538	−0.499	−0.524	−0.529	−0.509	−0.402
S_2	0	0	0	0		0
r_5	−0.538	−0.499	−0.524	−0.529		−0.402
d_3	0.03	0.05	0.066	0.03		0.096
D_3	0.70	0.63	0.80	0.344		0.534
G_3	621/362	613/370	648/338	617/366		617/364
r_6	−3.64	∞	−6.50	∞		−0.809
Source	Anal.	(13)	Anal.	Des.	(12)	Anal.

Minimum f' was estimated from experience alone.

The illustrations given are not necessarily to scale nor are the spatial sketches in true linear perspective. Distortion is present in most examples for two reasons: (a) to exaggerate for greater clarity and (b) because the writer is no draftsman.

Eyepiece Prescriptions

The prescriptions or elements of construction of several types of oculars are listed following the eyepiece types. Construction data from patents are not included for several reasons. Prescriptions for some patented eyepieces can be found by consulting the patents listed in the eyepiece types section. The abbreviations are:

No. Serial number from the eyepieces types section.

r_1, r_2 etc. Radius of curvature of first, second, etc. surface, + if centered to the right, − if centered to the left.

d Axial thickness

D Diameter

A Aperture.

S Axial air thickness or separation.

G Glass type, according to International Critical Tables notation, $1000\ (N_D - 1)/10\ \nu_D$. (517/647 indicates $N_D = 1.517$, $\nu_D = 64.7$)

No.	28	29	33
r_1	1.86	0.615	−3.03
d_1	0.053	0.342	0.06
D_1	0.33	0.75	1.47
G_1	525/600	615/370	617/366
r_2	−1.33	0.273	1.40
S_1	0	0	0
r_3	−1.33	0.273	1.40
d_2	0.047	0.614	0.54
D_2	0.33	0.3	1.47
G_2	576/412	518/600	517/645
r_4	0.470	−0.341	−1.40
S_2	0	0	0.04
r_5	0.470	−0.341	2.80
d_3	0.117	0.597	0.31
D_3	0.33	0.65	1.47
G_3	525/600	615/370	517/645
r_6	−0.933	−0.939	−2.80
S_3			0.02
r_7			1.18
d_4			0.48
D_4			1.37
G_4			517/645
r_8			−1.42
S_4			0
r_9			−1.42
d_5			0.07
D_5			1.37
G_5			617/366
r_{10}			−6.14
Source	Anal.	(14)	An. 1943

Source of data: Comp. means computed by author. Anal. = analysis of actual eyepiece by author. ( ) indicates literature reference at end of chapter. The unit of measurement is the efl. of the specimen.

Testing

The best procedure to follow in eyepiece testing is the direct one. Mount the eyepiece in the telescope and observe the axial and extra-axial images of as great a variety of objects as possible, under all possible conditions. Simultaneously, compare the performance of known oculars. By this practice, the behavior of an eyepiece with the observer's eye and one particular objective or mirror can be ascertained without doubt. Such a comparison should include

No.	33	33	34	38	42	56a
T_1	−2.98	−2.925	−5.08	∞	2.522	−0.979
d_1	0.06	0.040	0.053	0.15	0.046	0.05
D_1	1.58	1.38	2.22	0.9	0.796	0.5
G_1	621/363	615/368	617/366	510/634	649/338	517/645
T_2	1.38	1.365	1.43	−1.00	0.788	0.979
S_1	0	0	0	0.80	0	
T_3	1.38	1.365	1.43	0.803	0.788	
d_2	0.54	0.514	0.432	0.155	0.182	
D_2	1.58	1.38	2.22	0.9	0.796	
G_2	517/640	517/643	517/645	589/612	517/645	
T_4	−1.38	−1.353	−1.43	∞	−1.138	
S_2	0.07	0.048	0.063	0	0.055	
T_5	2.80	2.661	1.71	1.25	1.138	
d_3	0.31	0.323	0.515	0.175	0.182	
D_3	1.58	1.38	2.22	0.7	0.796	
G_3	516/640	518/640	517/645	510/634	517/645	
T_6	−2.80	−2.663	−1.14	−0.76	−0.788	
S_3	0.01	0.040	0	0	0	
T_7	1.18	1.154	−1.14	−0.76	−0.788	
d_4	0.47	0.475	0.087	0.05	0.046	
D_4	1.42	1.25	2.22	0.7	0.796	
G_4	516/640	517/640	650/336	613/370	649/338	
T_8	−1.42	−1.402	−2.80	2.00	−2.522	
S_4	0	0	0.005			
T_9	−1.42	−1.405	1.36			
d_5	0.065	0.069	0.448			
D_5	1.42	1.25	1.92			
G_5	621/363	617/365	517/645			
T_{10}	−6.12	−5.85	−0.910			
S_5			0			
T_{11}			−0.910			
d_6			0.70			
D_6			1.92			
G_6			648/340			
T_{12}			−2.24			
Source	An. 1930	An. 1947	An. 1946	(13)	Comp.	Comp.

as objects the full moon, the gibbous moon, Venus, Saturn, faint double stars on a black night and a sunlit landscape. Obviously, the test cannot be completed quickly. Just as obvious is the fact that the results are not reportable numerically and therefore cannot be shared on a uniform basis with other TNs.

Certain characteristics of eyepieces can be determined very well with the aid of an optical bench. Since bench methods are applicable to many systems other than eyepieces, no such methods will be described here. Instead, a general chapter on the subject has been prepared and the interested reader will find eyepiece testing mentioned there.

No.	56d	57	58	61	62	63
T_1	−1.316	−1.21	−0.740	2.29	9.80	∞
d_1	0.085	0.05	0.08	0.073	0.262	0.148
D_1	0.30	0.48	0.42	0.71	1.67	0.914
G_1	649/338	611/588	605/380	604/380	616/366	523/586
T_2	−0.398	1.21	−0.250	0.812	2.175	−1.047
S_1	0		0	0	0	2.14
T_3	−0.398		−0.250	0.812	2.175	
d_2	0.030		0.035	0.224	0.46	
D_2	0.30		0.42	0.71	1.67	A0.218
G_2	517/645		515/648	517/645	573/568	
T_4	0.618		0.937	−3.175	−5.98	
S_2				0.55	28.0	0.75
T_5				+3.175	2.60	∞
d_3				0.224	0.436	0.120
D_3				0.71	2.53	0.725
G_3				517/645	514/636	523/586
T_6				−0.812	∞	−1.256
S_3				0	2.83	4.26
T_7				−0.812	0.914	1.443
d_4				0.073	0.195	0.262
D_4				0.71	0.92	1.42
G_4				604/380	514/636	523/586
T_8				−2.29	∞	∞
S_4				3.40		0.96
T_9				∞		
d_5				0.20		
D_5				1.00		A0.941
G_5				514/64		
T_{10}				−0.801		
S_5				0.77		1.450
T_{11}				0.727		0.786
d_6				0.10		0.154
D_6				0.3		0.695
G_6				514/64		523/586
T_{12}				∞		∞
Source	Comp.	Comp.	Anal.	Comp.	Comp.	Comp.

Series of Eyepieces

It has been the writer's opinion for many years that eyepieces sold under a single name or as a certain type should perform similarly within a given series in such a way that the user would be able to substitute various powers without inconvenience. This entails parfocalization, a constant large eye relief, constant degree of correction of aberrations and constant apparent field of view when used with a specific objective or mirror.

Apparently, no such homologous series of eyepieces is commercially made at present.

It is considered that this chapter will have been well worth the trouble entailed in its preparation if, by its aid, astronomical eyepieces tend to receive more nearly the attention which the author considers to be due them.

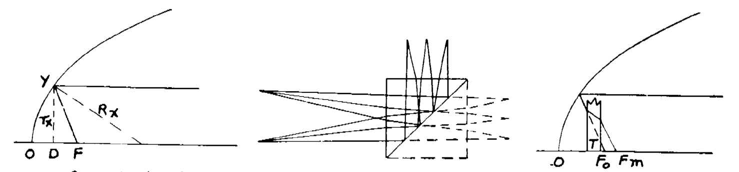
REFERENCES

1. Hardy and Perrin, The Principles of Optics, 1932, p. 188. New York, McGraw-Hill Book Co.
2. van Heel, *Jour. Opt. Soc. Am.*, Vol. 36, No. 4, pp. 237–239 (1946).
3. Glazebrook, Dictionary of Applied Physics, 1923, Vol. IV, pp. 70–74. London and New York, The Macmillan Co.
4. Martin, Applied Optics, 1932, Vol. I, retitled 1949 Technical Optics. New York, Pitman Publishing Corp.
5. Bennett, *Bur. Stds. Jour. Res.*, Vol. 9, No. 2, pp. 187–225 (1932), Washington, D. C.
6. Conrady in *Photography as a Scientific Implement*, pp. 95–99, 1934.
7. Smith, T., *Transactions Opt. Society*, Vol. 23, p. 311; Vol. 25, p. 117; Vol. 28, p. 285. Imperial College of Science and Technology, London.
8. Dowell, *Proceedings of the Optical Convention*, 1926, pp. 965–981. Imperial College of Science and Technology, London.
9. Valasek, *Elements of Optics*, 1932. New York, McGraw-Hill Book Co.
10. Conrady, *Applied Optics and Optical Design*, 1929. London and New York, Oxford University Press.
11. Hastings, *New Methods in Geometrical Optics*, 1927, pp. New York, The Macmillan Co.
12. ATM
13. Hastings in *Amateur Telescope Making*, Part VIII, Ch. II.
14. Gleichen, *Die Theorie der Modernen Optischen Instrumenten*, 1911, p. 146.
15. Ambronn, *Handbuch der Astronomischen Instrumentenkunde*, 1899, p. 355. *Transactions Cambridge Philosophical Society*. Vol. 2, 1827 and 1830.
16. König, *Die Fernrohre und Entfernungsmesser*, 1923, pp. 39–41.
17. Schultz, *Zeitschrift für Instrumentenkunde*, Nov. 1937, pp. 445–449.
18. Herzberger, *Annals. N. Y. Acad. Sciences*, Vol. 48, pp. 1–30; also several papers in *Jour. Opt. Soc. Am.*, 1943–1947.
19. Bouwers, *Achievements in Optics* (Monograph No. 1, Progress of Research in Holland During the War), 1947, pp. 67–72. New York, Elsevier Publishing Co.
20. Stempel, *Jour. Opt. Soc. Am.*, Vol. 23, No. 5, pp. 278–292 (1933). New York, American Institute of Physics.
21. Jacobs, *Fundamentals of Optical Engineering*, 1943, pp. 433–442. New York, McGraw-Hill Book Co.
22. Bell, *The Telescope*, 1922, pp. 134–149. New York, McGraw-Hill Book Co.
23. Taylor, *Journal of Scientific Instruments*, Vol. 22, pp. 43–48 (1945). London.
24. Gardner, Scientific Paper No. 550, 1927, National Bureau of Standards, Washington, D. C.
25. Holeman, *Sky and Telescope*, Vol. 7, pp. 128–130 (1948), Cambridge, Mass.

Prism Diagonals

Axial Aberration Effects

Let's assume that a perfect telescope which uses a perfect optical flat for diverting the axis 90° to the side of the tube gives perfect definition. If a perfect 90° deviation prism is substituted for the flat, the axial definition may suffer, due to the introduction of spherical and chromatic aberrations. The object of this appendix is to show the magnitude of these aberrations so that the telescope user may decide whether or not he wishes to employ a prism diagonal in conjunction with his mirror or objective.



Paraboloid — 11° Field at f/4 — Paraboloid + Prism

The left-hand drawing shows a ray from ∞ being reflected from a paraboloid in such a way that it intersects the axis at F. If the mirror is of perfect figure, all rays from a given point at ∞ will cut the axis at the same point, F, regardless of the value of the zonal radius, r_x, within the limits of diffraction theory. If, now, a prism is introduced anywhere along YF, it will act optically as if it were a plate of glass of thickness T equal to the length of the cathetus or entering face of the prism. Therefore, it is treated here as a plane-parallel plate, as in the central and right-hand drawings.

If we know the distance OF_m for every value of r_x, we can easily construct a curve which will represent the spherical aberration introduced by a right-angle prism. Also, the chromatic effects of the prism can be determined. In order to find OF_m, we need know the following data:

R_o, the radius of curvature of the central zone or twice the focal length.
r_x, the radius of any zone of the mirror or objective.
T, the length of the prism face, assuming sharp edges.
N, the refractive index of the prism material for the particular color of light to be considered.

In a previous communication (*Scientific American*, April 1941) prism aberration was described directly in terms of these variables plus R_x, the radius of curvature for a particular zone. The result was rather cumbersome. Therefore, the equations have been simplified for presentation here by the use of an angular function derived from the above variables. This function is the sine of angle OFY, which will be called angle α. Since the magnitude of α depends only on the f No. or aperture ratio of the telescope, $\sin \alpha$ and $\sin^2\alpha$ have been computed for various f numbers and are given in Table 2 as a computing aid.

Axial Spherical Aberration: Marginal spherical aberration is a commonly-considered aberration in telescopes. It is expressed as the difference between

TABLE 2

$$\sin\alpha = \frac{2r_xR_0}{R_0^2 + r_x^2}$$

f No.	sin α	sin²α	f No.	sin α	sin²α
1.0	0.470588	0.221453	5	0.099750	0.009950
1.5	.324324	.105186	6	.083188	.006920
2	.246153	.060616	7	.071337	.005089
2.5	.198019	.039211	8	.062439	.003898
3	.165517	.027395	10	.049968	.002496
3.5	.142132	.020201	12	.041648	.001734
4	.124513	.015503	15	.033324	.001110

the OF_m for the marginal ray and that of the paraxial ray. If the marginal OF_m is greater than the paraxial, the aberration is considered minus or over-corrected. Mathematically, this aberration equals

$$L_{sph} = T\sqrt{\frac{1-\sin^2}{N^2-\sin^2}} - \frac{T}{N}$$

Zonal spherical aberration may remain after the marginal error is corrected. It is frequently a maximum at the 0.7 zone and can be determined with the above formula by substituting the proper $\sin^2\alpha$ for the marginal f No. divided by 0.7. In both cases, yellow light is considered when speaking of spherical aberration. Often it is 5555A.

Axial Chromatic Aberration: The change in OF_m which occurs when two colors of light are considered is called chromatic aberration. The colors are usually near the ends of the visible spectrum. Hydrogen C and F or C and mercury g are popular pairs. The zone chosen for computing chromatism is usually the 0.7 zone although some prefer the margin. If OF_m red is greater than OF_m violet, the aberration is said to be plus or undercorrected. Its magnitude is:

$$L_{chr} = T\left[\sqrt{\frac{1-\sin^2\alpha}{N^2_{red}-\sin^2\alpha}} - \sqrt{\frac{1-\sin^2\alpha}{N^2_{violet}-\sin^2\alpha}}\right]$$

For approximate results, chromatism can be found equal to

$$T\left(\frac{1}{N_{red}} = \frac{1}{N_{violet}}\right)$$

Chromatic Variation of Spherical Aberration: Spherical aberration at a given aperture is not constant for all colors. Therefore, it is sometimes useful to know what effect to expect, for example, when photographing through filters. In order to check this, it is merely necessary to compare spherical aberration results as found for one color with the other colors of interest, substituting the proper N values for the glass used. Unless extreme aperture ratios are used, however, the effect is insignificant, as shown in Table 3.

TABLE 3

$N_C = 1.514$ $N_D = 1.517$ $N_g = 1.526$

f No.	2	3	4	8	15
T	4.0 inches	3.8 inches	2.5 inches	1.5 inch	1.25 inch
L_{sph} C	−.04679	−.01970	−.00729	−.00109	−.00026
D	−.04684	−.01969	−.00730	−.00109	−.00026
g	−.04694	−.01967	−.00730	−.00109	−.00026
⅓ Rayleigh limit	.00048	.0011	.0019	.0075	.026
L_{chr}	.02092	.01979	.01300	.00778	.00649
Rayleigh limit	.00036	.00080	.0014	.0057	.0195
$\odot_{chr}$	.00522	.00330	.00162	.00049	.00022
Airy disk	.0001	.00015	.00019	.00039	.00072

The above arbitrarily-chosen examples may give the erroneous impression that aperture ratio alone determines the aberration magnitude and that focal length is immaterial. The fact is that the second factor, prism size, is greatly affected by efl and diameter of image field.

To illustrate, compare two $f/4$ telescopes, the first, of 12-inch aperture covering a 2-inch diameter field with the image 8 inches from the axis and the second, of 4-inch aperture, 1-inch field, 4 inches off axis. Applying John M. Pierce's formula (ATM, p. 382, 1935) the first instrument will require a 3.67-inch prism while the second will need one of 1.75-inch face.

Effect on Definition: Optical designers have found through the years that the Rayleigh limit of ¼ λ of path difference due to spherical aberration is a rather large allowance, if excellent definition is required in telescopes. Therefore it is customary to consider one third, approximately, of the Rayleigh limit as standard. Considerations of contrast as well as resolving power make this desirable. On this path difference basis, the allowable longitudinal aberration is, for yellow light:

$$\text{marginal spherical} = \frac{0.000029 \text{ inch}}{\sin^2\alpha}$$

For chromatic aberration, however, the full Rayleigh limit of $\frac{0.000022 \text{ in.}}{\sin^2\alpha}$ is frequently satisfactory. The reason that the marginal spherical tolerance appears greater than the chromatic when it is in fact smaller is that optical path difference is expressed in terms of longitudinal aberration in each case. A good explanation is by Conrady in Glazebrook's "Dictionary of Applied Physics," Vol. IV, 1923, pp. 216–227.

The seriousness of the aberration effects can be judged in other ways which do not consider path differences. Knowing the longitudinal chromatic aberration, L_{chr}, the blur diameter will be found to be

$$\odot_{chr} = \frac{L_{chr}}{2A} \quad \text{where } A \text{ is the aperture ratio.}$$

If this approximates the diameter of the Airy disk, which, for yellow light, is 0.000049A, definition will not be greatly affected although slight degradation may occur.

Another way of judging sharpness is to remember that the average eye considers an image sharp if its diameter is less than 0.005 inch at 10 inches and that telescopic images are usually seen as virtual images some 10 inches in front of the eye. Therefore, if the blur diameter as determined above is of the order of 0.005 inch divided by the magnification of the eyepiece used, the blur will not be noticeable.

Unfortunately, the blur diameter of an image of a point object is not a simple function of the longitudinal spherical aberration. The diffraction nature of images makes simple geometrical treatment of spherical effects meaningless. Under some circumstances, in fact, small spherical residuals can decrease the diameter of the central disk.

A rule of thumb tolerance, which experience has shown to be valid, is to consider 0.0002 inch times the f No. squared as the maximum allowable longitudinal spherical aberration for excellent definition. According to this empirical rule, an $f/1$ system needs marginal spherical correction within 0.0002 inch of perfection whereas $f/8$ telescopes can tolerate 0.013 inch.

Again, if a mirror has been figured to the tolerance given by Wright (ATM, pp. 257–261, 1935) and the longitudinal spherical aberration is small compared with this tolerance, expressed in terms of $r^2/2R$, it is evident that image blurring will not be serious.

Extra-Axial Aberrations: Astigmatism, coma, lateral chromatism, distortion and field curvature are affected to some extent by the introduction of a prism into a telescope. They are not considered here, however, because the factors of extent of field and type of instrument have significant effects on the results, as does the prism location under certain circumstances, making computation complex. Moreover, when prisms are close to the eyepiece and fields are not wide, the effects are not serious in the average case.

As has been indicated, chromatic aberration tolerances are reached in the more common cases before violation of the spherical tolerance occurs as the f number decreases; so little overall benefit would be obtained by undercorrecting a mirror to compensate for the spherical aberration caused by a prism. If such compensation is desired, however, it can be obtained by figuring a

mirror so that knife-edge movement less than $r^2/2R$ is obtained. The proper amount will be

$$-2\left[L_{sph} + \frac{R_x\sqrt{R_x^2 - r^2} - R_x^2}{2\sqrt{R_x^2 - r^2}}\right]$$

R_x is the radius of curvature of the edge zone, or $R_o + r^2/2R$

Prism Glasses: The usual glass for reflecting prisms which are to cover small angular fields at $f/8$, $f/15$, etc. is a borosilicate crown, N_D 1.517, N_C 1.514, N_g 1.526. This is highly transparent and stable. The critical angle, δ, for yellow light with this glass is 41°. Therefore, if rays strike at smaller angles, total reflection will not occur; so the hypotenuse must be silvered—causing some light loss—or a denser glass must be employed. Flint glasses are undesirable because of their high dispersion which increases the chromatic aberrations and because flints are usually less hard and stable. It is customary, therefore, to use a medium barium crown, N_D 1.572, N_C 1.569, N_g 1.584, in wide field, high speed instruments. This glass has a δ value of 39°.

Referring back to the illustration, it can be seen that some rays, in extreme cases, hit the hypotenuse at incidence angles of even less than 39°.

Optical Bench Testing

By Horace H. Selby

An optical bench is an instrument on which optical elements and systems can be mounted and held in proper and variable relationship to one another for the purposes of analysis, demonstration and testing. There are many types and sizes, varying from simple saddle clamps riding on a wooden meter stick to intricate, massive arrangements weighing a ton or two.

By means of a nodal slide optical bench, complete telescopes and binoculars, as well as eyepieces, telescope objectives, camera lenses, enlarger objectives, magnifiers, projection lenses and lens elements can be examined for general performance. Also, many of their characteristics and properties can be determined, their various aberrations can be estimated and the radii of curvature of surfaces can be measured.

About 1820, Gauss discovered that a lens or a lens system could be accurately described in terms of axial points and that from these the foci could be measured, no matter how complex the system, so long as it produced an image of an infinitely distant object. When a lens receives parallel rays and joins them at a focus, as in Figure 1-*A*, the refracted rays behave as if they reached F' from the surface $P'Y'$. Similarly, rays propagated in the opposite direction Figure 1-*B*, appear to have reached F from PY. P and P' are called the first and the second principal points, respectively, of the lens and the surfaces PY and $P'Y'$ are called the principal surfaces. Geometrically, the principal surfaces are the loci of the junctions of the projected rays—dashed lines—and the principal points are the intersections of the principal surfaces with the axis. Mirrors and negative lenses have similar principal points (Figure 1, *C* and *D*).

When a lens is rotated slightly about its second principal point P', the focus, F', does not leave the original axis. (Figure 2.) If, then, a lens is mounted in such a manner that the image does not shift laterally when the lens is oscillated about a line perpendicular to the axis, this line must pass through P' and the focal length can be determined by measuring the distance from the axial focus to the center of rotation. When P' is used for such focometry and F' is in air, P' is referred to as the node of emergence or the exit node. P is called the entrance node. Thus, a sliding lens holder which can be rotated about a vertical axis is called a nodal slide. The use of a nodal slide is by no means limited to the determination of focal lengths.

A system of lenses, such as the photographic objective of Figure 3 or Figure 4, has the same nodal property as has a simple lens and can be treated accordingly. The single lens corresponding to a system is called the equivalent lens—dashed in Figures 3 and 4—and the focal length of all systems is therefore stated in terms of the focal length of this imaginary lens. This explains the term, equivalent focal length (efl or f').

When a lens receives divergent instead of parallel rays, as in Figure 5, it can also be oscillated about a point without causing transverse image movement. This point is called the null point and its position differs from that of the exit node. The use of the null point enables photographic objectives, erector systems, process lenses and other systems used on near objects to be tested for performance but not for determination of efl. For efl determination, the exit note is used.

A general purpose nodal slide optical bench is shown in Figure 8. The collimator comprises a paraboloidal mirror M and a pinhole illuminator P with its pinhole at the axial focus of M. S is the nodal slide, which carries the lens holder W. S can be rotated about K and the amount of rotation is indicated on J. V is a combination microscope-telescope, having a reticle C at the eyepiece focus. U is a reading microscope with cross-hairs used to read the position of the carriage X with respect to the scale N. Z is an illuminator, which may be a penlight bulb. Y represents the bench holding the apparatus. It should be sturdy. T is a transformer or battery supplying P, the brightness of which is regulated by means of the rheostat R. L, L_1 and L_2 form the optical bench proper, the right portion of which carries the slide X, to which U and V are rigidly attached. X may be provided with a graduated cross-slide similar to the crossfeed carriage of a lathe.

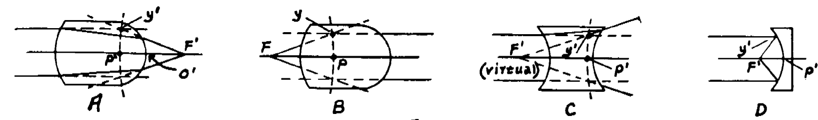


Fig. 1

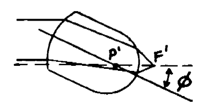


Fig. 2

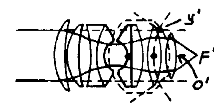


Fig. 3

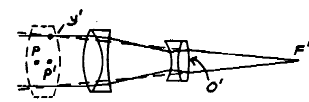


Fig. 4

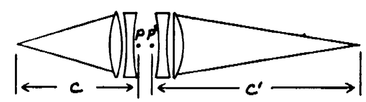


Fig. 5

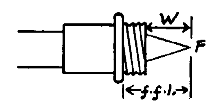


Fig. 6

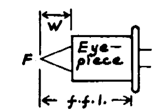


Fig. 7

All drawings by the author

For the most accurate work, something as elaborate as shown is practically necessary. Fairly good work can, however, be done with a precision of ± 0.02 to 0.05 inch on an optical bench which has a pointer in place of U, a snug bushing instead of preloaded ball bearings to hold K and parts L, S and X of wood. As in telescope making, almost anything can be made to serve if the essentials are present and if basic theory is not violated. For testing the alinement of binocular field glasses, the cross slide at X is desirable.

The basic parts and their arrangement are:

Illuminator: P should be compact. A 2.5-volt penlight bulb (Mazda No. 222), a sleeve socket, a clear, symmetrical 5 mm (0.2-inch) glass bead [1] and a very fine pinhole in a copper disk can be mounted in a short piece of ½-inch diameter copper tube. This can be soldered to four pairs of hard copper wire (Figure 8, P) which form a spider support similar to that of the diagonal in a Newtonian telescope. The supporting wires carry the bulb current. M repre-

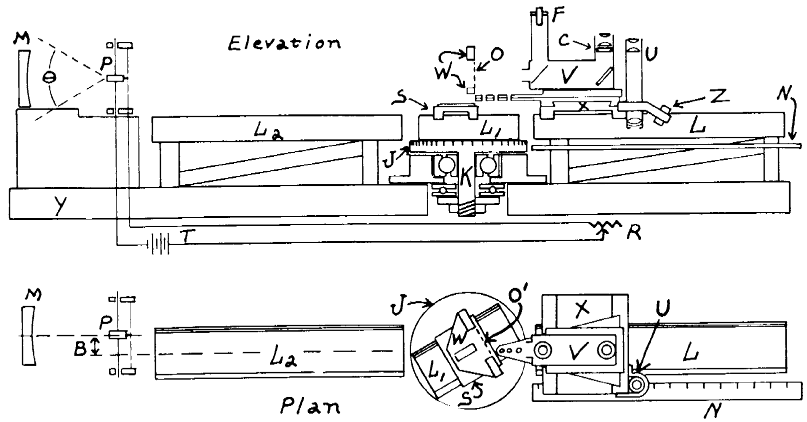


Fig. 8

sents any excellent paraboloid, larger than any specimen aperture. P is placed accurately at the axial focus of M.

Nodal slide S is any arrangement incorporating a sliding member exactly perpendicular to shaft K, which must be accurately vertical and capable of rotation with a minimum of wobble. J should have a circular scale, graduated in degrees, for measuring its angular rotation. The nodal slide should be leveled, securely mounted on the bench and offset from the illuminator axis by an amount, B, equal to ½ the outside diameter of P plus ⅜ inch.

Telescope-microscope V: This should have a spirally focusable ocular of 0.5 to 1-inch efl, a reticle for measurement, three eyelens filters of red, yellow-green and blue-violet and two or more interchangeable objectives. A 90° prism diagonal is not essential, but very convenient. The ideal reticle, Figure 9, is a net micrometer disk. Second choice is any type having parallel, equally spaced rulings. Excellent filters are Eastman's Wratten filters No. 29 (F), No. 61 (N), and No. 49 (C4) not mounted in glass. The telescope objective should be of 6 to 7½ inches efl and have an aperture of ¾ to 1½ inch. It should give

[1] Kimble No. 13500, obtainable from laboratory supply firms.

a sharp image when used with the ocular and focused on infinity. No one microscope objective will serve for all purposes, for some tests require that the objective accommodate the entire cone of rays from a specimen which has an aperture ratio of $f/1.5$, for example, and others require that the objective have a long working distance. These requirements conflict. To illustrate the point, assume that Huygenian, Airy or Mittenzwey oculars, the focal surfaces of which are within the eyepiece proper, are to be tested. In order to reach the foci, an objective with an efl of approximately ¾ the efl of the ocular, as a minimum, will be needed. Say that a 2-inch ocular is the lowest power to be tested. The efl of the microscope objective must then be about 1.5 in. or 37 mm. 40 and 48 mm objectives are standard and they work in the neighborhood of $f/6.3$ (N.A. 0.08). Since Huygenian eyepieces rarely perform well

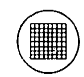


Fig. 9

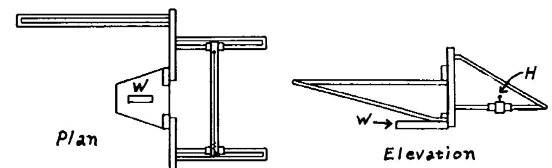


Fig. 10

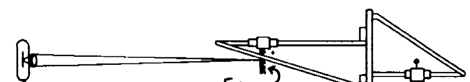


Fig. 11

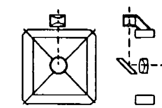


Fig. 12

beyond $f/6.3$, either objective is good. However, if a photographic objective of $f/1.5$ is to be examined critically, the nearest standard microscope objective which will suffice has an efl of 8 mm and works at $f/1.2$ (N.A. 0.50). Its working distance is only 1.5 mm (0.06 inch); so it cannot possibly reach the interior of a "negative" eyepiece of efl greater than about 0.1 inch. The reader must choose for himself from the list in Table 1 the objective or objectives which best suit the work which he contemplates.

War surplus achromatic doublets can be found and at times can be pressed into service in lieu of the expensive standard objectives for fairly accurate work. The better short focus doublets (12–20 mm) work well if stopped down to $f/6$. Two such doublets, crown to crown, give fair results at $f/4$ in exceptional cases. Due to the lack of uniformity among war surplus items, no useful figures can be given here.

The various objectives should be mounted so that they can be interchanged rapidly in such a way that the telescope objective is always focused for infinity and each microscope objective focuses on a constant individual object distance. Standard microscope objectives are corrected for a tube length of 6.3 inches and perform well when from 6 to 7.5 inches from the eyepiece focus.

TABLE 1—*STANDARD AMERICAN ACHROMATIC MICROSCOPIC OBJECTIVES* (1) *

efl	N.A.	Limiting f No.	Magnification ($C' = 6.3$ inch, Fig. 5)	Working Distance	Approx. Cost
48 mm.	0.08	f/6.3	2.0×	52 mm	$20
40	0.08	f/6.3	2.5×	40	20
32	0.10	f/5	4×	21–38	25
16	0.25	f/2.1	10×	5–7	35
8	0.50	f/1.2	20×	1.5	50

* Numbers in parentheses refer to references at end of chapter.

This is why a telescope objective of 6 to 7.5 inch efl is desirable. Parfocal mounting is easier.

Although microscope objectives are designed for use either with or without cover glasses, the difference is slight for the average optical bench determination. However, if new objectives are purchased, it is well to specify that they be corrected for use on uncovered objects.

V should be mounted on X so that V can be rotated in the horizontal plane about a vertical pivot, the projected axis of which coincides with the microscope objective focus. One method of doing this is shown in Figure 8, where holes for three pivots corresponding to low, medium, and high power objectives are shown.

The vertical illuminator F consists of a good quality, thin, semi-reflecting diagonal which can be turned either parallel to the axis of V or at 45° to it and a pinhole which can be similar to P but of larger aperture. The pinhole-to-objective distance must be optically equal to the reticle-objective path.

The optical bench proper: This should be in two sections, L, L_2, with the nodal slide between them. Each section should be as long as the efl of the longest specimen to be tested plus the length of slide X. It may be economically made of 4 or 6-inch channel iron, properly planed, one lip flat, the other a 60°–80° angle. A short length of similar material, L_1, may be mounted on J to support S. A 3-inch channel-iron bench is commercially available with accessories (2) at moderate cost.

The slides X and S: These may be of any stable material, shaped to slide on L without side play. A cross slide similar to the crossfeed of a lathe is practically essential on X or S for testing binocular alinement and is convenient if on both.

The scale N should be an *accurate* steel tape under tension or a steel rule, preferably with decimal graduations.

The reading microscope U, if used, should have cross-hairs at the eyepiece focus. It need be neither an erecting microscope nor well corrected. A fine pointer and a magnifier, both rigidly attached to X, are nearly as good, especially if N is tilted outward to give headroom. A simple pointer will give sufficient accuracy for approximate work.

Alinement: As with Cassegrain telescopes, so there are many ways of alining this test bench. The following is satisfactory.

I: Square P and its ring support with the bench and with a level and clamp it permanently in position, being sure that its height is approximately that of the axis of V. Be sure the pinhole is illuminated when viewed throughout angle θ. Realine bulb and bead, if necessary.

II: Arrange V as a telescope and verify its infinity focus by examining a very distant outdoor object. Permanently correct, if necessary. Mark eyepiece focusing mount and do not disturb until all alinement operations are completed.

III: Verify the perpendicularity of K with a level on S for various angles of rotation. Clamp W on S and stretch a fine wire or thread O vertically across the exact center of the lens-mounting hole in the face of W. Slide S until O is approximately over the axis of K.

IV: Arrange V as a microscope, mount it on L and observe O through V, sliding X to obtain a sharp image. By systematically moving L toward and away from the end of V and by sliding S on L_1, find a position in which J can be rotated as far as possible on both sides of zero without any movement of O being discernible through V. If this condition cannot be obtained, it indicates that the hole in the face of W is not centered, but is to one side and must be corrected. When this operation is complete, O is accurately over the center of K.

V: Mark the position of X on L, slide X to the right, remove the objective of V and slide X to its former position. Temporarily but firmly mount a magnifier or other lens of ½ to 1-inch efl above the eyepiece of V so that O is slightly out of focus (the magnifier being somewhat too close to the eyepiece) and centered in the field of view. Mount a cross wire perpendicular to O on W with adhesive tape so that it, too, bisects the field of view. Slide X to the right end of L and observe any shift in the apparent position of O or O'. Rotate and shim V on X so that O and O' remain centered for all positions of X on V. Clamp X permanently and recheck. The axis of V is now parallel with the ways of L. Remove magnifier.

VI: Arrange V as a telescope, light P and have an assistant move M until the image of P is visible through V. Have M adjusted to center the image of P. Change V to a microscope, observe O and O' and center them in the field by shifting L. Keep L level at all times and maintain dimension B.

VII: Repeat VI until the images of O, O' and P remain centered in their fields and the image of P is sharp and absolutely symmetrical. Clamp M and L permanently. M and P are now coaxial, the axes of V, P and L are parallel and the axis of V intersects the projected axis of K.

VIII: Remove O'. Using V as a microscope, focus on O. Rotate J through large angles on both sides of zero, sliding S on J, if necessary, to the point where the image of O remains stationary. Slide X on L until O is in sharpest focus. Adjust N parallel with L until the zero of N is seen coincident with the cross-hairs in U. Clamp N in place temporarily. N may have to be shifted due to shrinkage or warping or to a change of microscope objectives.

IX: Set J on zero, illuminate the face of W and examine with the microscope, using only the cross-slide of X. The face on both sides of the hole should be sharply focusable without moving X on L, proving it perpendicular to the axis horizontally. Check vertical perpendicularity with a square level. Correct if necessary.

X: Light F, arrange V as a telescope and mount a first surface mirror on S or on W, facing V. Turn mirror until the pinhole image of F is seen in V and adjust F to make image needle sharp. Change V to a microscope and focus sharply on some flat, fine-textured surface, such as the ungraduated portion of a steel rule held against W. The image of the pinhole should be centered and sharp. If it is not, adjust F and its reflector and recheck with the mirror and telescope. The image of F must be sharp and centered both with the telescope mirror and with the microscope-flat surface combination.

XI: Light pinhole P and examine its image with V as a telescope, using all three eyepiece filters in turn and adjusting the eyepiece to maximum sharpness. Mark each position so that the focus for each color can be used at will later, or record it in a notebook. Change V to a microscope and stretch a fine white thread across the opening of W, illuminating it with F. Again use all three filters and mark the sharpest focus positions on another portion of the eyepiece focusing mount or record them as before. The reticle should appear reasonably sharp with all colors. It is the writer's practice to use a graduated sleeve on the ocular and to record the positions as follows: $M_{40r} = 0.32$, $M_{40y} = -0.06$, $M_{40w} = 0.00$ and $M_{40v} = 0.34$ for the microscope with a 40 mm objective, $M_{8_{r,y,w,v}}$, for the 8 mm objective and $T_{r,y,w,v}$ for the telescope, red, yellow-green, white and blue-violet being the colors indicated by the subscripts.

XII: Sit back and admire your handiwork. The gadget is ready to use.

Testing Methods

The methods to be presented are applicable to all refracting optical elements and systems as well as to some reflecting elements and instruments. They are not necessarily the best methods, however, in all cases, for all mechanical tests are subject to error and optical bench errors are larger for some types of work than those inherent in purely optical methods or in other mechanical procedures.

Bench methods are rapid, direct and of a fundamental nature, however. They are of wide application and of sufficient inherent accuracy for practical purposes.

In order to judge the precision of his results, the beginner should repeat the first determination of any type several times from the very beginning. The spread of the values obtained will serve to indicate the reproducibility of the particular method employed.

Tests on the Axial Image

Equivalent Focal Length (efl, f′, P′F′ in Figure 1)

1a. *Well corrected Positive Systems:* Mount specimen in W with surface which normally faces infinity or the major conjugate (C', Figure 5) toward P. Eye lenses of eyepieces send out parallel rays (face ∞); so they should face P. Using appropriate microscope objective in V, light P and observe its image, having checked alinement operation VIII. Rotate J slightly from zero. If image moves against rotation, slide S away from V and conversely. Continue oscillating J across zero while moving S until image shows no lateral movement whatever for a 5° oscillation. Set J to zero, move X to sharpest image and read efl directly on N.

1b. *Poorly corrected Positive Systems and Simple Lenses:* Mount specimen in W with shorter convex radius towards P. Mount a small diaphram with an $f/30$ aperture close to specimen. Use the yellow-green filter on the eyepiece and focus it accordingly. Proceed as in *1a*, reading the paraxial efl for the middle of the visible spectrum on N.

1c. *Negative Lenses and Systems (Barlow Lenses, Telephoto attachments, Microscope Amplifiers, etc.):* On L_2 mount a positive lens of longer efl than the specimen. An achromatic refractor objective is ideal but not essential. Arrange V as a microscope, set U to the estimated efl of the specimen on N and move the positive auxiliary lens so that a sharp image of P is seen through V, using a diaphram at the auxiliary if necessary. Mount specimen in W on S, change V to a telescope, use the yellow-green eyelens filter and observe the image of P, sliding S to obtain sharpness. Oscillate J across zero and slide S and auxiliary approximately equal amounts in the same direction to the points which enable J to oscillate a few degrees without lateral image shift. Set J to zero, slide auxiliary only to sharpest focus, closing diaphram if necessary and remove specimen. Change V to microscope, slide X to position of sharpest focus and read efl directly on N.

1d. *Alternative for Huygenian and Similar Eyepieces:* It is preferable to test all systems in the proper rather than in the reverse position on W because settings are most precisely made on images of wide aperture and reversed systems usually have worse definition, necessitating reduced apertures for good definition. This aperture reduction increases depth of focus which reduces setting precision.

However, an occasional eyepiece with an inaccessible focus can be checked for efl (but not for definition and field aberrations) when a microscope objective of suitably long focal length is not at hand by reversing the eyepiece, for the paraxial efl of any system is an invariant, not being affected by the direction in which light traverses the specimen.

Procedure: Mount specimen with field lens toward P and determine efl by method *1b*.

Back Focal Length
(b.f.l., O′F′, Figures 1, 3, 4)

2a. *Telescope Objectives, Camera Lenses, Elements, etc.:* After determining efl and without disturbing any part of the arrangement, place talcum on surface of specimen nearest V. Light F and slide X to obtain sharp focus on talcum particles. Read N. Subtract from efl. Difference is b.f.l.

2b. *Direct Method:* Set V to zero on N. Set J on zero. Mount specimen in W as for efl. Place talcum on specimen surface nearest V, light F and slide S to sharp microscope focus on powder. Blow powder away with syringe, light P, extinguish F and slide X to sharp focus on image of P. Read b.f.l. directly on N.

2c. *Eyepieces Only:* Mount specimen in W with field lens facing collimator. Proceed as in *2a* or *2b*.

Working Distance
(W, *Figure 6, Figure 7*)

3a. *Magnifiers, Eyepieces:* Mount specimen in W with surface which normally faces object or image which is magnified facing V. Set J to zero. With cross slide of X, move microscope in line with the most projecting portion of the specimen. Move S to left, set V to zero on N and slide S to focus of V on specimen projection. Move V back to axis with cross slide and slide X to sharp focus of image of P. Read quantity on N. If no part of specimen projects beyond lens surfaces, cross slide is unnecessary and center of projecting lens surface is used to obtain reference point.

3b. *Microscope Objectives:* Mount entire microscope tube, including a microscope ocular and the specimen in W with ocular facing P. If microscope tube is adjustable, set it to 160 mm. Proceed as in *3a*.

3c. *Microscope Objectives:* On the left section of L mount an illuminated pinhole, slit, cross wires or other small target. Mount specimen in W as in method *3a* and proceed as there stated until projection is in focus. Now move illuminated target to a position 150 mm (5.9 inches) to the left of the Society screw shoulder of the specimen. Finish method *3a*, using target image instead of the image of P.

Flange Focal Length
(*f.f.l., Figures 6 and 7*)

4. *Motion Picture Camera Objectives, etc.:* Use method *3a*, except that the zero point is adjusted with the use of the mounting flange instead of the projecting portion of the specimen.

Caution: Specimen should be tested at full aperture and the objective of V should have suitable N.A. or f No. to receive full cone from specimen. White light should be used.

Axial Critical Aperture Ratio or Aperture Tolerance

5a. *Positive Systems Used on Distant* ($> 10\ f'$) *Objects, also Eyepieces:* If the specimen has no adjustable diaphram, provide an iris diaphram or a series of circular stops between P and the specimen and close to the specimen. Mount specimen in W with surface which normally faces distant object or which faces the eye toward P. Using proper microscope objective and with J

on zero, examine image of P with V, employing a small specimen aperture. Increase aperture until image at its best focus deteriorates to the point where specimen barely performs satisfactorily as far as definition is concerned. Measure aperture. Divide by efl of specimen. Quotient is f No. of critical aperture for axial use. For extra-axial images, use combination of *5a* and *8a* or *8b*.

5b. *Positive Systems Used on Near* ($< 10\ f'$) *Objects:* Use combination of methods *5a* and *8c* or *8d*.

5c. *Negative Systems:* Use method *1c* and place iris diaphram to right of specimen. Calculate results as in *5a*. Auxiliary lens must be well corrected and preferably the one with which specimen is to be used.

Axial Chromatic Aberrations[2] (Δ_{chr})

6a. *Positive Systems Used on Distant Objects:* Proceed with method *5a*, stopping at the critical aperture. Close the diaphram until definition is sharpest. Use the red eyelens filter, slide X to sharpest focus and read N. Repeat with other filters. Red reading minus violet reading equals primary axial chromatic aberration. Average of red and violet readings minus yellow-green reading equals secondary axial chromatism. Pri. Δ_{chr} is usually slight in good systems. Sec. Δ_{chr} usually runs about 5 to $20f' \times 10^{-4}$ in acromats (from 5 to 20 ten-thousandths of the focal length).

6b. *Positive systems used on near objects:* Use methods *6a* and *8c* or *8d*.

6c. *Negative systems:* Use method *1c* with auxiliary lens intended for use with specimen and diaphram as in *5c*. Use filters and calculations of *6a*. The Δ_{chr} obtained will be that of the positive-negative combination. Therefore, the auxiliary lens should be well corrected.

Axial Spherical and Zonal Aberrations
($\Delta_{sph.}$ $\Delta_{zon.}$ *or* LA')

7a. *All Systems:* Use appropriate method for Δ_{chr} but, instead of an iris diaphram, use a series of stops (Figure 13 or 14) between specimen and illuminator. Axial opening should be $f/20$ to $f/50$. Total area of usable opening should approximate area of axial opening. Minimum number of stops is three: axial, 0.7 of full aperture for dimension X and 0.98 of full aperture.

Figure 13 masks are theoretically proper and the dimension X and the width W of the annulus to match any axial stop can be calculated from the efl (f) of the specimen as in Table 2.

Table 2

axial stop size	$f/20$	$f/30$	$f/40$	$f/50$	$f/60$
W	$f^2/1600\times$	$f^2/3600\times$	$f^2/6400\times$	$f^2/10{,}000\times$	$f^2/14{,}400\times$

They are not practical, however, for small lenses, for when $W_{marginal}$ becomes less than 0.02 inch, diffraction becomes bothersome.

[2] For a description of the aberrations, see chapter on eyepieces.

Figure 14 (Hartmann) masks are practical and much easier to use, for extra-focal images are doubled and diffraction is less. The centers of the holes should lie on the zones to be tested. Each zonal hole may be 0.707 of the axial hole diameter and marginal holes may each equal the axial hole in diameter because they are approximately divided in area by the rim of the specimen.

Δ_{sph} is the difference between the readings on N for the axial and the marginal stops. Yellow-green light is usually employed. Δ_{zon} is the difference on N found between that stop giving the smallest N reading (often the 0.7071 stop) and the axial stop. Δ_{zon} has little significance unless Δ_{sph} is small.

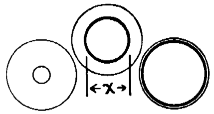


Fig. 13

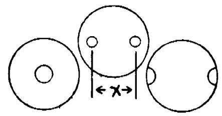


Fig. 14

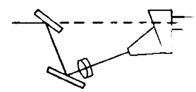


Fig. 15

Δ_{sph}, of which Δ_{zon} is only a part, can be plotted as a curve, as in Figure 8, chapter on "Telescope Eyepieces," by using a series of stops. It varies with color, this being called "Chromatic Variation of Spherical Aberration." By estimating Δ_{sph} for the various colors, the chromatic variation of Δ_{sph} can be found.

Tests Using Extra-Axial Images

Curvature of Image Field

8a. *Systems Used at Infinity:* By Computation. Use method *1a*. When axial infinity focus is found and its position noted on N, turn J to any desired angle and move X to sharpest image, rotating V about the appropriate pivot to maintain maximum image brightness. Read N. Continue for other angles. Field is flat if every reading on $N = \text{efl} \div \cos\phi$ where ϕ is angle from zero on J. Deviations from flatness are determined by subtraction. Results are accurate for object distances as close as $10f'$. For good results, repeat on opposite side of axis.

8b. *Systems Used at Infinity:* Direct Method. Arrange a fine wire under spring tension in such a way that it crosses the axis horizontally, moves with W and can be placed at varying distances from it. Figure 10 illustrates one method of accomplishing this. Mount specimen as in method *1* and center on exit node, precisely as for determining efl. Wire H must be between V and specimen. Slide H to point where it is sharply focused slightly above or below image of pinhole. H should be perpendicular to axis. Slide X to right and rotate J to right, say exactly 5°. Slide X left to focus sharply on wire where it is nearest to pinhole image. Without disturbing X, turn J past zero to exactly 5° left. Examine wire. If sharply focused as before, F is sufficiently perpendicular to axis. If not, move ends of H in opposite directions enough to correct. Repeat entire process until the axial pinhole image lies on the same vertical plane as the wire and the wire is simultaneously perpendicular to the axis. Measurements can now be made with confidence, using the technic of method *8a*. If, at each angular position of J, the best possible pinhole image is found to be contiguous to the wire, particularly if both sides of the axis are checked, the field of best definition of the specimen is proved to be flat. If not, the actual field can be charted by taking a reading on N when the wire is focused and another when the pinhole image is sharpest and noting the difference, which will be the deviation from flatness. This difference is determined at suitable intervals throughout the field of view.

8c. *Systems Used on Near Objects:* By Computation. Mount an illuminated target with vertical and horizontal cross lines on L_2 at the proper distance from the specimen. This distance will be $f' + Mf'$, where M is the magnification at which the specimen is normally used. ($M = 2$ for enlarger objectives, for example, in this case.) Arrange specimen to rotate around its null point as directed in *8d*, below. Note the position of the axial focus of the target on N in its relation to the projected axis of K. Call this distance C'. Measure the distance of the target from the projected axis of K. This distance is C. (C and C' are determined with J on zero.) Now, for each angle, ϕ, from zero, the target must be moved away from the specimen to a new position $C/\cos\phi$ from its original location. If the field is flat, V must be moved to the right $C'/\cos\phi$ from its original position to focus the sharpest image. Deviations from flatness can be calculated arithmetically.

8d. *Systems Used on Near Objects:* Direct Method. Process lenses should be tested when the ratio $C/C' = 1.0$ to 1.5 (Figure 5). Enlarger objectives are best examined at $C/C' = 2.0$. Erectors and transfer lenses should be tested at their normal conjugates. In order to facilitate such testing, the standard illuminator is not used. Instead, the part E of Figure 11 is employed. E is a strip of 400-mesh bronze wire cloth under tension, backed with a piece of opal glass. It is held on a sliding carriage similar to that holding H and is illuminated by a spotlight placed on the axis of V on L_2. The illuminated area of E should be no wider than ×1/16 inch. This is conveniently arranged by using a line filament bulb,[3] the filament of which is imaged near E by a high speed projection microscope objective or war surplus achromat, as shown. Examine E or a remnant of the same wire cloth with V and note the size of one screen opening in comparison with the reticle. Record this reticle calibration value.

Mount the specimen on W and place E at such a distance that the image of E, seen in the microscope V, is the proper fraction of the size noted when calibrating the reticle. This fraction is C'/C (Figure 5) for any specific application. Adjust the specimen to rotate about its null point by sliding S to the place which enables J to be oscillated without causing a lateral shift of the image of the narrow illuminated portion of E. Aline E so that the image position 10° to the right of zero occupies the same position, measured on N, as it does precisely the same angular distance to the left. Slide H to the place where the wire is sharply in focus with the image of E when J is on zero. Aline H at +10° and −10°, just as E was alined. Return J to zero and recheck the

[3] Central Scientific Co., Chicago 13, Ill., Cat. No. 86615 approx. $3.

image of E to be sure it is coplanar with H. Field curvature can now be measured exactly as in method *8b*.

For determining field curvature and estimating the extra-axial aberrations (see later) of mirrors, V must be removed from the axis to avoid obscuration. The arrangement of Figure 12 is useful for this purpose. The microscope objective of V, with a small elliptical flat or a 90° prism, is mounted on a spider support similar to that of P. The eyepiece and reticle are mounted on the spider ring. The wire representing a plane image is stretched across the specimen tube, so that it moves with the mirror. The open tube microscope support ring can be affixed to X of Figure 8 and used on L_2. With this Rube Goldberg contrivance, the principal methods of the optical bench can be applied to mirrors, although computation yields the results with less time and expense, if the equation of each surface is accurately known.

Lateral Chromatic Aberration

9a. *Specimens Used at Infinity and Corrected for Axial Chromatism:* Determine efl by *1a* for red and for blue-violet light. If the two efls are equal, lateral chromatism is absent. If not, the longer efl will yield a larger extra-axial image and "edge color" will be evident. Example: $f'_{red} = 7.86$ $f'_{viol.} = 8.03$. Lateral chromatism is overcorrected by 2 percent. An image 4 inches from the axis will therefore have a color spread of 0.085 inch, red toward the axis, blue-violet toward the edge.

9b. *All Specimens:* Examine extra-axial images with V while determining field curvature. Use a small aperture to reduce the effects of coma and astigmatism. If lateral chromatism is corrected, image color will be symmetrical or absent. If undercorrected, the axial side of the image will be violet and vice versa. The amount can be determined with the reticle of V.

Distortion

10. *All Specimens:* Proceed as for field curvature. Use small aperture and yellow-green eyelens filter. If the image leaves the axis laterally by the time the edge of the field is reached, distortion is present and is proportional to the amount of image shift at any given angle.

Comatic, Lateral Spherical or Sinical Aberration

11. *All Specimens:* Proceed as for field curvature. The comatic flare caused by this aberration can be recognized instantly, if not masked by other aberrations. Its amount and sign can be estimated fairly well even in the presence of other aberrations, if chromatic effects are minimized with a yellow-green filter at the eyepiece of V and if observations are made both at full aperture and "stopped down." Coma will be greatly reduced at small apertures because it varies as the square of the aperture, while the size of the blur due to astigmatism will be less markedly changed due to its characteristic of varying approximately as the aperture. Coma is zonal in nature. The entire image field should be examined.

Astigmatism

12. *All Specimens:* Proceed as for field curvature. This image defect (see chapter on "Telescope Eyepieces") can be measured very accurately by determining the positions of the two focal surfaces which it forms. If method *8a* or *8b* is used, start at the edges of the field and chart the positions at which the pinhole image is (a) a short, fine, vertical line and (b) a similar horizontal line. The difference between the positions of these two line foci is a measure of the astigmatism at any one angle. Move inward toward the axis. Use a yellow-green filter to avoid chromatic confusion and a small aperture to minimize coma.

If method *8c* or *8d* is the one employed, plot the sharpest foci of the horizontal and vertical elements of the target used.

Testing Complete Telescopes

Astronomical telescopes, transits, sextant telescopes, individual sides of field glasses and the telescopes of spectrometers, cathetometers, etc., can be checked as units with their eyepieces on the nodal slide or on separate pivots, if they are too large. The following are some of the many possible determinations:

13. *Magnification:* Whiten the face of P, Figure 8, facing M and illuminate it from the side. Using V as a telescope, note the diameter of P in terms of reticle divisions. Place specimen on L_2 or on S, depending upon length, and again determine size of P image on reticle. Size of image divided by image without specimen equals magnification. Refractors and Cassegrainian and Gregorian reflectors can be checked so. Newtonian reflectors can be checked by mounting V in front of the eyepiece at the side. This method is so cumbersome for large telescopes, however, that it is far preferable to employ conventional tests and calculations.

14. *True Field of View:* With specimen on L_2 or, if small, on S, and pivoted over P' (Figure 1–c) of the objective or mirror, examine pinhole image with the eye. Swing specimen around P' until image touches edge of field. Read angle on each side of zero on J or measure traverse of tube and length of tube from P' and calculate angles from tangents. Example: A point 40.0 inches from P' was moved 0.265 inch past center before image was lost. Tangent of the half angle was therefore 0.265/40, or 0.00662. Half angle was therefore 0°22′.8. Total angle = 0°45′.6.

15. *Eyepoint Distance and Exit Pupil Diameter:* These may be determined by illuminating the mirror or objective strongly with a spotlight or floodlight off the axis and receiving the image of the objective or mirror which the eyepiece forms on a ground glass, where its distance from the eyepiece (eye relief)

and its diameter can be approximately measured. For greater accuracy, V, used as a microscope, can be employed.

16. *Character of Axial Definition:* The axial image can be examined with the aid of V used as a telescope, employing diaphrams corresponding to the eye pupil diameters which would exist in practice. In this way, errors are magnified directly as the magnification of V, which is normally $5 - 10\times$.

17. *Testing Binocular Instruments:* If M, J and S are sufficiently large and the entire apparatus is sturdy and accurate, binocular field glasses and microscopes can be checked for alinement and the field glasses can be checked for definition. For this work, the pinhole of P is best replaced with a slit. If the ocular tubes are parallel, the instrument can be clamped anywhere on J with the tubes parallel with the axis. If the tubes converge, the intersection of their axes should be on the projected axis of K. The objective of a microscope should be focused on the infinity focus of a substage condenser capable of filling both ocular tubes with light. (Double-objective microscopes of the Greenough type need large-diameter condensers.) The stage should hold a cross-hair slide, or something marking the center of the field. Inclined eyepiece tubes should be horizontal, the objective axes being brought on the same plane by means of two first-surface mirrors, attached to the condenser, as in Figure 15. (Condenser and/or mirrors remain fixed, leaving the instrument free to rotate in the case of convergent or inclined tubes.) The entire instrument in question is mounted in the proper position on J with its objective or condenser facing M. It is leveled and squared with the axis as well as possible, using whatever surfaces seem best. V is changed to a telescope and the image of P is examined through one eyepiece by means of V, using the cross slide of X or of S for parallel tubes and rotation of J for convergent tubes. The image of P is brought to the center of the field by shifting and shimming the specimen slightly and keeping the objective of V centered on the eyepiece of the specimen. X is now moved along L to check the parallelism of the specimen axis with that of the bench. If the image does not move, fine. If it does, shift slightly and repeat until no movement occurs and V is still centered on eyepiece. Parallel tubes **ONLY.** Measure interpupilary distance accurately, using edges of lens cells, if possible. Move cross slide precisely this distance and examine image through other eyepiece. If centered and if it remains so along L, alinement is perfect. If not, correct first by rotating entire instrument about axis of first tube and then rechecking first tube. If alinement cannot be perfected thus, complete correction by moving prisms, objective or other adjustments. Repeat for at least one other interpupilary distance to check stability of pupilary distance adjustment mechanism (hinges, rack and pinion or pivot). At same time, check focusing of both sides and correct if necessary. Definition can also be judged.

Convergent Tubes: Change to other side by rotating J until eyepiece is precisely alined with objective of V. Reflections from F are useful here. Image should be centered and should remain so along L. If not, correct as above, under Parallel Tubes.

General Caution: The correction of misalinement is not easy and the novice is advised to proceed with deliberation and the greatest of care. In fact, it is much wiser to entrust such work to the maker of the instrument unless the worker knows himself to be adept and capable.

The methods given above are suitable for the determination of efl, working distance, eyepoint distance (b.f.l.) and the axial aberrations of eyepieces. If a diaphram is placed at the eyepoint and varied in aperture from 1.5 to 7 mm (0.06 to 0.28 inch), valuable information can be obtained concerning axial definition and the extra-axial aberrations. However, the oblique errors are profoundly influenced by the corresponding aberrations of objectives and mirrors with which eyepieces are used. A considerable amount of experience in the testing of eyepieces, objectives and mirrors is necessary before accurate judgment of the extra-axial aberrations of eyepieces alone on the optical bench is possible. For this reason, the beginner is advised to test his eyepieces for extra-axial performance in conjunction with the system with which it is used.

Approximate Refractometry

The refractive indices of simple lenses for various colors of light can be determined on the optical bench when the radii, thickness and efl of the specimen are known.

18. Determine efl by Ib or Ic, using an $f/30$ diaphram, repeat for other colors, if desired, and enter data in the appropriate formula in Table 3.

TABLE 3

Second Surface Plane — A. Exact

$$N = 1 + \frac{r_1}{f'}$$

Both Surfaces Curved — B. Exact

$$N = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

Both Surfaces Curved — C. Approximate

$$N = 1 + \frac{1}{f'\left(\frac{1}{r_1} - \frac{1}{r_2}\right)}$$

N = refractive index
r_1 = radius of first surface
r_2 = radius of second surface } + if centered to right, − if centered to left.
t = axial thickness
f' = paraxial efl
$a = f'(r_2 - r_1 + t)$
$b = f'(r_1 - r_2 - 2t) - r_1 r_2$
$c = f't$

The direction of propagation of the light is from left to right. By using formula A or B with good technic, N can be determined to ± 0.002 under very favorable conditions. For high accuracy, immersion and goniometric methods are employed, using costly apparatus such as monochromators, spectrometers, refractometers and/or precision hollow prisms. (3), (4), (5)

Measurement of Radii

19. *Convex Sectors and Segments of Circular or Cylindrical Objects of Any Material:* Sector gears, cams, cylindrical and toroidal lenses, Woodruff keys, etc., can be measured for radius of curvature by mounting them on *S* at the level of the axis of *V*, lighting *F* and focusing the microscope on the surface of the specimen by sliding *X*. If, now, the specimen is oriented by sliding so that *J* can be swung around *K* without losing sharp definition of the specimen surface, the radius can be read directly on *N* if alinement operation IV, above, is first performed.

20. *Concave Sectors, etc.:* Change *V* to a telescope and mount a positive lens of greater efl than the radius to be measured on the objective of *V*, thus making it a long focus microscope. Focus it on the projected axis of *K* as in IV above. Read *N*. Mount the specimen level with *V* and with the surface to be measured facing *V*. Continue as in 19. Read *N* again. Difference is radius. For short radii, *V* as a microscope can be used by shifting *N*.

21. *Spherical, Unpolished Surfaces:* Use method 19 or 20, taking care to orient the specimen vertically so that the greatest bulge or depression is on the axis of *V*.

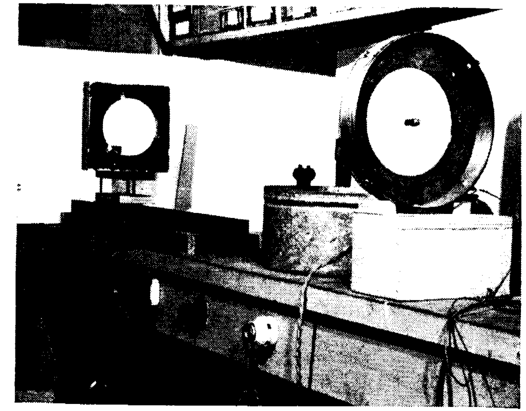
22. *Concave Spherical, Polished Surfaces:* Before measuring transparent material, smear the surface not to be measured with vaseline to avoid confusing reflection. Arrange *V* as a microscope. Check IV above. Mount specimen in *W* on *S*. Set *U* and *J* to their respective zeros and light *F*. Slide *S* until dust, talcum or an ink dot on the center of the surface is in sharp focus. Slide *X* to the right until pinhole image is sharp. Read radius directly on *N*. If pinhole image is not centered in *V*, specimen should be reoriented and determination repeated.

23a. *Convex Spherical Polished Surfaces:* (Of radius shorter than working distance of microscope *V*.) Set *U* to zero on *N* after checking IV, *P*. Smear back surface of specimen with vaseline and mount in *W*. Light *F* and slide *S* to sharp focus of *F* in *V*. Slide *X* to right until specimen surface is in sharp focus (dust, talcum or ink dot). Read radius directly on *N*.

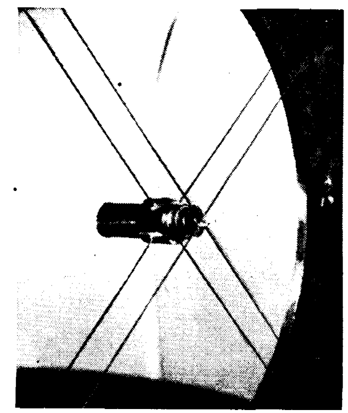
23b. *Convex Spherical Polished Surfaces:* (Longer radius than working distance of microscope *V*.) Change *V* to a telescope. On *W* mount an achromatic lens of longer efl than radius of specimen. Mount specimen on L_2, facing *V*. Dust talcum on right surface, grease left surface and light *F*. Move specimen until powder is in sharp focus in *V*. Note position of specimen holder. Blow away talcum with syringe and move specimen to right until pinhole image is in focus. Distance through which specimen holder was moved equals radius of curvature.

Radius Measurement in General. By using objectives on *V* of large aperture and excellent correction (shallow depth of focus), it is possible to determine radii with an accuracy of ±0.2 percent on the average with good technic and equipment. Such objectives are costly, however, and conventional methods serve as well as or better than bench methods in many cases. For example, long concave radii are best measured by Foucault's knife-edge method; concave and convex radii of moderate length are handled by spherometers of many types and interference methods, using master curves, are best for checking replicate surfaces, as in volume production.

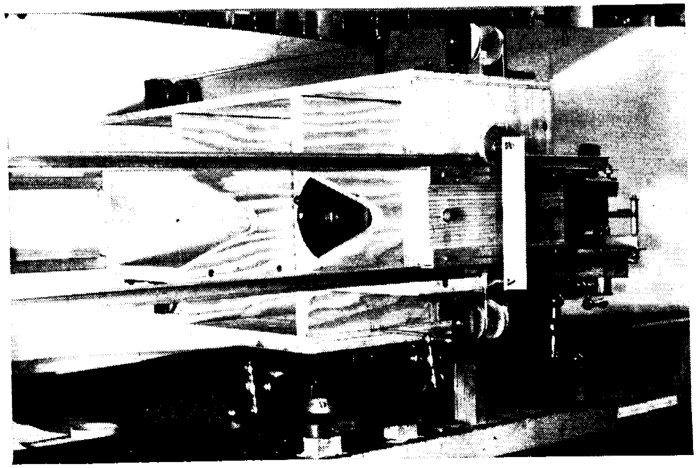
Methods 22 and 23 are among the best available, however, for determining the lengths of short radii such as those used on microscope elements of small diameter and on elements of high-power eyepieces.



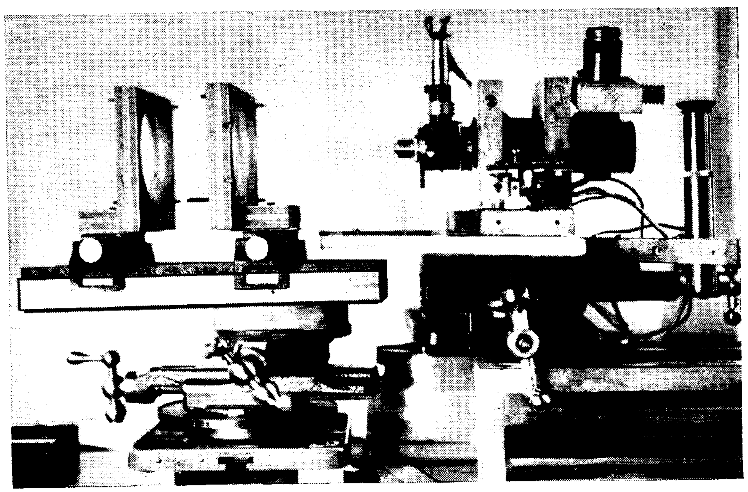
The Collimator.

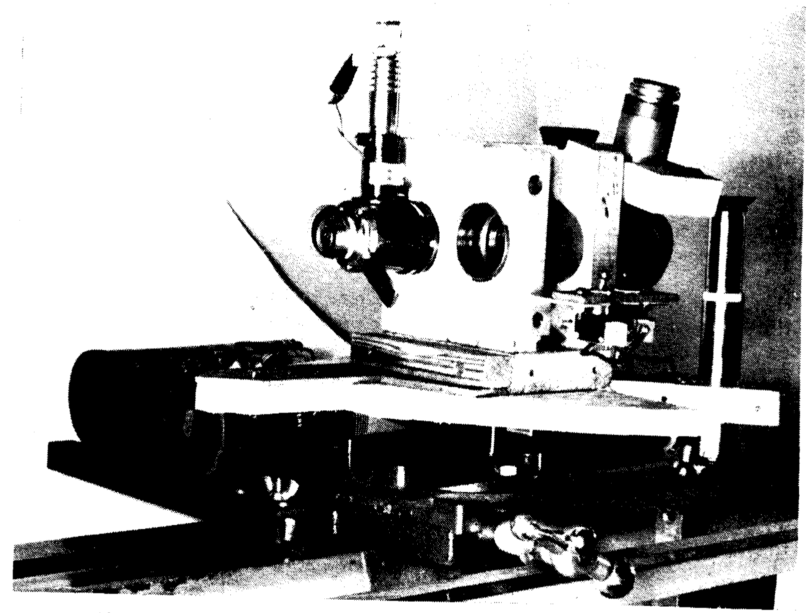


Detail of pinhole illuminator. Maximum diameter 0.48 inch.

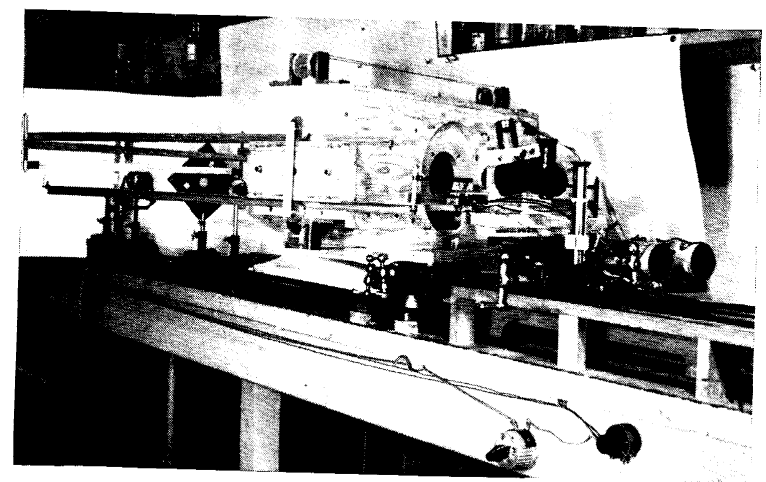


Above: Compensating object and image-plane holder (front). *Below*: convenient auxiliary bench with holders for two or four specimens.





Above: Counterpoised cross slide. *Below*: Compensating object and image-plane holder (rear).



Summary

An optical bench, used with due regard for its mechanical nature, is a most useful and instructive instrument of wide application. Anyone pursuing general optics as a hobby should have one in his possession, though it be of the simplest type.

The instrument, as described in the above chapter, is only one of many types (6), (7), (8), (9), (11) and the methods outlined by no means cover the field of testing exhaustively.

For those wishing to construct a slightly more versatile optical bench than that described, photographs of the writer's equipment are reproduced. The apparatus accommodates objectives up to 8 inches in diameter, will allow the study of 120° fields by method *8a* and of 30-inch diameter object and image fields by *8b* and *8d*. Focal lengths of from zero to 10 feet can be handled with little trouble. Also, objectives of 15-inch efl can be tested at unity magnification by method *8d*.

The major differences to be noted are largely for convenience and for the saving of time. They are:

1. Separate microscope and telescope.
2. Metal angle-supported *H* and *E* elements, which slide into position and are automatically alined by a music wire-pulley linkage.
3. Reverse illumination of target *E*, which is of engraved metal.
4. Double cross-slides.
5. Graduated scales at *H* and *E*.

Despite the fact that wood is employed, the unit is capable of giving good accuracy.

Although some of the methods presented are thought to be original, they may not be so. They are theoretically correct and practically satisfactory and have been intentionally made applicable to fairly inexpensive apparatus. The chromatic aberrations, for example, can be determined more accurately if a monochromator and an apochromatic or "orthokumatic" (10) objective are substituted for the reflecting collimator and the filters which are recommended. The cost, however, would not be justified for occasional use.

References

1. Catalogs of American Optical Co., Buffalo, N. Y. and Bausch & Lomb Optical Co., Rochester, N. Y.
2. Central Scientific Co., Chicago, Ill.
3. *Applied Optics,* Steinheil and Voit. Trans. French, Vol. II, 1919, pp. 45–68.
4. *Bur Stds. Jour. Res.,* series of papers on refractometry by Tilton, Research Papers No. 262, 575, 776, 919, 934, 971, 1535 and 1572.
5. Faick and Fonoroff, "Precision Apparatus for the Rapid Determination of Indices of Refraction and Dispersion by Immersion," Bur. Stds. Research Paper No. 1575.
6. Kingslake, *Jour. Opt. Soc. Am.,* Vol. 22, pp. 207–222.

7. *Practical Optics,* B. K. Johnson, 1945, pp. 21–36.
8. *Dictionary of Applied Physics,* Glazebrook, 1923, Vol. IV, 5–7 and 164–167.
9. *Photographic Lenses,* Beck and Andrews, 2nd ed., pp. 273–288.
10. Hastings, *Jour. Opt. Soc. Am.,* Vol. II, p. 63.
11. *Bull 156-74,* Gaertner Scientific Corp., Chicago.

Elementary Camera Lenses

By James W. Shean
Scientific Bureau, Bausch & Lomb Optical Company

It is assumed that designing of even the simplest photographic lens is outside the interests of the average amateur telescope maker or camera fan. If this is granted, examples of a few representative systems will be offered, some of which are drawn from expired patent data. No claim is made that the examples to be given are the best possible solutions with the available variables, but they should perform to the satisfaction of the hobbyist.

Some of the expired patents (now public property) to be quoted have been checked and supplemented for completeness; additional references to patents place the reader on his own. By rummaging in various publications he can find specifications for many more lens systems, some good, and many that are impossible to duplicate because of the unavailability of glass and/or incomplete data. It is hoped to alleviate this predicament somewhat and to provide more favorable systems on which the amateur can test his skills.

Many aspects of photographic lenses will necessarily be neglected: mechanical mountings, iris diaphrams, shutters, and photographic technic. Nothing will be said about how to grind and polish these lenses, as other writings cover that problem adequately.

Aberrations of Lenses: The general problem of photographic lenses, contrasted with that of astronomical mirrors or object glasses, immediately brings to mind two requirements of a photo lens that are usually absent in an O.G. or mirror, viz., speed and a considerable field coverage. These two requirements are mutually incompatible and always imply that somewhere in the field of view compromises have been made with the Airy disk definition that we TNs strive for in our mirrors. The stipulation of an extended usable field (usually a flat field) with reasonable speed commits the designer to relatively drastic and complicated action within the lens.

In order that in what follows we shall have a common language, let us discuss and define in simple terms the aberrations of lenses. We will do this by use of the *wave-front* concept from physical optics, not because of any theoretical nicety, but because of its close relation to the knife-edge test with which the amateur is well acquainted. (Opening chapters of ATM and ATMA.)

A wave front is considered as the locus of all points of equal optical distance from the object. The "rays" of geometric optics are perpendicular to the wave front.

Consider a spherical mirror tested at its center of curvature *c* in Figure 1. As the knife-edge, *k-e,* is passed across the returned image of the pinhole *p* the mirror darkens approximately evenly. Here we can conceive of a series of spherical waves *w* (drawn in cross-section) from the pinhole, *incident* on the mirror *M* and returned as *emergent* spherical wave front *w'* (disregarding edge effects). In the Foucault test one is, for practical purposes, looking at the emergent wave front.

Figure 2 shows a plane wave *w* (parallel light) incident on a parabolic mirror, being returned again a spherical wave *w'* toward the focus. The knife-edge applied at *f* would show us the same thing as in Figure 1, an evenly darkening emergent spherical wave surface. This spherical wave shrinks to the focus (likened to a portion of the surface of a collapsing balloon) and gives a point image, the size of which is limited only by the physical phenomenon giving rise to the Airy disk. In our photographic lenses we desire

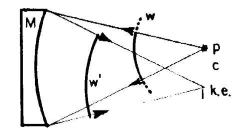


Fig. 1 SPHERE at C. of C.

Drawings by the author

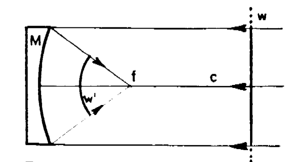


Fig. 2 PARABOLOID at ∞

wave fronts that *emerge* spherical (hence giving stigmatic images) and focus in the proper place. In actual practice, with finite field and finite aperture, neither of these two conditions is ever satisfied completely. The departures from these conditions are termed aberrations.

It is interesting to note that we do not care what happens to the wave front *inside* the optical system—it may go through all kinds of distortions and it does—just so it emerges properly. In a telescope, the eyepiece turns the spherical wave from the objective back into an approximately plane wave for the eye to view. In a photo lens the emergent spherical waves are to form point images of object points on the photographic plate.

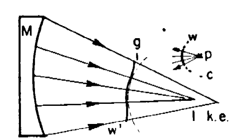


Fig. 3 PARABOLOID at C. of C.

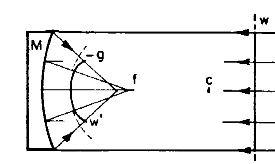


Fig. 4 SPHERE at ∞

Referring now to Figure 3, we have a paraboloid tested at the approximate c of c. Here the mirror does not darken evenly under the k-e because the emergent wave front curls away from true spherical form (grossly exaggerated) giving rise to the characteristic shadows.

Figure 4 is a spherical mirror with an object at infinity. Here again the emergent wave front curls away from the desired spherical form (reference sphere). If tested under such conditions, the shadows would appear similar (reversed) to those of the case in Figure 3. Note that in these two cases the curl is symmetric to the axis of the bundle. This departure from spherical wave front form is called *spherical aberration* and is measured by the gap *g,* Figures 3 and 4, between the actual wave and a chosen reference sphere. The numerical value of g, relative to the focus for very small apertures in both cases is given quite closely by $r^4/4R^3$, a small amount but very significant.

Since "rays" are perpendicular to the wave front, the difference between the intersection points of these rays through the distorted wave front, with the axis, is called *longitudinal* spherical aberration, and is a convenient and much used measure of spherical aberration. This longitudinal spherical aberration is the familiar r^2/R for a paraboloid at c of c, Figure 3, and is equal to $r^2/4R$ for a sphere working at infinity, Figure 4. Longitudinal spherical aberration is defined as *overcorrected* when the rays from any zone of the lens intersect the axis farther away from the lens or mirror than the rays very close to the axis. Thus Figure 3 shows overcorrected spherical aberration and Figure 4 shows *under*corrected spherical.

The same type of symmetric deformation of a wave front can occur in oblique bundles as depicted in Figure 5. This distortion is not necessarily like

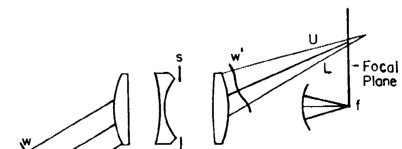


Fig. 5 OBLIQUE SPHERICAL ABERRATION

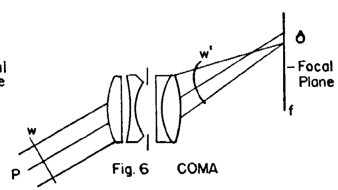


Fig. 6 COMA

that of the axial bundle of the same lens, and to differentiate it from the latter we call it *oblique* spherical aberration. Its effect is similar to spherical aberration of an axial bundle in that the intersection of the upper and lower rays through the lens lies beyond, or inside of, the intersection of the rays in the vicinity of the principal or central ray or bundle. If one could isolate a case of pure oblique spherical, it would look under the knife-edge very much like any other case of pure spherical aberration. It is defined overcorrected or undercorrected in the same sense as the axial spherical aberration.

Notice that some mechanical restriction (stop) within the lens could chop off a part of this symmetric oblique wave front and leave it *un*symmetric.

An unsymmetric oblique wave surface, resulting in the 'spraying' of some light below the main image point, gives rise to a one-sided flare in the image at the focal plane as is shown in Figure 6. We shall generalize the term *coma* to include all such phenomena (a lateral spraying of the light at the focal plane).

Since a centered optical system is symmetric to the optical axis, there is nothing in the system that could impart to an incident axial beam any unsymmetric deformation of the wave front. Hence coma is not possible on the optical axis. If the system is decentered, coma will appear on the (mechanical) axis. For a centered system, therefore, coma is strictly a field aberration, usually but not always becoming worse as the field angle increases. This aberration is extremely damaging to the performance of a photographic lens and, ordinarily, efforts are made to eliminate it completely.

As a matter of definition, coma will be called inward coma when the flare is toward the center of the field (Figure 6) and outward coma when the flare is away from the center of the field.

Astigmatism is the case where the cross-sections through the oblique wave front w' have different curvatures along different diameters of the wave front. These give rise to different focal points for the wave front in different orientations.

In Figure 7 the side view shows the cross-section of the emergent wave w' as having a relatively long radius centered about T. Looking down from the top, in this case, w' appears to have a shorter radius focusing at S. The effect at T is that the image of a point source is a short horizontal line (t below) tangential to the field, and at S a vertical line s radial or sagittal to the field. Somewhere, approximately one half way between the tangential and

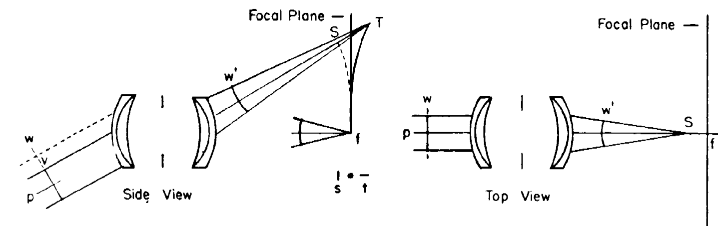


Fig. 7 ASTIGMATISM

sagitta foci, there is a roughly round patch of light, larger than desired. T and S can occur on either side of the focal plane and can occur on either side of each other. When T is farther from the lens than S we commonly speak of astigmatism as overcorrected.

Thus astigmatism is a *longitudinal* aberration, generally increasing in magnitude as the field angle increases. In many modern lenses S and T can be made to come together again at some point in the field, called a *node*. The term *anastigmat* sometimes connotes such a state of correction.

The reader may be better able to understand astigmatism if he will refer to the drawing by R. W. Porter in ATMA on page 70. Imagine that the mirror surface is any oblique wave front; then the effect is what we are calling astigmatism.

All the aberrations discussed here arise in photographic lenses from the use of spherical surfaces and are inherent in the design—not ground and polished into the lens by poor manufacturing technic. The latter only aggravates the situation.

Even in the absence of all the above aberrations the best image may not lie on the desired flat surface. A field that curves toward the lens has *inward curvature* of the *field*. One that bends away from the lens has a *backward-curving* field (Schmidt camera). Figures 8 and 9.

Several aberrations can conspire to give field curvature. In Figure 8 the tangential and sagittal focal surfaces lie together on a curved surface (Petzval). By overcorrecting the astigmatism (Figure 9) the field may be flattened "artificially" or even become backward-curving. The desirable state of correction would be to have T and S lying together on a flat surface—practically impossible in the limit.

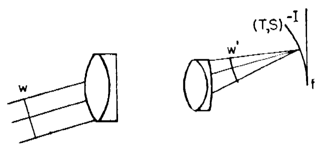


Fig. 8 INWARD–CURVING FIELD

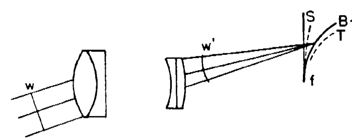


Fig. 9 BACKWARD–CURVING FIELD

Figure 5 shows that the oblique spherical aberration also can affect the field curvature. If that lens were stopped down, the best focus would move from the neighborhood of the U, L intersection toward the (hypothetical) focus of the rays close to the ray P at the focal plane. Thus, field curvature can change as the lens is stopped down, although this effect is usually covered by a simultaneous increase of depth of focus.

Distortion is a peculiar obstinacy of a lens in which, regardless of the shape of the emergent oblique wave fronts, it refuses to turn the incident wave through the proper angle in passing through the lens. This causes the image

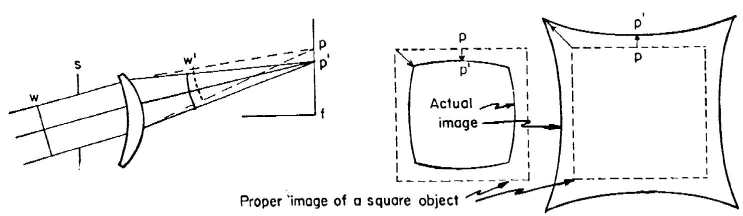


Fig. 10 DISTORTION — Barrel Pincushion

point to lie above or below its proper place as determined by the scale of the lens (focal length). If the emergent wave front is turned too far from the axis, image thus high, it gives rise to pincushion or positive distortion. The opposite case is called barrel or negative distortion. These were named because of their effect on the image of a square object.

In Figure 10 the dotted lines represent the position of the proper emergent wave front w' that would give an image at p. In this case, p' is the actual image, the bundle being turned too low. The distance pp' is the distortion. The corner of a square is further from the center of the field than the midpoint of a side, and usually suffers more distortion, hence the effect. Percentage distortion is the actual distortion times 100, divided by the image height (distance from the axis).

Various means effect control over this aberration which, if present, usually increases rapidly with increasing field angle. This means that the magnification is changing as field angle increases. Small amounts of distortion generally are not objectionable, as the presence of this aberration does not deteriorate the image quality. It is interesting to note that the type of distortion is reversed when a photo lens is used for projection.

It should be realized that only rarely do any of the above aberrations occur alone, and that they will not be the same for all colors of light. This will be exemplified if any lens system is put to the knife-edge test both axially and extra-axially with the pinhole set at some large multiple of the focal length in front of the lens. Combinations of all the above aberrations, except distortion, will give queer shadows [1] and will, with white light, give different shadows of different colors.

This brings us to the chromatic aberrations of lenses, which arise from the dispersive properties of transparent substances.

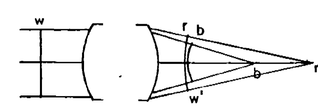


Fig. 11 CHROMATIC ABERRATION

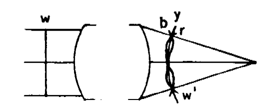


Fig. 12 SPHERO–CHROMATISM

In keeping with our discussion of wave fronts, longitudinal chromatic aberration is loosely defined here as the distance (b to r) along the optical axis between the "focal points" of the axial wave fronts of various *color*. Figure 11 shows undercorrected longitudinal color; the c of c (focus) of the red wave lies beyond the c of c of the blue wave. Lenses, in which these wave fronts of various colors have foci in the same place within certain limits, merit the term achromat. In Figure 11 the wave fronts were both drawn spherical, implying that the lens is spherically corrected in both colors. Usually this is not the case. If the lens is spherically corrected in one color (yellow), the wave fronts of progressively longer (red) or shorter (blue) wavelengths assume shapes like the w primes of Figure 3 or Figure 4. All colors from the whole aperture cannot ordinarily have wave fronts of the same shape. This is called *spherochromatism*, or *chromatic difference of spherical aberration*. Figure 12. It may be thought of as a difference of "figure" from color to color. The appearance of sphero-chromatism in the image is similar to ordinary chromatic aberration or secondary spectrum. Sphero-chromatism looms much larger than secondary spectrum in photographic lenses and entirely masks the latter in all but special systems. In an ordinary O.G. at $f/15$ spherochromatism is virtually absent.

---

[1] Conrady, Miss H. G., "Study of the Significance of the Foucault Knife Edge Test when Applied to Refracting Systems"; *Transactions of the Optical Society* (London), Vol. XXV, No. 4, 1923–24, pp. 219 ff.

For oblique bundles the dispersion of glass can again change the shape of the emergent wave front from color to color. This effect, in a manner similar to sphero-chromatism, gives rise to chromatic differences of all the oblique aberrations. Included in this, dispersion can change the "direction" of the emergent oblique wave front, like distortion, from color to color. This aberration has many titles in use, all having the same meaning: *oblique* color, *lateral* color, *transverse* color, or *chromatic difference of magnification* (distortion). Oblique color is positive or overcorrected when the blue image lies above the red image.

It is thus seen that the process of image formation is complex and that, when one includes the ever-present diffraction effects, it becomes tedious to predict in advance the performance of a given system by analysis, and very difficult and sometimes discouraging to synthesize a system to given performance specifications.

If the reader is confused by the above rather loose exposition on aberrations, the writer strongly suggests as denouément the consultation of the more conventional discussions of aberrations to be found in any elementary text on optics.[2]

Glass: In the present chapter an attempt has been made to select design and patent references for duplication of lenses out of the more common glasses. Even so, the amateur, if he obtains his glass through uncertain channels, may have little way of knowing its exact index, and this may be a source of gross error in his execution of a lens. Systems specified in this chapter are not too sensitive to index. Means will be given with each example for overcoming, at least in part, index and whatever other *small* errors creep into the execution.

Glass quality should be considered. Bubbles, unless they occur in sheets, should be thought of only as beauty defects, but not as particularly detrimental to the performance of the lens. Striae are questionable, as always. For lenses of the shorter focal lengths especially, a light ream stria will do little damage if it is oriented perpendicular to the lens axis. Fine striae should be acceptable for most of the work proposed here. Badly strained glass is unusable, of course, and the reader is advised to examine his glass for strain before using it. If it shows no more strain between crossed Polaroids than good polished plate glass (blank immersed if necessary) it may be of acceptable quality for the hobbyist's purposes. Polarized light can also reveal striae in even a translucent pressing.[3]

Radii and Thicknesses: As hinted previously, compared to an O.G., photographic lenses make use of relatively strong curves for like focal lengths. It is necessary to play strong surface powers against each other to gain proper control of more aberrations. Generally speaking, these strong curves give

---

[2] In a section devoted to microscope objectives in Vol. IV of Glazebrook's "Dictionary of Applied Physics," A. E. Conrady gives a mathematical treatment of some of the aberrations in a manner which suggested portions of the above discussion. The serious reader is referred to this as a practical quantitative discussion of the axial aberrations.

[3] For a complete discussion of the defects in optical glass see Ordnance Department Document No. 2037, "The Manufacture of Optical Glass and of Optical Systems," pp. 28–41. (Out of print.) See also ATM, pp. 461–464.

rise to much larger aberrations at each surface. Such playing off of comparatively large aberrations of one surface against those of other surfaces would lead one to expect rightly that the performance would be very sensitive to slight changes of power (radius) and separations (thickness and airspace) of surfaces.

Some lenses are more sensitive to thickness and airspace errors than others. Some types get all their power from thicknesses alone or from airspaces alone. Fortunately, the amateur should not have too much trouble controlling these variables, as they are, for all practical purposes, mechanical problems. He is urged to exercise patience in these matters, saving what leeway is available for those details with which he will have more difficulty. Some idea of tolerances involved will be given in the examples that follow.

Controlling radii will be more of a bugaboo. To hold radii to a fraction of a percent of the nominal value and at the same time maintain truly spherical surfaces generally dictates the use of test glasses whose radii are accurately known.

Those lens types that are well corrected are more sensitive to manufacturing errors than those of poorer corrections. For example, a given error in a radius, or a thickness, in a simple landscape lens would not be nearly as noticeable as a like error somewhere in a Cooke triplet, because the large aberrations of the landscape lens cover up the error. In the simpler types of lenses, especially in the shorter focal lengths, the use of templates alone will suffice. See R. E. Clark, ATMA, p. 158 ff. The worker can mike the templates to .001 inch, and if the final curve on the glass is a light-tight fit it will be satisfactory. Templates are a useful aid to any method of radius control.

The classical method of determining radii is to make direct readings on the surfaces as they are being ground, with a spherometer, in principle like the one shown in ATMA page 242. The accuracy obtainable with such an instrument depends much upon the operator and the instrument itself, and for small lenses the novice will do as well with templates.

Radii can be obtained by optical-mechanical methods. The "optical spherometer" using a vertical illuminator and traveling microscope provides a means for short radius convex and concave surfaces. This method is described in this volume by Irvine C. Gardner and also in the chapter by H. H. Selby on the optical bench.[4] For concave surfaces one has the Foucault test. How well the k.e.-pinhole-to-vertex-of-lens distance is measured determines the accuracy of this method. The Foucault test has the advantage that the figure of the concave surface becomes known at the same time. Before a measurement for radius is made the pinhole and knife-edge must be at equal distance from the concave surface. The closer one keeps the pinhole to the k-e, laterally, the better.

---

[4] See also, for this and other methods: Several pages in B. K. Johnson's "Practical Optics"; J. Guild in *Trans. Opt. Soc.*, Vol. XXII, No. 3; or in Glazebrook, "Dictionary of Applied Physics," Vol. IV, pp. 787–797.

To know accurately the radius and figure on a convex surface requires the use of test glasses and interference methods. This means, unfortunately, making at least an auxiliary spherical concave mate for every different convex surface in the lens system. The radius and figure of this concave mate can be determined by any combination of the above methods. Such a procedure, applied to refractors, was outlined by Patrick A. Driscoll of Kodak in *Scientific American,* March and April 1945. Also included were explanations and interpretations of the fringe patterns.

For mass production test glasses are made up in pairs, the concave glass fitting a convex mate to a 'solid color' by interference, and the radius controlled by an accurate spherometer or other means. Sadly, for the hobbyist who is going to work only half a dozen surfaces, this is an academic method.[5] Mechanical methods for determining radii will not be wholly satisfactory. Departures, in any element, from spherical form of a magnitude far less (few rings) than can be detected by mechanical means could be just as detrimental or worse than a small error in radius. If a surface is spherical but slightly off in radius, the chances are that one can empirically adjust the final lens to compensate. It is unlikely that any empirical adjustment could overcome zonal surface irregularities. Such steep curvatures as are involved here should not lead the worker into extreme difficulties if he has developed any technic at all.

A final point must be mentioned: One does not, in photographic optics, polish up all the surfaces to the proper radii, neglecting the figure on each surface, and then expect to autocollimate the assembled lens against a flat to polish out the zonal irregularities on some selected surface, as one does on an O.G. Photographic lenses are expected to cover a large field and such figuring, while improving the axial imagery, will upset the field corrections. Photo lenses, unless designed otherwise, demand that each surface be spherical. A majority of good photographic lenses, when autocollimated, will not show an emergent axial wave front that is spherical, but will give shadows resembling those of a pronounced oblate spheroid. This is no cause for alarm, the point being that the shadows belong there and do not indicate that the lens is not of high quality. Attempts to promiscuously figure away this zonal appearance could be ruinous to the off-axis imagery.

To sum up, then: Allow yourself practically no tolerances on thickness of the lenses and the airspaces in the final mechanical mount. We may want to adjust the latter, however. This does not mean that a lens is useless because it is .015 inch too thin, but that one may get into dangerous territory. The amateur can well afford to spend the time insuring that his thicknesses and airspaces are right. Second, try to keep the surfaces spherical and strive for the right radius.

The remaining cause of possible error will be in the indices of the glasses. Unachromatized systems offer no problem. If one has done well in his shop

[5] Test plate methods are described also in Johnson's "Practical Optics." Die-hard TNs will find that Chapter VI of their copy of Dévé's "Optical Workshop Principles" covers the subject thoroughly.

work, any sacrifices in the performance of the lens that he will allow can be used to cover up index errors—the one item where the TN is likely to be in the dark. Reputable glass manufacturers can hold indices within stipulated tolerances far smaller than the TN would require for this work, but the rummaging hobbyist is apt to get his glass from unpredictable sources. A total variation of .002 or .004 on index is acceptable for fine photographic objectives in mass production, but where the amateur will be making a single lens and can afford to fuss with it, he can make it perform to his own satisfaction with index errors considerably larger than this, depending on the lens type.

Shop technic is adequately covered in principle throughout the ATM series. The chapters "Introduction to Small Lenses" and "Metal Laps" in ATMA are especially pertinent to this work. What is given in the series as *good* practice in the making of eyepieces and refractors is usually good practice for photo lenses.

Mechanical Considerations: No specifications are given for the mountings of any of the lenses that follow. The many photographic lenses on the market will provide enough examples of mounting methods. The amateur has considerable leeway in regard to how he chooses to mount lenses, provided he keeps certain requirements in mind.

Centering of the lenses is a mechanical problem. They should be centered themselves, and must be centered in the mount. The requirement is, if anything, more stringent than for an O.G., because a decentered element in a lens, in addition to introducing coma on the axis, tips the field of view at a considerable leverage. The latter is of little importance in an O.G. The center line of all the individual cells must coincide, and the optical axis of all the lenses must lie on the mechanical axis, else the system will be decentered. The optical-mechanical axis must be perpendicular to the photographic plate.

Spindle edging of the lenses, with stationary images, assures that the lenses themselves are centered. When making the metal cells, bore to fit the lenses at the same time the mounting threads and shoulders are cut. If the lens is to be burnished in its mount, it should be done at this time, if possible. When the lens and cell are centered in this way no image wobble should be seen when the headstock spindle is rotated. Cells should not cock when screwed tight in the barrel. Do not introduce strain into the lenses through mechanical stress.

When laying out the lens mount, be careful not to provide any obstructions to any beams passing through the lens. Remember that photo lenses need considerable clearance angles at the front and rear lenses to pass the oblique bundles, depending on the field coverage.

Note how commercial lenses have the internal surfaces blackened, including the edges of the lenses. This suppresses ghost images and improves the image contrast.

Iris diaphrams or stops represent another problem. Iris diaphrams are tricky mechanisms. (If you don't think so, take one apart and be sorry!) They are difficult to make without the proper equipment and it would be best to salvage these and shutters from other lenses and incorporate them, if needed, in the new mount. A camera back with a focal plane shutter for use with these lenses relieves the shutter problem. A substitute for an iris is simply a hole in a metal plate. Several of these, in different sizes, can be made up like Waterhouse stops to slip into the proper place through a slot in the side of the lens barrel. Sometimes this series of holes of different sizes is arranged on a simple turret mounted eccentric to the lens. An indexing mechanism then allows the proper stop to be rotated into place.

A diaphram or stop is an important member of an optical system and it also must be centered accurately and located properly or it will adversely affect the aberrations.

All separations of lenses are given in terms of axial distances. Edge spacer dimensions will be determined by the diameter of the lenses, using the exact sagitta formula, and keeping in mind any bevel characteristics. If we can, we should engineer our lens mounts so that they can take up our machining and optical thickness errors and provide for airspace adjustment.

Regarding the lens diameters, it is pointed out that every surface in the lens has its own clear aperture. No mechanical part should cover these clear apertures else useful light will be blocked out. One should not allow clear apertures in the lens that are larger than specified, for he may then be passing light that will be detrimental to the image. For mounting purposes one has freedom in choosing the actual diameters of lenses and bevel characteristics to suit mounting methods.

One does not have to make a given lens at its maximum f number. There would be no harm in taking an $f/4$ lens formula, halving all its clear apertures and making it permanently $f/8$—but not vice versa.

General Testing and Adjusting Procedures: Since these lenses are intended for photographic use, it would be proper to make adjustments photographically. Preliminary adjustments, if needed, can profitably be made visually.

A simple method is just to examine the ground glass image formed by the mounted lens. An old bellows plate camera with a ground glass back is useful, as is any press-type camera. A makeshift substitute should be easy to improvise.

If the lens has been made to specification, no adjustment other than focusing will be necessary. Since this is unlikely for the novice, the ground glass image of a flat object at some distance will reveal much. Newsprint on the wall is a satisfactory test object. There are many test charts made for lenses, all usable, some more easily interpreted than others. The National Bureau of Standards has published test charts in the form of sheets of targets like that shown in Figure 13. A booklet explaining their use, which also contains 12 charts, can be had from the Superintendent of Documents, Government Printing Office, Washington 25, D. C., for 75 cents, money in advance, no stamps. Ask for the National Bureau of Standards Circular C428, "A Test of Lens Resolution for the Photographer." Letter symbol and full title must be given. Additional charts can be obtained from the Superintendent of Documents in a folio containing a number of pages of several charts each, "National Bureau of Standards Circular 533, Supplement," entitled

"Lens Resolution Charts." When testing a lens these charts are cut apart and arranged in some array on a copy board or wall.

Any form of test object, an actual landscape or newsprint, etc., will suffice as long as the user can interpret the results. A few trials will explain more than words. Curvature of field and distortion are easily recognized. Spherical aberration contributes to just plain fuzziness, lack of resolution and contrast. Astigmatism results in loss of resolution in the field. Line objects in different orientations come to focus at different times as the ground glass is moved through the "focal plane." The NBS targets reveal astigmatism very nicely. Coma is manifest in any point images in the field, e.g., images of the sun reflected off the shiny curved portions of automobiles, etc. The chromatic

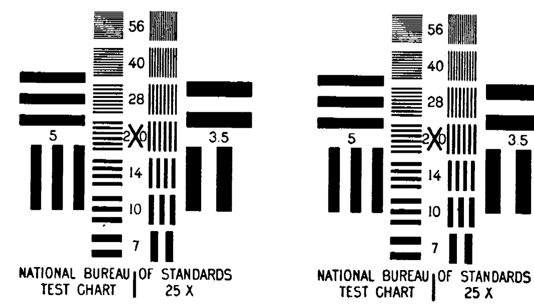


FIGURE 13

aberrations are more subtle than others, especially in landscape views through the ground glass. The effect is sometimes pleasing to the eye but not to the photographic plate. Oblique color is discerned by color fringing of the tangential borders of extra-axial images.

Strictly speaking, test objects described above should lie in one plane perpendicular to the lens axis for test purposes but, for landscape viewing, if the focal length of the lens is not too long, everything beyond a couple of hundred feet may be assumed to lie in one place at infinity. Because aberrations are not stable for all object distances (except certain aberrations under special circumstances) lenses should be tested at the conjugates at which they were designed. With the exception of astronomical objectives, relatively little harm can come from using finite object distances, provided this distance is a large multiple of the focal length, say 20 to 50 times or more—the other end of the basement anyhow—for focal lengths less than 6 inches. For those lenses, process and enlarger types that are designed for use near unit magnification, there is no reason why they cannot be tested at the proper conjugates.

The Foucault test is too sensitive and too difficult to interpret to be of general use in photographic lens work. Autocollimation is relatively useless for short focal length lenses, as it will not work very well off axis because of the length of photographic lenses. A modification of the eyepiece test will do quite well. Page 89, ATM. The pinhole is placed at a large multiple of the focal length in *front* of the lens and can travel perpendicular to the lens axis. Its image, formed by the lens, can be observed by an eyepiece or a microscope. The motion of the pinhole must be at right angles to the lens axis (lens fixed), if field curvature is to be investigated. For example, if a lens is being tested with the pinhole at the opposite end of the basement, it should move laterally along the far wall. Then its image will move laterally in the opposite direction and can be examined in the focal plane by the eyepiece. A little thought will show that if the pinhole is fixed and if the lens is turned to examine the off-axis images, the object is effectively moving in an arc. One could not expect to obtain the flat field characteristics of the lens under such conditions.

The above finite source is in reality a substitution for an optical bench. It is all to the better if one has access to an optical bench or can construct one along the lines of the one described in this volume.

It is impossible to predict what kind of diffraction patterns and image blobs the TN is likely to encounter in his work. The definition of the aberrations, plus the principles given in Selby's chapter, should enable the reader to recognize the defects of his lenses by these methods. See pages 428–436 ATM.

The ultimate criterion of a photographic lens is, of course, photographic performance. After a visually adjusted lens is assembled in a camera it may require photographic readjusting, if for no other reason than to find the best photographic focus. This is especially true in unachromatized simple lenses where non-color sensitized emulsions must be used and hence where the peak sensitivity of the film lies far from that of the eye. Lenses afflicted with considerable spherical aberration have a maximum contrast focus that may be considerably displaced from the highest resolution focus. In photographic lenses, where the manufacturing processes are controlled, these factors, if any, are known and can be allowed for easily. What to call the best focus depends on the observer's prejudices. The reader, after a little conscientious effort, will find it not too difficult to assess his negatives in terms of aberrations.

Any alteration of the performance of a lens, if possible through airspace changes, will depend on rules for specific types and will be discussed with each example. These adjustments can be performed visually, or photographically, or in combination. Each airspace available for adjustment will provide control over at least one aberration, and if the lens is not too bad at the start, one can manipulate as many aberrations as there are airspaces. One cannot, however, expect too much, for if such adjustment is carried very far everything will be upset. If a large change is necessary to bring an aberration that should be corrected to within limits, it is probable that something is wrong. A check and a fresh start, if necessary, should be made.

A decentered element is evidenced by a one-sided flare on the axis of the lens when a pinhole image is observed on the optical bench or with the finite source. Rotation of each element in its cell, one at a time, will locate the

offender in multiple element systems. It may be that the cell and not the lens is decentered. Slight decentering of elements can sometimes be overcome by finding the proper orientation of the elements, the centration errors of one lens compensating those of another element somewhere in the system.

Ratioing to Focal Length: Dimensions for lenses are given in most cases without units. The reader need only to scale any system up or down (except indices!) when he chooses the focal length he desires. An example will illustrate: A lens has its specifications in terms of a focal length of 100. The maker, desiring a 4-inch lens, merely multiplies all radii, thicknesses, clear apertures, airspaces, etc., by 4/100. The rule is: Assume that the specifications are in the unit of measurement that is the same as the desired focal length (although it is usually more convenient to ratio in terms of millimeters).

$$\text{new specifications} = \text{original specification} \times \frac{\text{desired focal length}}{\text{original focal length}}$$

It is feared that the beginner will succumb to the same kind of temptations that we TNs have occasionally been known to do—to start right out making a big, long focus photographic lens. He must be forewarned that, in ratioing any lens system up to longer focal lengths, we ratio the intrinsic aberrations of the lens along with the focal length. The tolerance on residual aberrations, set by given performance standards, remains the same. In other words, the picture quality goes down as the focal length increases for a given lens type as judged, for example, by lines per millimeter resolution on the photograph. To justify themselves longer focal length lenses should be inherently better corrected. The finite grain structure of an emulsion negates the last statement a little. Sometimes, for a given print magnification, there is an advantage in going to longer focal length lenses of the same type.

More important is the fact that on a percentage basis the maker loses shop tolerances, for he also ratios up the effect of his errors. This means that he cannot allow himself as much variation in indices, radii, etc., before it becomes noticeable in the image. The whole matter rests on the user's conception of quality in the image. He will find his troubles magnified as he attempts the better corrected, longer focal length lenses and will be doing well to get the best out of good lenses of any focal length.

A given example cannot be ratioed to any focal length because thicknesses become obstructive, either uncomfortably thin or extravagantly thick. Here each specification has its own limitations.

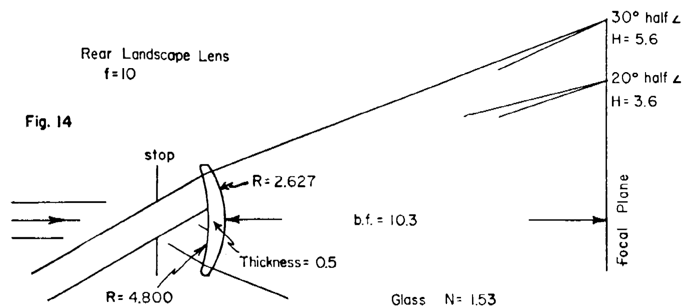
A useful formula used in ratioing is $H = f \tan \theta$, where f is the focal length, $H = \frac{1}{2}$ the diagonal of the usable field, and θ is the half-angular field in the object space. If one knows the useful half-angular field of the lens, θ, and desires the half diagonal H of the plate, the equation can be solved for f, etc. In the presence of distortion this formula is an approximation but still useful.

Finally, it is very important to make a scale drawing of your lens before starting work, to better visualize the problem.

Rear Landscape Lens

This simple meniscus lens, Figure 14, will serve to illustrate many of the principles discussed previously. The characteristics of this lens were computed using a glass index of 1.53. Since there is but one piece of glass in this system, we cannot do anything about its performance in more than one color. No matter what glass we make this lens from, it would have the computed characteristics in that color of light for which the glass has an index of 1.53. Normally we would desire to use this lens in the blue end of the spectrum with non-color sensitized emulsions. Several common glasses have $N = 1.53$ in the blue violet. Borosilicate crown (BSC) of the type $N_D = 1.517$, $V = 64.5$

Fig. 14



Diameter of hole in stop: for f/11=0.91, for f/16=0.62
Stop located 1 38 from vertex of first surface

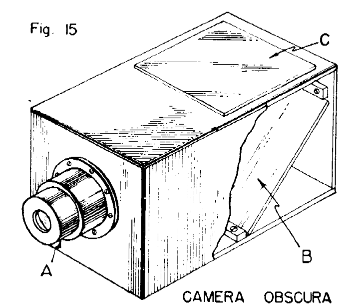
has an index of 1.53 in the violet. Any common optical crown glasses, with N_D running from 1.51 to 1.523, V from 58 to 65, also plate glasses and ophthalmic crowns, have their 1.53 indices in the range from F light to beyond mercury h light. Any of these glasses will be suitable. Ophthalmic crown pressings might be found up to ½ inch thick and 50 mm diameter, which are gently meniscus and would be ideal for this lens. To keep the chromatic aberrations to a minimum, a glass with low dispersion (high V value) is preferable. The BSC glass would be better in this respect, but it is not too important. All these glasses are made in relatively large quantities. Selected plate glass would be satisfactory, too.

The clear aperture diameter of this lens should be at least 2.6 for a 30° half-angular field coverage. The radii are given to four significant figures on this example, but two or three figures are significant; the four figures are included to demonstrate some things later.

Suppose that it is desired to use this lens in a camera obscura such as some artists use for tracing the image of an object, say a vase. In Figure 15, A is the landscape lens and stop in a focusing draw tube; B is a 45° inclined mirror; and C is a clear or ground glass plate on which the tracing paper is

placed. The object is far off to the left and its image can be traced at C. Such arrangement gives a perverted image at C, but this does not seem to bother users unless there is lettering in the object, in which case an appropriate erecting system can be worked out. If an 8 by 10-inch tracing surface is desired, one would proceed as follows: The diagonal of an 8 by 10-inch rectangle is approximately 13 inches. Half of this is 6.5 inches. If the landscape lens is to work at a 30° half-angular coverage, the specifications show that at 30°, $H = 5.6$ for $f = 10$. We need $H = 6.5$, hence must scale up the lens by $6.5/5.6 = 1.16$. All the parameters multiplied by 1.16 would give the following specification for the camera obscura lens: $f = 11.6$ inches, back focus $= 12$ inches for infinity, $R_1 = 5.56$, $R_2 = 3.04$, thickness $= .58$ inch, stop distance $= 1.6$

Fig. 15



CAMERA OBSCURA

inch, diameter of hole in stop for $f/11 = 1.05$, clear aperture $= 3.0$ inches, etc. We would make the diameter of the lens 3.1 inches and have a tenth or so to mount the lens with.

This lens, carried to such a long focal length, would give poor images, perhaps usable visually but very unfavorable photographically. For the interval of indices from 1.52 to 1.53 it has a longitudinal chromatic aberration of 2 percent of the focal length and has very bad undercorrected oblique color, a serious drawback. The axial spherical aberration is undercorrected by nearly 4 percent of f at $f/11$, and the oblique spherical is similarly undercorrected, the two combining to give a uniform softening over the whole field. The lens has barrel distortion of the order of 4.5 percent at the 30° half angle, which is rather noticeable; at 20° the distortion is 1.8 percent. The astigmatism is rather bad. For small bundles through the center of the stop at 30°, the astigmatism is of the order of 7 percent of f, (.8 – .9 inch for the example worked out!); at 20° about 3 percent of f. Coma has been eliminated by the stop position. The field is flattened in this kind of lens by overcorrecting the astigmatism (above) similar to that shown in Figure 7. The lens is improved by stopping down to $f/16$ or $f/22$ and using only a 20° half field. The objectionable lateral color and distortion will remain no matter how far the lens is diaphramed down. The increased depth of focus will help cover up the remaining aberrations.

To see what the effect of manufacturing errors is, assume that the specifications are given in centimeters. If R_2 was executed to 26.00 mm instead of 26.27 mm, this error of .27 mm or .011″ would be equivalent to more than one hundred Newton rings away from a 26.27 mm test glass. Such an error, other things remaining fixed, would shorten the focal length by 2 mm and the back focus by 3 mm. The other properties of the lens would be imperceptibly affected, the astigmatism being very slightly reduced, the field moving a trace toward inward-curving, etc.

If one ground the lens too thin, to 4 mm instead of 5 mm, the focal length would increase by 1½ mm. The only noticeable change would be in the astigmatism which would decrease by .2 mm at 20° and the field moving toward inward-curving again. Results of these errors are insignificant when compared with the original aberrations of the lens and might even be considered an improvement! A well-corrected lens could be ruined by such liberties.

In the matter of adjustment there is only one thing that can be changed to compensate errors after the lens is completed, viz., the diaphram position. The proper place for the stop is the position that eliminates coma in the lens. As the stop is moved closer to the lens, from the coma-free position, outward coma appears. As the stop is moved away from the lens, the comatic flare becomes inward. Using the finite source method, or an optical bench, one can adjust the assembled lens and stop to coma-free position. While observing an oblique point image, the centered stop can be shifted longitudinally along the lens axis until the flare around the oblique image becomes reasonably symmetric.

The coma-free position of the stop gives also the most backward-curving field possible. If the final coma-free field is now inward-curving from processing errors nothing can be done. If it is backward-curving, it can be flattened by the undesirable introduction of coma by shifting the stop in either direction. One sees that the stop is very important to this lens. In fact, the lens would be useless without it. Movement of the stop affects every aberration except axial spherical and color.[6]

If a shutter is used with this lens, it should be placed adjacent to the diaphram or in the focal plane. (This applies to any lens.)

It has been pointed out that this type of lens should not be belittled, in spite of its relatively poor performance, for to convince one's self of the usefulness of this lens with its diaphram, compare the image it forms on ground glass with that of a simple achromat of the same focal length without an external stop!

[6] The true diffraction images arising from the monochromatic aberrations are difficult to see because the chromatic aberrations confuse the image badly. In this case, near monochromatic light is desired when testing this lens with a pinhole. A sodium lamp, or a mercury source with a filter to isolate the appropriate lines, solves the problem. Any filter with a continuous source is better than the source alone. Interference filters lend themselves well to this work. Almost monochromatic light can be obtained by placing one of these filters in front of a continuous source. The diffraction images of the pinhole now formed by the lens are crisp and the aberrations easily recognized.

Front Meniscus Lens

If one changes the system in Figure 14 by moving the stop to the other side of the lens and "bending" the lens accordingly, one obtains a solution similar to the previous case. This type is favored in box cameras because the over-all length of this system is shorter—for like focal lengths—permitting a shorter camera. In addition, the external front element provides protection for the stop and shutter mechanism and it looks nicer.

The specifications for this lens are taken from British patent 271,186 (three sheets) 1927, by Denniss, and are reproduced in the copy of the patent drawing, Figure 16.

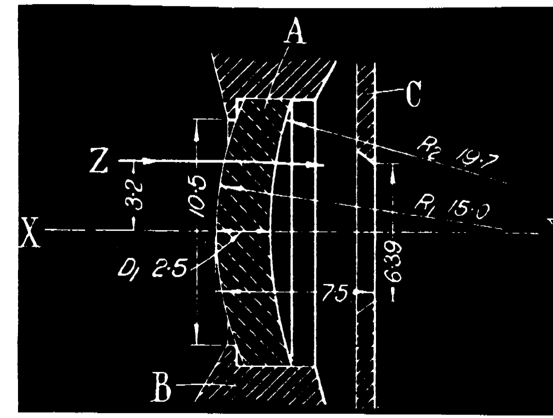


Fig. 16 FRONT LANDSCAPE BP 271,186

The dimensions are given for a focal length of 100. The 3.2 dimension can be ignored. C is the stop; B shows a simple mount.

The same glasses are permissible as in the rear landscape lens, the patent stipulating $N_F = 1.53$, approximately. The stop dimension 6.39 is for $f/14.4$. The lens, as revealed in the patent, has some inward coma and some inward curvature of field. It is felt that its performance could be improved by the following changes: Increase the clear aperture dimension from the 10.5 given, to around 15; move the stop to the right until it is 11.5 from the first surface instead of 7.5; decrease the maximum diameter of the hole in the stop to 5.5 (approx. $f/16$) instead of 6.39. The distance from the stop to the film plane will then be about 84.

The performance will be similar to the previous example. Distortion is about the same amount, 1.8 percent at 20°, but is of opposite sign—now pincushion. Lateral color is again bad, being overcorrected this time.

For a half-angular coverage of 20°, the image distance from the axis is 37. Adjusting procedures are similar to the preceding type. As the diaphram is moved to the right this time, from its proper position (away from the lens), outward coma is introduced; vice versa introduces inward coma. The previous arguments for the case of astigmatism hold in this lens also.

Page 4 of BP 377,036 (5 sheets) 1932, by Lee, contains specifications for three lenses similar to the above, all made from ordinary crown.

Achromatized Landscape Lens

The chromatic aberrations of a landscape lens can be eliminated by making the meniscus out of two different glasses.

F. Weidert in USP 1,643,865 (1927) gives three examples of such lenses. One is chosen to work with here and is shown in Figure 17. The crown glass for lens A, given in the patent, is a borosilicate crown; its equivalent in domestic glass is a standard BSC $N_D = 1.511$, $V = 63.5$. This is relatively inactive glass. The flint lens B is the more common dense flint $N_D = 1.617$, $V = 36.6$. Use of these glasses results in the elimination of both longitudinal and lateral color (95 percent, anyhow), a major improvement over the simple landscape even though the remaining aberrations are quite similar to the original type.

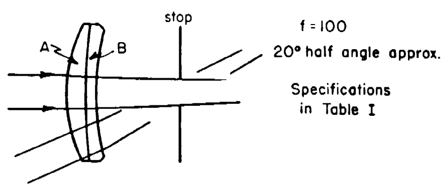
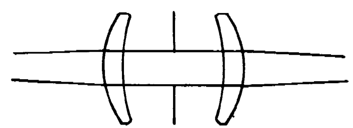


Fig. 17 ACHROMATIC MENISCUS – from USP 1,643,865



Two lenses from Fig. 14

Fig. 18 SYMMETRIC PERISCOPIC LENS

The only damage that results from the substitution of the prevalent BSC 1.517/64.5 for the crown glass is the re-introduction of an almost imperceptible trace of oblique color which would not be worth worrying about. The focal length of the lens will shorten to 96 with such a change.

Table 1 gives the specifications for this lens. Rules for the stop shift are the same as for the simple front landscape lens.

The remaining two examples given in Weidert's patent contain less usual glasses. In addition to the BSC 1.511/63.5 discussed above he has used a dense barium crown (Chance or Schott), and two extra light flints.

Symmetric Periscopic Lens

If two rear landscape lenses, Figure 14, are placed symmetric to a central stop, Figure 18 (each lens 1.38 from the common stop), and the lens is used at unit magnification, the lateral aberrations of each half cancel out, and the longitudinal aberrations add. The elimination of coma, distortion, and lateral color is a valuable step. To maintain the same performance for the longitudinal aberrations the stop diameter should be decreased with the focal length.

Removing the object from $2f$ in front of the lens back out to infinity will put the lateral aberrations back in again, but these aberrations will not be as poor as in the simple lens alone. At least one of the lateral aberrations can be fixed up by moving the stop around longitudinally within the lens. For example, the now inward coma can be fixed up by shifting the stop to the rear a little (.3 from center). Stop movement to the rear produces outward coma. We also have a way now to control the field curvature. Separating the two lenses will bend the field toward backward-curving. With each change in the central airspace, the stop position should be kept at the middle or at the coma-free position. All these changes are apparent on the optical bench.

Table * 1—*ACHROMATIZED LANDSCAPE LENS*

Radii are plus when convex to the incident light.
Equivalent focal length 105 to 95. Back focus (from stop) 84 to 78.

Lens		A		B	
Glass		N_D 1.50 to 1.52 V 65 to 63		N_D 1.617 V 36.6	
Radii	+19.65		+270		+35.11
Axial thickness		3.0	(cement)	1.25	
Diameter		18 (Limited by edge thickness of A)		18	
Clear aperture		17	(Arbitrary)	17	
Stop		11.0 from rear vertex of lens B. Maximum diameter 7.2 (f/11).			
Half-field			20° to 30°		

* The vertical rules in the tables represent surfaces.

The compounding of these two lenses produces a system with a focal length of 6.2 instead of 10, and a back focus of 4.1. The stop diameter should be 0.6 or less ($f/8$). The diameters of the lenses can be arbitrarily set at 2.5 and the lens will cover say 25° (half field) with considerable improvement over the simple lens.

Unsymmetric Periscopic Doublet

By departing from symmetry the periscopic lens can be freed of the lateral aberrations for infinity. To do this and to avoid the awkwardly large system above, we adapt from a prior art citation by D. L. Wood in USP 1,954,340 the form shown in Figure 19 with specifications in Table 2. Now the residual

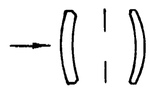

See Table II

Fig. 19 UNSYMMETRIC PERISCOPIC DOUBLET

lateral aberrations are negligible, resulting in a remarkably good lens considering that it is not even achromatized in the ordinary sense. The longitudinal aberrations are of the same nature as in all the previous types. The absence of oblique color will enable this lens to take acceptable pictures on 35 mm color film if the focal length is kept short, say no longer than the standard 50 mm (Table 2 × ½).

Table 2—*UNSYMMETRIC PERISCOPIC DOUBLET*

Equivalent focal length 100. Back focal length 91.

Lens		A				B	
Glass		$N = 1.53$				$N = 1.53$	
Radii	+29		+35		−29		−21.5
Axial thickness		3.5		17 (air)		2.5	
Clear aperture		20				20	
Diameter		22		(Arbitrary)		22	
Stop				In the middle of the airspace, maximum diameter 8.5 ($f/11$)			
Half-field				Arbitrary 25°			

Selection of glass for this type follows the arguments given under the rear meniscus type, as do all the previous types with the exception of the achromatized meniscus. Adjustment of this lens follows that of the symmetric periscopic type.

Note that the concave surface of the rear lens can be worked against the convex surface of the front lens, test glass fashion.

Extreme Wide-angle Lens

If the symmetric periscopic type is carried to an extreme there results an interesting and simple lens, the making of which will try the skill of any optician. Such a lens, Figure 20, known by the trade name of "Hypergon,"

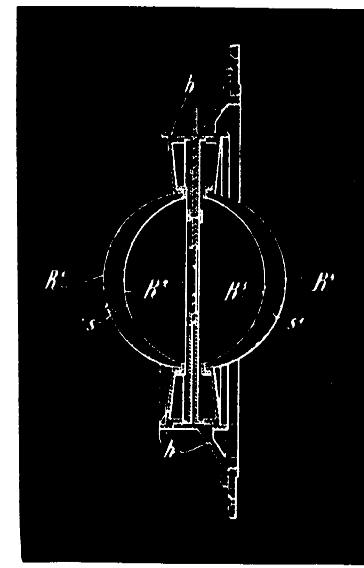


Fig. 20

THE "HYPERGON"
USP 760,650

was shown by Goerz in USP 706,650 (1902). One finds in the patent that the dimensions are given to six significant figures which shouldn't be taken as significant. Discounting these, data are reproduced in Table 3. Such a lens is capable of covering tremendous fields, the patent claiming a 130° total field, and the lens merits some discussion.

It is unachromatized but the oblique color is negligible throughout the entire field because of symmetry. Symmetry and the extreme shape also account for low amounts of coma and distortion, the latter being of the order of 0.01 percent at 45°—practically nothing! Astigmatism is extremely small

—none at 35° (node), a tenth of a percent of f at 45°. Longitudinal color and spherical aberration are tremendous, producing a soft picture and severely restricting the maximum opening of the lens to around $f/25$. Yet that such a simple lens will cover a plate whose diagonal is more than twice the focal length is remarkable. Unfortunately, the illumination in the focal plane drops off rapidly from natural causes with increasing obliquity. At 45° the illumination is only some 18 percent of that in the center of the field. Special devices are necessary to overcome this limitation. An air-driven rotating star-shaped

TABLE 3—*EXTREME WIDE-ANGLE "GLOBE" LENS*

Equivalent focal length 100. Back focal length 87.

Lens		I				II	
Glass		$N = 1.52$				$N = 1.52$	
Radii	+8.47		+8.51		−8.51		−8.47
Axial thickness		2.21		13.6 (air)		2.21	
Clear aperture		15				15	
Diameter		15–16				15–16	
Stop	In the middle of the airspace. Maximum diameter 3.4 ($f/25$)						
Half-field	45° ?						

diaphram has been used to reduce the relative illumination in the center of the field. A "vignetting filter" will accomplish the same thing. Without these special mechanisms, the amateur will be forced to use only that portion of the field in which the latitude of the (ortho) film will handle the decreasing illumination.

Table 3 shows that the strong menisci are very thin. For $f = 100$ mm (4 inches), thicknesses are 2.21 mm (.087 inch). If a much shorter focal length is attempted these thicknesses become suicidally small. Focal lengths too much longer than 4 inches are not advisable, as the aberrations become larger dimensionally and few can afford the plates that it will cover! Three or four inches is suggested for the first try.

The lenses are practically hemispheres and one will have to hog them out of fairly thick blocks of glass. To make a near hemisphere that has a maximum thickness of a millimeter or so without breaking half a dozen first is no easy task. Note that the inner and outer radii are almost equal. Here is a lens that gets most of its power from its thicknesses, small though they be.

If all radii are equal, it would still have power. It would not take much careless work to end up with a radius on the convex surface that is longer than that of the concave surface! In all, this lens requires close workmanship. It is difficult to polish these lenses to the very edge.

The same glasses can be used as in the rear landscape lens, the patent even saying that the exact index is unimportant. Adjustments follow those for the periscopic type.

Note that the hole in the central stop is much smaller than the lens diameter. A clear aperture of 15 is needed on each lens to clear the 45° bundles. These lenses become sharp-edged at 16.8, so that between the diameters of 15 and 16.8 the lens is very thin. All cell retaining rings will have to be judiciously used to avoid pressure, or breakage will result.

The stop should be made of thin metal; if the hole has an appreciable length, it will block oblique light. Figure 20 from the patent suggests a typical mount for the lens.

For a focal length of 100 mm, if the last radius were made 8.48 mm instead of 8.47 mm, the focal length would increase 0.7 mm, the field would move a little toward backward-curving, the astigmatic node would become lower, and the distortion would become slightly more positive—all quite insignificant changes. If the last thickness is 2.11 mm instead of 2.21 mm (an error of 0.1 mm or .004 inch!), the focal length will increase 2½ mm, the astigmatism will become overcorrected by 1½ percent of f at 45°, and the field correspondingly goes backward-curving by the same amount! Things happen rapidly at such extreme obliquities; even so, it is questionable that they should be too noticeable, as this lens, working at $f/25$ or below, has been called a glorified pinhole and would have considerable depth of focus!

COOKE TRIPLET

Of the many different types of highy corrected anastigmats, only one will be presented in conclusion. All photographic lenses in which the residual aberrations are small require workmanship and facilities beyond the probable means of the average amateur. It would be of little use to make a five element lens unless one's abilities and assets enabled him to get the best out of a four element design, etc. Good lenses are not obtained by the mere addition of elements.

A considerable majority of good photo lenses are of the Cooke triplet type or its derivatives. This type contains but three simple airspaced lenses, the minimum number needed to correct all the aberrations.

Unfortunately, there is no decent spherically corrected solution for the triplet using the common glasses we have been working with. The system becomes long, and any solution has large zonal aberrations. Use of the dense barium crowns shortens the system and improves the zonal characteristics. The following patent references on the triplet are offered for what they are worth, and may be tried if one has the glasses: Beck and Beck, BP 4714 (4 sheets) 1911, a triplet using ordinary crown and an available light flint, promising as a simple type, but the claims seem optimistic in spite of a large *f*-number (*f*/8); Beck and Beck, USP 1,035,408; Wandersleb, USP 1,073,789; Altman, USP 1,658,365. The last-named three use dense barium crowns and light or dense flints.

USP 540,122 and USP 568,052, in which in 1895 and 1896 H. Dennis Taylor revealed his invention of the triplet, have been pointed out as being of historical value and are a bargain for a quarter. The patents are long, containing discussions of aberrations, and one is not troubled with the usual argot of the patent attorneys. In the first patent he had not realized that the individual lenses need not be separately achromatized. Consequently, we would not be too interested in the specifications given there. (The glasses are

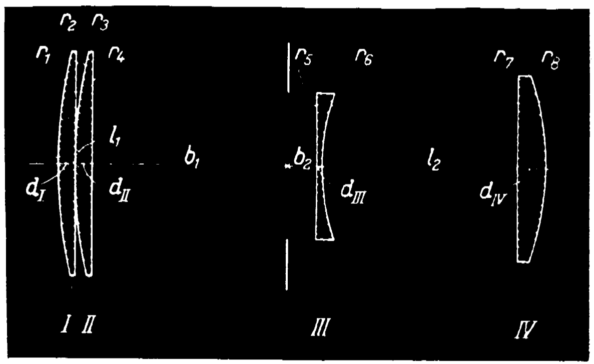


Fig. 21 MODIFIED "TRIPLET" FOR ASTRONOMICAL PURPOSES USP 1,825,828

difficult to obtain.) It is remarkable that the patent even contains several interesting pages on working instructions and adjusting methods, including the use of the finite source, some a little crude by present-day standards, but not without merit or interest. The second patent, in addition to another discussion on aberrations, contains specifications of his famous Series lenses. Some space is devoted to shop technic and procedures for adjusting. It would be enlightening to duplicate his lenses.

Reference is included here for those who are interested in Rudolph's original patent on the Tessar type, an improvement over the Cooke triplet (although not expressed as such). USP 721,240 contains some specifications.

A. Sonnefeld, in USP 1,825,828, revealed a modification of a Cooke triplet that should interest us "astronomers." He split the front elements of a Cooke triplet into two lenses, thereby reducing the spherical aberration of that member by four. An excellent solution is now possible, using ordinary glasses, which will enable us to take first class astronomical photographs. This lens was specifically designed for astronomical purposes and is shown in Figure 21

and Table 4, reproduced from the patent. (Note that the first two crown lenses are identical and are *concave* on the rear surfaces.) Specifications were for an *f*/5 lens with a focal length of 2000 mm (1970). Since such a lens (78 inches efl) represents several thousand dollars' worth of glass, out of reach of nearly everyone, Table 4 has the dimensions scaled down by a factor of 10 and the cost by a factor of at least 100!

First, a description of the lens: Whereas the splitting of the front lens has given us excellent correction for the aberrations, the system still remains long, and vignetting restricts the field. (The dotted part of the wave front in Figure 7 does not pass through the lens as it would for an axial beam.) This is not too serious, as the high image quality demanded in astronomical work limits the field anyway.

TABLE 4—*SPECIFICATIONS FROM USP* 1,825,828 (See Figure 21)

Equivalent focal length 197

	Radii		Thicknesses and distances
R_1	+89.7	d_I	3.0 mm
R_2	+363.6	l_I	0. mm
R_3	+89.7	d_{II}	3.0 mm
R_4	+363.6	b_I	34.2 mm
R_5	−98.0	b_2	5.0 mm
R_6	+38.9	d_{III}	.8 mm
R_7	+225.4	l_2	33.8 mm
R_8	−50.1	d_{IV}	5.0 mm

Kinds of glass

	I	II	III	IV
N_d	1.5163	1.5163	1.6129	1.5163
V	64.0	64.0	37.0	64.0

The spherical aberration is so low in this lens that sphero-chromatism is absent in the region used and secondary spectrum has to be reckoned with again. Nothing can be done about it, but it does cause image deterioration at very long focal lengths. The field is flat, practically free from astigmatism out to 5° off the axis (node), and the definition begins to drop off beyond 6° or 7° because of rapidly increasing astigmatism. The minimum back focus is deep in the blue end of the spectrum (4300A) and secondary spectrum, for even the focal lengths in which we are interested will restrict us to the use of Class O or similarly sensitized emulsions. The over-all quality of the lens is so high, and the firmament is such a rigorous test object, that we cannot countenance any compromises in workmanship.

All three crown lenses are given in the patent as made from Schott's BK-7, which is very close to the domestic 1.517/64.5. The flint glass is Schott's F-3, relatively far from the domestic 1.617/36.6. The lens, of course, could be made straightforwardly from the patent, using BK-7 and F-3, but this lens will now be fixed up so that it can be made from refractor blanks, thus eliminating the glass problem, since all the major suppliers of optical glass stock list refractor blanks. This system is here standardized around the American glasses 1.517/64.5 and 1.617/36.6. Chance Bros. have indicated willingness to supply refracting telescope blanks of 1.518/64.1, which is satisfactory, and 1.617/36.6. Schott's BK-7 is practically 1.517/64.5 and will not upset a recomputed system either. Unfortunately for this problem, Fish-Schurman's postwar list of Schott refractor blanks shows that they supply F-2, 1.620/36.3, uncomfortably far from the 1.617/36.6. Schott's F-4 is the type we shall be working with and this no doubt could be supplied. With one glass a possible exception, all suppliers are in accord on glass types for refractor disks. These two glasses are in such wide use that other sources may well turn up. Use of refractor blanks will assure the quality of glass this lens deserves. Note that three crown blanks and only one flint blank are needed.

If we scale down the original specification to 15 or 20 inches focal length, the thicknesses become dangerously thin on the first three elements. We will increase these thicknesses somewhat to avoid breakage or warping, but we cannot go too far, otherwise we shall not be able to get them out of the 8:1 or 9:1 ratio of diameter to thickness usual in refractor disks. Bausch & Lomb's $4\frac{1}{2}$ and $3\frac{1}{2}$-inch blanks are much thicker than this and give a comfortable margin. Perhaps others will supply them thicker if requested. In any case, the lens will be engineered to take the standard sizes.

With these slight changes in glasses and thicknesses, and a little alteration of the patented system, the specifications now appear in Table 5.

It would be well to discuss Table 5 item by item, where necessary. The zero airspace between lenses I and II means that they are touching (but no pressure) or slightly separated (.001 inch) at the center.

The minimum clear aperture diameters are given for every surface, as we are now working to closer limits. The front clear apertures can be made larger, the rear clear apertures should not be made larger, and none should be made smaller than the values given. Since we would not be using a diaphram with this lens for astronomical photography (it would be placed just in front of or behind lens III if it were used), one of the lenses must be the aperture stop for the system. This should be the flint lens. The cell or bevels for lens III should restrict the clear apertures to the values given—no more, no less.

The actual diameters are arbitrary, but cannot be changed too much on the crowns, for the edge thicknesses are already small. The theoretical minimum blank thicknesses are given also, taking into account only the axial thicknesses plus the "sags" at the true diameters of the concave surfaces on lenses I and II; the minimum needed thicknesses at the clear apertures on lens III; and the axial thickness of lens IV. (See Figure 22). It is best to add *at least* a millimeter or two to the minimum blank thicknesses. Make certain to choose the thicknesses that will permit pressing defects to be ground off.

Before discussing the remainder of the table, labeled "preferred system,"

TABLE 5—*MODIFIED COOKE "TRIPLET" AFTER USP 1,825,828*

Equivalent focal length 196.4 mm (7.74 inches) (G' light) Back focal length 162 $f/4.9$

1. Lens		I				II				III				IV	
2. Glass N_D, V		BSC 1.517/64.5				BSC 1.517/64.5				DF 1.617/36.6				BSC 1.517/64.5	
3. Radii	+89.7		+363.6		+89.7		+363.6		−105.75		+37.8		+222.1		−50.26
4. Axial thickness		4.2		0 (air)		4.2		37.0 (air)		1.5		34.6 (air)		5.0	
5. Minimum clear aperture diameters	40		39.6		39.3		38.6		25.7		25.1		33.7		33.8
6. Recommended actual diameter with above		42				42				>28				35.8	
7. Edge thickness		2.3				2.3				>4.5				1.0	
8. Minimum blank thickness		4.9				4.9				4.5				5.0	
Preferred System															
5a. Preferred clear apertures	50		49.5		48.5		47.7			Same		as		above	
6a. Recommended diameter for preferred c.a.		52				52				"		"		"	
7a. Edge thickness		1.3				1.3				"		"		"	
8a. Minimum blank thickness		5.2				5.2				"		"		"	

9. Minimum dimension of the photographic plate 40 (6° half field).

Tabular values are in terms of the focal length in millimeters.
Ratio factors are to be applied to items 3 to 9, and to the focal lengths.

let us digress with some examples. For a given set of glass disks, either the diameters or thicknesses of the disks will limit the longest focal length of the lens that we can make with the glass on hand. Suppose that we had three 4½-inch crown blanks, 115 mm in diameter by 20 mm thick, and that we were sure we could get a finished diameter out of them, after centering, of 110 mm. Dividing the 110 by 42 (from the tabulated diameter of lenses I and II) gives us a factor of 2.6. We then make out a new table, multiplying all dimensions in the original table by 2.6, and check to see that everything fits. The exact factor is not important (two significant figures) but, once chosen, should be applied to each dimension accurately. The new thicknesses for I and II are 10.9, the minimum blank thicknesses around 13 for I, II, and IV, etc.—all satisfactory for these blanks. The new table should show that we need a

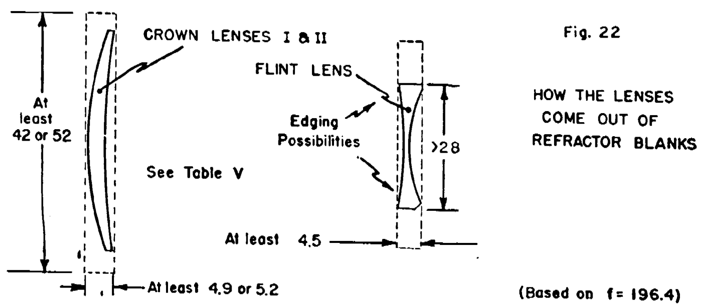


Fig. 22

flint blank of 80 mm by 13 mm, which could possibly be a thick 3½-inch blank. If this flint thickness is not available in a 3½-inch blank, use of a larger blank is dictated, with the possibility of considerable glass wastage around the periphery of this lens (Figure 22). This factor of 2.6, applied to Table 5, will produce an $f/4.9$ lens of 20-inch focal length for use with 4 by 5 plates.

If the 115 mm blanks are of the usual 9:1 ratio, having a 13 mm thickness, this thickness will now be the limiting factor for the maximum focal length obtainable. Our factor of 2.6 produced a 13 mm thickness for the minimum crown blank thicknesses. To take the theoretical minimum would be risky, as it would hardly be possible to get lens IV, for example, finished to an exact thickness of 13 mm when the original blank is close to 13. It is necessary to take a safer factor, say 2.0 or 2.3, and be satisfied with a 15 or 17-inch lens even though some of the diameters of the blanks are wasted. It may be that the dimensions of a specific flint blank will be the limiting factor, and it also should be watched.

Approximate edge thicknesses without bevels are tabulated for reference also. These edge thicknesses are rather small. Any feathered sharp edges likely to result in the crowns before centering are to be handled carefully. The center thicknesses of the lenses are none too thick either, even though they have been increased over the patent, and the lenses could be sprung easily

in processing if maltreated. It would be best to grind the convex surfaces of lenses I and II before the concave surfaces. The four concave surfaces can be held spherical by the Foucault test. Something should be done to insure that the three different convex surfaces are spherical too, and that all are near the correct radii. A ten ring radius error on any surface is undesirable.

The considerable length of this system causes a loss of more than one third of the illumination at 5°, relative to the center of the field, because of vignetting. Although it is not necessary, something can be done to increase the off-axis illumination. With the flint lens as the aperture stop, the two front lens diameters can be increased. The aberrations are behaving very well as this is done and a better lens results—not so when the other lenses are opened up. The bottom of Table 5, labeled "Preferred System," gives appropriate new dimensions for lenses I and II. This now means that the first two lenses are going to need even larger blanks for the same focal lengths, and the system will have to be laid out again.

If we return to our original example with 115 mm blanks, 110 divided now by 52 gives us a new ratio factor of 2.1 and 410 mm (16.3-inch) focal length results. A new table will show that minimum blank thicknesses are: I, 11 mm; II, 11 mm; III, 9.5 mm; and IV, 10.5 mm—all possible with any 9:1 refractor disks. We now have, with the same 4½-inch blanks, an $f/4.9$ 16-inch lens instead of a 20-inch lens, but we have picked up the relative illumination off the axis.

Adjusting the finished lens of either type could be complicated. Provision should be made in the mechanical mount for the adjustment of the positions of the last two lenses. Adjustments should be made, photographically, on a bright star field with short exposures. Start with the elements well centered in their cells and separated by the nominal airspaces. Find the best photographic focus. Record data on each plate. If the best performance at the nominal airspace is questionable, increase or decrease the third airspace (34.6) by one or two percent of the airspace. Find the best photographic focus again. If this is better than the original best focus, continue increasing, or decreasing, the third airspace in steps until the best position of lens IV is definite. The direction of the shift of lens IV may have been taken in the wrong direction at the start. When this is apparent, go in the opposite direction, finding the best photographic focus each time, etc.

When the best position of lens IV is known, the image quality may still be in question. If this is the case, we will then change the second airspace (37.0 in the table for $f = 196$) by a percent or so. Starting with the best third airspace as found previously (this means that lenses III and IV were moved together), we again find the best focus. Then we repeat the whole series of alterations of the third airspace as above, if needed.

This will finally give us two plates—one taken with the nominal second airspace and the best third airspace, the other taken with a changed second airspace and a new best third airspace. Comparison will show whether the change in the second airspace was in the right or wrong direction. Then the whole process can be repeated again with new values of the second airspace, with corresponding new best values for the third airspace, etc., until the airspaces that give the best performance have been bracketed within narrow limits. The lenses should then be locked in position. This procedure will use an extravagant quantity of plates but is worthwhile. If one can keep track of what he is doing, he can accomplish many of the above steps on one photographic plate, while using interrupted star trails.

It is very important that one duplicate Table 5 for every contemplated focal length for this lens. A scale drawing should then be made and the glass blanks drawn around the lens layouts to insure that no principles have been violated. The final specifications should be set only after the glass has been obtained and after one has taken stock of his courage and the blanks' usable dimensions. One would be very wise to make up an 8-inch system out of 2-inch blanks to become acquainted with the lens type before investing money in a bigger lens. A 20-inch lens of this kind, properly made, represents a glass cost of less than $50 and will be capable of taking astro-photographs comparable to lenses whose values are many hundreds of dollars.

Patents: Printed copies of U. S. patents referred to in this chapter and elsewhere can be obtained from the U. S. Patent Office directly. Letters should be addressed to the Commissioner of Patents, Washington, D. C., and should contain the patent number and a remittance of 25 cents in advance for each patent desired. Postage stamps are not accepted. All payments should be to the Commissioner of Patents in the form of a P.O. money order or certified check. Those who are likely to be ordering patents from time to time will find it convenient to use coupon books provided by the Patent Office. A $5 book contains twenty 25-cent coupons and a $25 book contains 100 coupons. One merely tears out a chit, writes the patent number and other information on it and sends it in. These are useful for other purposes also.

Many institutions in the nation keep patent files. The following are listed by the Patent Office as maintaining files of patent specifications for public use: Albany, New York—University of the State of New York; Atlanta, Georgia—Georgia Tech. Library; Boston, Massachusetts—Public Library; Buffalo, New York—Grosvenor Library; Chicago, Illinois—Public Library; Cincinnati, Ohio—Public Library; Cleveland, Ohio—Public Library; Columbus, Ohio—Ohio State University Library; Detroit, Michigan—Public Library; Kansas City, Missouri—Linda Hall Library; Los Angeles, California—Public Library; Madison, Wisconsin—State Historical Society of Wisconsin; Milwaukee, Wisconsin—Public Library; Minneapolis, Minnesota—Public Library; Newark, New Jersey—Public Library; New York, New York—Public Library; Philadelphia, Pennsylvania—Franklin Institute; Pittsburgh, Pennsylvania—Carnegie Library; Providence, Rhode Island—Public Library; St. Louis, Missouri—Public Library; Toledo, Ohio—Public Library; Washington, D. C.—Patent Office Search Room.

The fortunate readers having access to these libraries should find copies available of most U. S. patents, listed numerically. Many other libraries have (less complete) data and the interested reader is advised to explore that possibility in his own community.

The situation with regard to foreign patents is not so favorable. Photostats of foreign patents (give patent number, year, and country) are available from the same U. S. Patent Office, Washington, D. C., at 20 cents a sheet (use your coupons), sheet being the equivalent of page in Patent Office terms. Unfortunately, one is not likely to know beforehand how many sheets are contained in any foreign patent; and how far one should try the Patent Office's patience in this matter is a moot question. One suggestion is to tear off half a dozen coupons and send them along. If you overpay, the Commissioner will return the excess coupons.

The New York Public Library has a very complete collection of foreign patents, also, and photostats may be obtained from them. Contact their Photographic Service, giving the patent number, year of issue if possible, and country, and requesting an estimate on a photostatic copy.

As it is contemplated that there will be some readers with enough time and interest to explore the patent files in general, a procedure will be outlined for doing this, but this procedure is involved and *not* very satisfactory

Some two and a half million patents have been issued to date in the U. S. As one cannot thumb through all the patents looking for things in which he is interested, the Patent Office has a workable classification system, the use of which will locate the desired patents. A specific example will serve as an illustration. Let us suppose that we are interested in the subject of prisms. First we should go to the "Index to Classification of Patents" (a U. S. Patent Office publication, like a subject index, available in libraries). The "Index" would show us that patents pertaining to prisms are contained in the Patent Office's classification "Class 88 Subclass 1." Since we are looking for the numbers of prism patents, we next would have to obtain the numbers of all patents in Class 88 Subclass 1. This might involve a few patents or a thousand. To ascertain their numbers, one would have to write to the Commissioner of Patents requesting a list *by number* of all patents in Class 88 Subclass 1. (Do not think of ordering all the patents in a given subclass, or make the mistake of asking for a list by number of all patents in a whole class and forgetting to name the subclass. These lists cost 20 cents a sheet, a sheet in this case consisting of one sheet of an IBM tape. Again there is no way of knowing in advance how many sheets will be required to list a subclass at, say, 100 to the sheet. A guessed average would be ten sheets. In any case, overpay the Office and save trouble. Send them a handful of coupons. (The serious student of the patent files could with advantage open a "Deposit Account" with the Patent Office and avoid these troubles. Coupon books, subclass lists, etc., can be charged against this small bank account, minimum balance, $25. Address inquiries to the Publications Division of the Patent Office.)

Now, having the class and subclass list by number, we would return to the patent files and look up every patent by number, possibly finding that nine tenths of the patents in the subclass do not pertain to prisms at all since it is a miscellaneous subclass.

In case no patent files are available, an even less satisfactory procedure is to go to the "*Official Patent Gazette*" after the patent numbers have been obtained. The many volumes of the *Patent Gazette* (available in many libraries) contain short descriptions, usually one drawing and one claim, of every patent issued, arranged chronologically by patent number. After looking up every patent number in the subclass, it will be possible to choose the patents that look interesting. These then would have to be obtained from the Commissioner again, at 25 cents a copy.

General remarks: Class 88 is optics, Class 95 is photography, etc. Class 88 has approximately 100 subclasses. For example: Class 88–1 Miscellaneous; 88–1.5 Camera finders; 88–15 Kaleidoscopes; 88–32 Telescopes; 88–33 Prismatic telescopes; 88–34 Field and Opera glasses; 88–39 Microscopes; 88–57 Lenses. Most of the photographic lenses are contained in Class 88–57. At mid-century the list of subclass 57 contained some 560 patents. To make a thorough search of a subclass one should request from the Commissioner, with the subclass list, a list by number of the "Official Cross References." This is a similar listing of patents which conceivably could pertain to Class 88–57, but which are more appropriately classified elsewhere. For class 88–57, the cross references contained about 340 patents, making a total of some 900 patents to be explored on "lenses" alone.

It is easily seen that one undertakes a considerable task in surveying just one subclass of the patent literature. The writer's advice, although he knows it will not deter those for whom this was written, is to leave the studying of the patent files to corporations and patent attorneys, and to be content in obtaining those patents whose numbers are made known to him. Patent attorneys could provide any of the above services, but they usually do not solicit this work. The reader should realize that, in addition to the basic cost the attorney must pay to the government, he must add his fees.

To make the lenses described in this chapter it is not necessary to obtain the patents referred to. The useful information, usually meager, has been extracted from the patents and given here.

On Computing the Radii of an Achromatic Objective

By Charles L. Woodside

[Editor's Note: The following chapter is reprinted from the *Scientific American Supplement* 1897, December 11. Concerning it Lt.-Col. Alan E. Gee says, "This is an approximation method giving results about midway between Ellison's method and the algebraic G-sum method as to accuracy of design. Spherical correction is closely approximated. Coma is left to chance. This is a very neat system, much easier than the algebraic G-sum method—as easy as Ellison's yet giving much better results." It has the added advantage that it permits the use of glasses with unknown constants. A search reveals that its author, who lived in Boston, died in 1934.]

When the writer decided to grind an achromatic of 5 inch aperture, he found that although the lenses might have been ground on curves similar to some others, yet the element of uncertainty in the result was so great, owing largely to the fact that nothing was known of the refractive or dispersive powers of the glass which was intended to be used, that the writer decided to investigate the subject, first theoretically, then practically, in the hope of evolving some simple method of ascertaining the proper curves under such conditions.

The formula employed in computing the radii is practically that of Littrow, and an objective constructed according to this plan will have its crown lens double convex and its flint lens double concave generally, though sometimes concavo-convex. The first two surfaces, I and II, reckoning from the front of the objective, will always be of equal radii; III will be of nearly the same radius as II, and in certain cases the radii of I, II, and III may be alike, while IIII will usually be of long radius, nearly flat. [If the sign of IIII is +, the surface is concave, if − it is convex.—*Ed.*]

In the making of an objective, if the indices of refraction and the ratio of the dispersions of the two pieces of glass are known, the four radii and resulting focal length may be computed with reasonable exactness before the work begins; but, if these quantities are not known, they must be assumed, and the resulting focal length will therefore be uncertain within small limits until the work has reached a certain stage of completion.

Presuming, then, that these quantities are known, we have

μ = mean index of refraction of the crown glass.
$D\mu$ = dispersion of the crown glass.
μ' = mean index of refraction of the flint glass.
$D\mu'$ = dispersion of the flint glass.
λ = ratio of the dispersions [By $D\mu'$, or dispersion, the author means $N_F - N_C$.—*Ed.*]
δ = ratio of the dispersive powers (that is, the dispersions combined with the refractions) = ratio of the focal lengths of the lenses.
I = radius of the outer surface of the crown lens.

II = radius of the contact surface of the crown lens.
III = radius of the contact surface of the flint lens.
IIII = radius of the outer surface of the flint lens.
f_1 = focal length of the crown lens.
f_2 = focal length of the flint lens.
F = focal length of the objective.

Let us first compute λ, which we use as the argument of the "Table for Computing Radius III," thus:

$$\frac{D\mu}{D\mu'} = \lambda \qquad (1)$$

and then compute δ, the ratio of the dispersive powers (and consequently the ratio of f_1 to f_2, inasmuch as the focal lengths of the lenses must be proportional to the dispersive powers), thus:

$$\lambda \div \frac{\mu - 1}{\mu' - 1} = \delta \qquad (2)$$

Having determined upon the focal length of the objective, we next compute f_2 thus:

$$F \times \frac{1 - \delta}{\delta} = f_2 \qquad (3)$$

and f_1 thus:

$$f_2 \times \delta = f_1 \qquad (4)$$

We now compute the radii of I and II thus:

$$f_1 \times 2 \times (\mu - 1) = \text{I} = \text{II} \qquad (5)$$

and then, referring to Table 1, and using λ as the argument, we take out the quantities α, β, and γ, and compute III thus:

$$f_1 \times [\alpha + (\beta \times (\mu - 1.50)) + (\gamma \times (\mu' - 1.60))] = \text{III} \qquad (6)$$

It only remains for us to compute IIII thus:

$$\frac{\text{III} \times (f_2 \times (\mu' - 1))}{\text{III} - (f_2 \times (\mu' - 1))} = \text{IIII} \qquad (7)$$

and we have the complete data for the construction of the objective.

Let us, for example, compute the radii of an objective of 60-inch focal length, using hard crown and dense flint glass, for which we find that:

$$\mu = 1.52$$
$$\mu' = 1.63$$
$$D\mu = 0.014$$
$$D\mu' = 0.028$$
$$\lambda = \frac{0.014}{0.028} = 0.5 \qquad (1)$$
$$\delta = 0.5 \div \frac{0.52}{0.63} = 0.60577 \qquad (2)$$
$$F = 60 \text{ inches, and}$$
$$f_2 = 60 \times \frac{1 - 0.60577}{0.60577} = \frac{0.39423}{0.60577} = 39.0474 \qquad (3)$$
$$f_1 = 39.0474 \times 0.60577 = 23.6537 \qquad (4)$$
$$\text{I (and II)} = 23.6537 \times 2 \times 0.52 = 24.5998 \qquad (5)$$

From the Table, with λ = 0.5 as the argument, we find that

$$\alpha = 1.00273, \quad \beta = 1.331 \quad \text{and} \quad \gamma = 0.623; \text{hence,}$$
$$\text{III} = 1.00273 + (1.331 \times 0.02 = 0.02662) + (0.623 \times 0.03 = 0.01869)$$
$$= 1.04804 \times 23.6537 = 24.7900 \qquad (6)$$
$$\text{IIII} = \frac{24.79 \times (39.0474 \times 0.63)}{24.79 - (39.0474 \times 0.63)} = \frac{609.8305}{0.1902} = 3206.26 \qquad (7)$$

Therefore, we have:

I = 24.60 inches
II = 24.60 inches
III = 24.79 inches
IIII = 3206.26 inches
F = 60.00 inches

It will at once be seen that the computation of the radii is extremely simple and direct, and requires no more knowledge of arithmetic than is commonly acquired in our public schools.

It has been stated above that in certain cases the radii of I, II and III may be made of equal length. The condition upon which this depends is that the computed radius of II (and I) must be slightly shorter than that of III. Such being the case, the radii of I and II may then be increased to equal that of III and the lenses separated a certain small distance exactly equal to the increase in focal length of the crown lens resulting from the increase in the radii of I and II. However, the distance by which the lenses are separated must not be large, and ought not in any case to exceed say 1/25 of the focal

Table 1—*For Finding Radius III*

λ	α	β	γ	λ	α	β	γ
.500	1.00273	1.331	.623	.602	1.01050	1.474	.554
.502	1.00300	1.337	.621	.604	1.01047	1.477	.554
.504	1.00327	1.344	.620	.606	1.01045	1.480	.553
.506	1.00354	1.349	.618	.608	1.01042	1.483	.552
.508	1.00381	1.355	.616	.610	1.01038	1.486	.552
.510	1.00408	1.360	.615	.612	1.01034	1.489	.551
.512	1.00434	1.365	.613	.614	1.01029	1.492	.550
.514	1.00461	1.369	.612	.616	1.01024	1.495	.550
.516	1.00487	1.374	.611	.618	1.01018	1.498	.549
.518	1.00512	1.377	.609	.620	1.01013	1.501	.549
.520	1.00538	1.381	.608	.622	1.01007	1.503	.549
.522	1.00563	1.384	.606	.624	1.01000	1.506	.548
.524	1.00588	1.387	.604	.626	1.00994	1.509	.548
.526	1.00612	1.391	.603	.628	1.00987	1.512	.547
.528	1.00636	1.393	.602	.630	1.00980	1.515	.547
.530	1.00659	1.396	.601	.632	1.00974	1.517	.547
.532	1.00682	1.399	.599	.634	1.00966	1.520	.546
.534	1.00705	1.401	.598	.636	1.00959	1.523	.546
.536	1.00727	1.403	.596	.638	1.00952	1.525	.545
.538	1.00748	1.406	.595	.640	1.00945	1.528	.545
.540	1.00768	1.408	.594	.642	1.00938	1.530	.545
.542	1.00788	1.410	.592	.644	1.00931	1.532	.545
.544	1.00808	1.413	.591	.646	1.00925	1.534	.544
.546	1.00826	1.415	.589	.648	1.00919	1.536	.543
.548	1.00844	1.417	.588	.650	1.00912	1.538	.543
.550	1.00861	1.419	.587	.652	1.00906	1.540	.543
.552	1.00878	1.420	.585	.654	1.00902	1.541	.543
.554	1.00894	1.422	.582	.656	1.00897	1.542	.542
.556	1.00909	1.424	.581	.658	1.00893	1.543	.542
.558	1.00923	1.425	.580	.660	1.00890	1.544	.541
.560	1.00937	1.428	.579	.662	1.00887	1.544	.541
.562	1.00960	1.430	.577	.664	1.00886	1.545	.541
.564	1.00962	1.432	.576	.666	1.00884	1.544	.540
.566	1.00973	1.433	.574	.668	1.00884	1.544	.540
.568	1.00984	1.435	.573	.670	1.00885	1.544	.540
.570	1.00994	1.437	.572	.672	1.00887	1.542	.541
.572	1.01003	1.439	.570	.674	1.00890	1.541	.541
.574	1.01011	1.441	.569	.676	1.00894	1.539	.541
.576	1.01018	1.443	.567	.678	1.00899	1.537	.541
.578	1.01025	1.445	.566	.680	1.00906	1.534	.541
.580	1.01031	1.448	.566	.682	1.00914	1.531	.541
.582	1.01036	1.450	.564	.684	1.00924	1.527	.542
.584	1.01041	1.452	.563	.686	1.00935	1.523	.542
.586	1.01044	1.454	.561	.688	1.00947	1.519	.543
.588	1.01047	1.456	.561	.690	1.00962	1.513	.543
.590	1.01050	1.459	.560	.692	1.00978	1.507	.543
.592	1.01051	1.462	.559	.694	1.00997	1.500	.544
.594	1.01052	1.464	.558	.696	1.01017	1.494	.544
.596	1.01053	1.466	.557	.698	1.01039	1.487	.545
.598	1.01052	1.469	.556	.700	1.01063	1.480	.545
.600	1.01051	1.472	.555				

Explanation.—The table is computed for a refractive index of 1.50 for the crown glass and 1.60 for the flint glass.

λ represents the ratio of the dispersions of the two lenses.

α represents the radius of the third surface (III), the unit of measure being 1.

β represents the factor to be multiplied by the variation of the crown index from 1.50.

γ represents the factor to be multiplied by the variation of the flint index from 1.60.

α, β and γ are then to be added together and their sum multiplied by the focal length (f_1) of the crown lens; the result will be radius III.

length of the crown lens. It should also be noted that, although the actual focal length of the crown lens is increased, its equivalent or effective focal length remains unchanged, inasmuch as the separation reduces the power of the crown lens and thereby exactly compensates the increase of the focal length in its effect upon the chromatic and spherical aberrations; so that the value if f_1 becomes $f_1 - d$, and this expression is to be used in all cases where the lenses are separated, to represent the value of the focal length of the crown lens.

If an objective is to be constructed upon this plan, we compute the radii of the four surfaces in the usual way and then find the distance d by which the lenses are to be separated, thus:

$$\text{I} - \frac{\text{II}}{\text{III}} \times f_2 = d \qquad (8)$$

and then simply make the radii of I and II of the same length as III.

If we take, for instance, the previous example, we find that the radii of I and II = 24.60, while that of III = 24.79. The radii of the crown being shorter than III, the condition of separation is fulfilled and we compute the distance between the lenses, thus:

$$\text{I} - \frac{24.60}{24.79} = 0.00772 \times 23.6537 = 0.1826$$

The radii of the objective will then be

I, II, III	24.79 inches
IIII	3206.26 inches
d	0.1826 inch
F	60.00 inches

By this method of treatment, we have an objective at once effective, extremely simple in form, and comparatively easy to produce, inasmuch as it requires but two pairs of tools, an item of no small consequence to the amateur. It may be urged, upon theoretical grounds, that the separating of the lenses is not conducive to the very best results; and while this is undoubtedly true when the separation is quite considerable, yet if the limit already named is not exceeded, the practical advantages of the form very much more than compensate any theoretical objection. The Clarks have separated the lenses of all their later large productions, including the 36-inch Lick objective.

Let us presume now that the objective is to be made from two pieces of glass, of the refractive and dispersive powers of which we know nothing. It is evident, from what has already been said, that the quantities μ, μ', λ and δ must be known before the radii of the objective can be computed. We must, therefore, proceed in a manner practically the reverse of that already employed, and first form the glass into lenses from which we may deduce these quantities with great accuracy, by the aid of which we may then compute the radii of the four surfaces in the usual way and complete the objective. In the absence of any definite knowledge of the constitution of the glass, we must assume μ and δ, and upon the correctness of these assumptions will the focal length depend to some extent.

Perhaps the best and clearest way of showing this method of procedure is by a practical example from my own experience, in the making of a 5-inch objective. The two pieces of glass for this objective were obtained at different times and, beyond the fact that they were made by Feil, nothing was known concerning their optical properties. The ratio of their dispersive powers, δ, was assumed to be 0.63, from which it was found from equation 3 that for an objective of 62½-inch focal length, f_2 should be 36.70 inches.

$$62.5 \times \frac{1.00 - 0.63}{0.63} = 36.70$$

and by equation 4 that f_1 should be 23.12.

$$36.70 \times 0.63 = 23.12$$

Next, the index of refraction of the crown glass, μ, was assumed to be 1.51, and the radii, I and II, necessary to give the required focal length, f_1, were found by equation 5 to be 28.51 inches.

$$23.12 \times 2 \times 0.51 = 23.58$$

As these computations were approximations only, the radii of I and II were made 23.50, and one pair of tools was prepared for that curvature. Work was then begun on the crown lens, and it was ground and polished complete, great care being exercised in keeping the surfaces as true as possible to the curve. The front surface of the flint lens III, was then ground with the convex mate of the tool used in grinding the crown lens, and for the back surface, IIII, a tool was used of 270-inch radius (which had strayed into my possession) and these surfaces were then polished. Had not this tool been at hand, it would have been necessary to grind IIII of the same radius as III; but, had this been done, then only a little more than one half the diameter of the lens (say 3 inches of a 5-inch) would have been ground, as, otherwise, the lens would be made too thin at the center, because of the great curvature of the tool.

After the lenses were polished, the exact radius of curvature was obtained by the reflection of light from the surfaces of the flint lens. This was easily done by means of a tin screen, through which a large pinhole had been made, placed around a light, the rays of which, emerging from the pinhole, impinged upon the concave surface of the lens and were reflected back to an eyepiece placed near the pinhole. A low-power positive eyepiece should be used, with a fine silk thread placed exactly at its focus. The lens was now focused carefully until a good clear image of the pinhole was obtained, and the distance was then measured from the surface of the lens to the thread of the eyepiece (or pinhole), which distance represented the actual radius of that surface of the lens.

The radius of III was found to be entirely correct, being 23.50 inches; but that of IIII was slightly longer than the radius of the tool and measured 278 inches.

The radii of I and II cannot be obtained in this manner, but as I, II and III were all ground on the same pair of tools, it was safe to assume that all were of the same radius.

The glass had now been formed into lenses of known radii and from them was to be ascertained by actual trial, their true focal lengths and their optical properties.

The crown lens was then mounted in a tube, and in front of the lens was placed a diaphram which cut off all the rays of light except a ring about ¼ inch wide, midway between the center and edge of the lens. The eyepiece with the thread in its focus was used, and the whole carefully focused on a bright star. The focal length was then measured from the middle of the edge of the lens to the thread of the eyepiece, parallel to the optical axis of the lens, and the mean of several trials was 22.82 inches. The quantities, I, II and f_1 now being known, μ was found by the following equation to be 1.51489.

$$1 + \frac{\mathrm{I} \times \mathrm{II}}{(\mathrm{I} + \mathrm{II}) \times f_1} \qquad (9)$$

$$1 + \frac{23.5 \times 23.5}{(23.5 + 23.5) \times 22.82} = 1.51489$$

The lenses were now mounted together, the surfaces II and III, being in contact with each other. The focal length F of the combined lenses was then measured as before from the same points, and found to be 66.82 inches. Then, by the following equation the focal length of the flint lens, f_2, was found to be 34.655 inches, thus:

$$\frac{F \times f_1}{F - f_1} = f_2 \qquad (10)$$

$$\frac{66.82 \times 22.82}{66.82 - 22.82} = 34.655$$

and by the following equation μ' was found to be 1.62526

$$1 + \frac{\mathrm{III} \times \mathrm{IIII}}{(\mathrm{III} - \mathrm{IIII}) \times f_2} = \mu' \qquad (11)$$

$$1 + \frac{23.5 \times 278}{(23.5 - 278) \times 34.655} = 1.62526$$

The lenses were again mounted in the tube, without the diaphram, and gradually separated until the color correction was the very best that could be obtained. Great care was exercised in this test, and several different objects were tried—the moon, Jupiter, Saturn, thermometer bulbs in sunshine, etc.—and the separation of the lenses was best effected by means of paper and cardboard rings placed between them. The distance between the lenses was then measured carefully, the mean of several trials being 0.719 inch. This showed that the focal length of the crown lens was too long by just the amount of separation required—that is, if f_1 had been 22.101 inches the objective would then have been achromatic when the lenses were in contact. From these quantities, then, f_1 and $-d$ and f_2, the ratio of the dispersive powers, δ, was found by the following equation to be 0.63774 inch, thus:

$$\frac{f_1 - d}{f_2} = \delta \qquad (12)$$

$$\frac{22.82 - 0.719}{34.655} = 0.63774$$

But while, for the purpose of obtaining the ratio of the dispersive powers of the lenses, the focal length of the crown was considered as too long by 0.719 inches, on the other hand, the focal length of the crown may be considered as correct and the focal length of the flint as too short by a proportionate amount; and this latter view is the one which will be adopted in the further consideration of the subject. The reason for this will at once be plain; for, while to shorten the focal length of the crown lens involves the regrinding and polishing of two surfaces, the lengthening of the flint lens involves one surface only, that of IIII. It will be evident, too, that the crown lens, being equiconvex, will always be correct in form, and with the lengthening of the flint focus by the increase of radius IIII, will be correct in focal length also; and the proper separation of the lenses, while effecting the color correction, at the same time brings the surfaces II and III into their proper relation with each other to correct the spherical aberration.

The optical properties of lenses were now all known quantities, and it remained to compute the distance d by which the lenses were to be separated, the focal length of the flint lens in order that it may be proportional to the ratio of the dispersive powers δ and the radius of IIII to produce the focal length.

First, then, by Eq. 1, λ was found to be 0.52517, thus:

$$0.63374 \times \frac{0.51489}{0.62526} = 0.52517$$

and with this as the argument the quantities α (1.00601), β (1.389) and γ (0.6035) were taken from the table and the distance between the lenses, d, was found by the following equation to be 0.2696 inch, thus:

$$f_1 - \frac{\text{II}}{\alpha + (\beta \times \mu - 1.50) + (\gamma \times \mu' - 1.60)} = d \qquad (13)$$

thus:

$$22.82 - \frac{23.5}{1.00601 + 0.02083 + 0.01527} = 0.2696$$

Then, by this equation, f_2 was found to be 35.3598 inches. Thus:

$$\frac{f_1 - d}{\delta} = f_2 \qquad (14)$$

$$\frac{22.82 - 0.2696}{0.63774} = 35.3598$$

and by equation 7, IIII was found to be 373.52, thus:

$$\frac{23.5 \times (35.3598 \times 0.62526)}{23.5 - (35.3598 \times 0.62526)} = 373.52$$

while the focal length, F, of the objective was found to be 62.249, thus:

$$\frac{f_2 \times (f_1 - d)}{f_2 - (f_1 - d)} = F \qquad (15)$$

$$\frac{35.3598 \times 22.5504}{35.3598 - 22.5504} = 62.249$$

Therefore, we have:

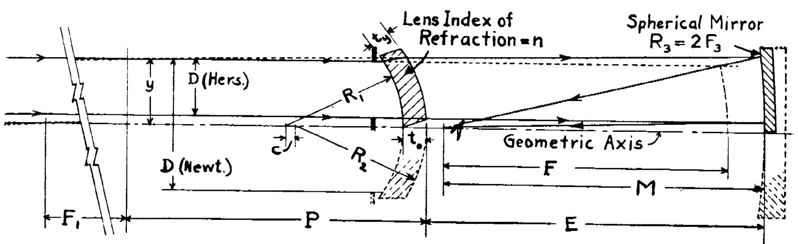
I, II, III = 23.50 inches
IIII = 373.52 inches
f_1 = 22.82 inches
f_2 = 35.3598 inches
F = 62.2490 inches
d = 0.2696 inch
[illegible] 1.51489 inch
[illegible] 1.62526 inch
δ 0.63774 inch

The back surface of the flint lens IIII was then reground and polished, figuring of any kind having been carefully avoided, the object being to keep the surfaces as nearly as possible to the computed curves; after which the objective was tested and proved even at this stage of completion to be very nearly correct. The objective was then finished by figuring where necessary, and has since proved to be most satisfactory in its performance.

The Maksutov Lens Applied to Herschelian and Newtonian Telescopes

By Franklin B. Wright

In the May, 1944 *Journal of the Optical Society of America* (Vol. 34, Number 5, pages 270 to 284) there was announced a valuable discovery [1] by D. D. Maksutov that an achromatic diverging meniscus lens can be made from a single piece of glass with spherical surfaces having very little magnification but with considerable spherical aberration. This lens is suitable for use as a correcting lens with reflecting telescopes such as Newtonians, Cassegrainians, Schmidt cameras, etc., when the mirrors are figured with either spherical or non-spherical surfaces. However, only the simplest arrangement with all surfaces spherical as shown in Figure 1 will be considered in the present chapter. The use of such an arrangement as a Herschelian telescope is especially attractive since it avoids the necessity for figuring the mirror as an off axis paraboloid, a difficult task at best.



Drawing by the author

FIGURE 1

Maksutov-Herschel telescope

An essential feature of the Maksutov correcting lens is that the radii of curvature R_1 (concave) and R_2 (convex) and the thickness on the geometric axis t_0 must satisfy Equation (1) for an index of refraction n at a wavelength about in the middle of the spectrum to be covered. This makes the lens, when used in a reflecting telescope, achromatic to a far greater degree than an ordinary refractor. In fact it is superior in this respect to an ordinary Schmidt telescope. Consider, for example, a Maksutov lens with $t_0 = 2.5$, $R_1 = 37.0000$ and $R_2 = 38.4127$. Its focal length F_1 is 4902.9 units for $n = 1.5163$ near the middle of the spectrum, 4903.1 units for $n_C = 1.5123$ at the C line, and 4903.1 units for $n_F = 1{,}5203$ at the F line. Thus the focal length is always at a minimum for the value of n for which Eq. (1) is to be satisfied, and changes scarcely at all throughout the bright part of the spectrum.

[1] Also discovered independently in Holland during Nazi occupation by A. Bouwers, apparently about the year 1940. His book, "Achievements in Optics," was published in 1946 by the Elsevier Pub. Co., New York.

This lens must always be treated mathematically as a "thick" lens no matter how small the actual thickness t_0 may be, because of the extremely meniscus shape imposed by Equation (1). As shown in Figure 1, a paraxial ray is refracted so as to leave the lens at a point noticeably further from the axis than it entered, as if it had come from an equivalent exceedingly "thin" lens placed as a distance P to the left of the actual lens (see dotted line) at a point called the "second principal point" of the lens. This causes the distance E between the lens and mirror to be considerably less for the elimination of coma than in the case of the ordinary Schmidt telescope, certainly an advantageous feature of the Maksutov lens.

Formulas for computing the various dimensions are listed at the end of this chapter, most of which have been obtained by substituting Eq. (1) in corresponding general formulas not given. Tables are also provided giving all the principal dimensions required for most cases of actual construction. With the aid of these tables either Herschelian or Newtonian style Maksutov telescopes of any focal length can be made without using most of the formulas at all, provided crown glass having nearly the index of refraction given is used for the correcting lens.

The tables are based on an elimination of spherical aberration of the "third order." In telescopes of wide relative aperture (i.e., $F/2y$ less than about 4) aberration of higher orders may be appreciable in the outer zones. This cannot in general be entirely eliminated when spherical surfaces are employed. However, Maksutov determined by ray tracings for the particular cases when $t_0/2y = 0.1$ a set of values for R_1 and other dimensions which give approximately the least possible amounts of residual spherical aberration of all orders. These values are shown in Table 1 in parentheses, and preferably should be used instead of the other figures when applicable.

In Table 1 each column is computed for a value of E which will eliminate coma as well as spherical aberration from the telescope, so that the resulting instrument corresponds to a Schmidt telescope in practically all respects. Long focus telescopes with small fields of view can conveniently be made with shorter spacing between lens and mirror without introducing more than a small fraction of the coma that is present in the ordinary Newtonian of like dimensions. So Table 2 is provided in which $E = F_3$, the focal length of the objective mirror. Moderate changes in E make very little difference in any other dimensions, so that Table 2 may be used for almost any case where E is to be made as small as practicable: e.g., for a Newtonian style where the diagonal flat is to be mounted on the back of the lens to eliminate spider diffraction.

It is proposed to give a simple procedure for the design and construction of a typical Herschelian telescope using a Maksutov lens, leaving largely to the mathematically inclined reader any detailed study of the formulas. The procedure would be almost the same for a Newtonian telescope. However, any differences in treatment which do not appear to be obvious will be explained. Suppose the Herschelian telescope is to be about $F = 60$-inch focal length with an aperture of about 5 inches and an objective mirror of 6-inch diameter. It is desirable to keep the focal length of such a telescope fairly long because of eyepiece aberrations, also to use only the best eyepieces. This is because an $f/12$ Herschelian is about the same as one side of an $f/5.2$ Newtonian to use the present example for illustration. Many eyepieces have considerable aberration at $f/5$ or $f/6$ which are quite satisfactory for longer aperture ratios.

It will be assumed that a good crown glass blank of somewhat more than 5 inches diameter is available which has a thickness of one inch. A 1-inch prism or diagonal flat will be needed close to the eyepiece as indicated in Figure 1. This will require say ¾ inch clear space above the axis, so that there will be no shadow of the diagonal on the mirror, plus $D = 5$ inches clear aperture, making $y = 5\tfrac{3}{4}$ inches. (For the corresponding Newtonian telescope $D = 2y = 11\tfrac{1}{2}$ inches clear aperture.) Suppose that the separation E is to be as small as practicable, so that Table 2 rather than Table 1 will apply to the present telescope.

In order to calculate the dimensions of the lens, suppose that about ⅛ inch of thickness will be ground off in making it. This leaves ⅞ or 0.88 inch of glass remaining which is composed of the thickness t_0 plus the depth of the concave side, which $= D^2/8R_1$, or $3.125/R_1$ in the present case. So the first step is to compute several sets of values for t_0, R_1 and R_2 by multiplying those given in suitable consecutive columns of Table 2 by $^{60}/_{100}$ and then compute $t_0 + 3.125/R_1$ for each of these sets. This is shown in Table 3 for $t_0 = .75, 1.00$ and 1.25 in the original Table 2.

The design being sought is one which will give 0.88 inch for the last line of Table 3, so that the other quantities may be interpolated as $(.88 - .78)/(.92 - .78)$ or 71 percent of the difference between the last two columns greater than the middle column, giving $t_0 = .60 + 71$ percent of $.15 = .71$ inch, $R_1 = 17.76 + 71$ percent of $.96 = 18.44$ inches and $R_2 = 18.10 + 71$ percent of $1.04 = 18.84$ inches. Curves should then be coarse ground in the two sides of the lens with these values of R_1 (concave) and R_2 (convex) to an accuracy of about 0.5 inch or better.

While grinding the curve for the second (convex) surface, the thickness around the edge should be measured at frequent intervals with a micrometer. The thickest point should be marked permanently on the edge to facilitate mounting the lens later with this point nearest to the geometric axis, and the grinding so done as to make the opposite side thinner by the amount given by Eq. (2). In the present case this difference amounts to 0.015 inch. Accuracy to one or two thousandths of an inch is usually sufficient. (For a Newtonian telescope the edge should be the same thickness t_y all around, and the difference computed from Eq. (2) must be added to the measured thickness on the edge to ascertain the thickness t_0 in the center.)

Fine grinding may then be completed on the concave side and the total change in lens thickness due to the fine grinding on this side should be measured as a guide to what may be expected to take place when the convex side is fine ground. Also R_1 should be measured again after the fine grinding is completed. A new value for R_2 should now be determined from Eq. (1) using the latest values for R_1 and t_0 after making allowance in the latter for the probable reduction in thickness due to fine grinding the convex side. The convex side may then be fine ground to this new value for R_2. It may be necessary to repeat some of the fine grinding stages in order to make sure that the lens is eventually polished and both sides figured spherical with the difference $R_2 - R_1$ within about one or two hundredths of an inch of the amount given by Eq. (1) for best achromatic performance.

A spherometer is extremely useful for repeated measurement of R_1 and R_2 during the grinding and polishing stages. During the polishing stage the distance c can be measured directly with the knife-edge at the center of curvature of the two sides in turn. In this case $R_2 - R_1 = t_0 - c$. (If the pinhole remains in a fixed position, the distance measured by the knife-edge would be $2c$.) While this method provides a useful check on spherometer readings while polishing, it is of no use during the grinding stages when frequent measurements of R_1 and R_2 are most needed.

Polishing and figuring the lens surfaces offer no special problems. First of all the front (concave) surface may be polished and figured spherical using the knife-edge test at center of curvature. Then the back (convex) surface may be similarly finished. The two surfaces are so nearly parallel that it is entirely practicable to figure the back as well as the front in this manner.

Seeing light reflected from both surfaces when testing the back should not be confusing since the centers of curvature are separated by the distance c which is appreciable. In the case of the Herschelian style with the knife-edge moving across the center of curvature, from above as shown in Figure 1, it would cover up the light reflected from the front completely or nearly so when testing the back, thus providing a clear view of the figure on the back. In case of the Newtonian style the centers of curvature would appear centered one directly behind the other at a distance apart equal to $2c$ with the pinhole light in one position, in which case any irregularity in figure when testing the back would be attributable to the back surface because the front would already have been figured spherical before polishing the back.

Incidentally, the knife-edge test can be improved in the case of this lens, as well as with any wide angle mirror, if a direct view finder for a camera is mounted between the knife-edge and the eye to reduce the apparent size of the surface under test. The same thing can be done by looking through the "wrong" end of a low-powered field glass or telescope in this position.

Having completed the lens it is comparatively easy to calculate the focal length F_3 of the mirror required to match it accurately to eliminate spherical aberration. In the example given the correct value of F_3 may be interpolated from the original Table 2 in the same way as was done for the dimensions of the lens. In this case $F_3 = {}^{60}/_{100} \times 101.3$ or 60.8 inches, provided the final dimensions of the lens are close to those originally calculated. The image distance M may likewise be interpolated as $M = {}^{60}/_{100} \times 102.7$ or 61.6 inches. In case of any doubt F, F_3 and M may be calculated from Eq. (5), (7) and (8) respectively, using the final dimensions of the lens. In such a case the value of k may be interpolated from the original Table 2 with sufficient accuracy. In the example given the mirror should be ground, polished and figured accurately spherical to a radius of curvature of $R_3 = 2F_3 = 121.6$ inches or thereabouts.

For the same degree of accuracy as specified in the writer's chapter on "Accuracy of Parabolizing a Mirror," in ATM, an error in R_3 of $\pm 0.0034 f^4$ inches is permissible, where f is the aperture ratio $F/2y$ of the corresponding Newtonian telescope. In the present example $f = 60/11.5 = 5.2$ and the tolerance in R_3 is $0.0034\ (5.2)^4 = \pm 2.5$ inches. It is easy to finish the mirror well within such limits, hence the reason for making the lens first.

TABLE 1—*COMA ELIMINATED ACCORDING TO MAKSUTOV'S FORMULA FOR* E

F = 100 units, n = 1.5163, "third order" spherical aberration eliminated.*

t_0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
$R_2 - R_1$	.28	.57	.85	1.13	1.41	1.70	1.98	2.26	2.55	2.83
R_1	24.9	29.5	32.6	35.0 (35.4)	37.0 (38.2)	38.7 (40.6)	40.2 (42.8)	41.5 (44.8)	42.7 (46.6)	43.8 (48.4)
E	169.	153.	145.	139.	135.	131.	129.	126.	124.	122.
k	.013	.019	.023	.026 (.026)	.030 (.029)	.033 (.032)	.036 (.034)	.039 (.036)	.042 (.038)	.045 (.041)
F_3	101.3	101.9	102.3	102.6 (102.6)	103.0 (102.9)	103.3 (103.2)	103.6 (103.4)	103.9 (103.6)	104.2 (103.8)	104.5 (104.1)
M	102.3	103.2	103.9	104.5 (104.4)	105.1 (104.9)	105.6 (105.3)	106.1 (105.6)	106.6 (105.9)	107.1 (106.2)	107.5 (106.5)

* Figures in ( ) based on Maksutov's ray tracings for minimum residual spherical aberration for the particular case when t_0 = 0.1 of Newtonian aperture.

The optical parts may be mounted in the telescope tube as described below. The correcting lens and objective mirror should be mounted with their centers at a distance $y - D/2$ from the geometric axis, the thickest point on the edge of the lens being placed nearest to the axis. The eyepiece and diagonal flat combination should be centered on and optically in line with the geometric axis of the system, not with the center of the mirror as in the case of a Newtonian.[1] To accomplish this the point on or near the edge of the mirror cell where the geometric axis is supposed to strike it should be plainly marked, and the eyepiece tube axis or the diagonal flat adjusted to make this point appear centered in the eyepiece tube, using a dummy eyepiece tube with two small holes centered in it to keep the eye in line with its axis. Then the objective mirror should be tilted to make the image of the correcting lens diaphram appear central in it when viewed from the center of the eyepiece tube. Finally the correcting lens should be tilted to give perfectly circular out of focus images of a star in the center of the field using an eyepiece of high power. After this adjustment it will no doubt be found that the centers of curvature of both lens and mirror will lie on the geometric axis as indicated in Figure 1.

[1] Unless the telescope (Herschelian) is equipped with exceptionally good eyepieces, it is possible that better results will be obtained by pointing the eyepiece-diagonal combination toward the center of the mirror or in some other direction to be determined by experiment instead of along the geometric axis.

A superb instrument will surely be produced if the required tolerances in dimensions are observed, all three surfaces are figured accurately spherical and all final adjustments are carefully made.

TABLE 2—$E = F_3$, *COMA NOT ENTIRELY ELIMINATED*

F = 100 units, n = 1.5163, "third order" spherical aberration eliminated.

t_0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
$R_2 - R_1$	.14	.28	.42	.57	.71	.85	.99	1.13	1.27	1.41
R_1	20.9	24.9	27.5	29.6	31.2	32.6	33.9	35.1	36.1	37.0
k	.004	.007	.009	.012	.014	.016	.018	.020	.022	.023
F_3	100.4	100.7	100.9	101.2	101.4	101.6	101.8	102.0	102.2	102.3
M	101.1	101.6	102.1	102.5	102.9	103.2	103.5	103.8	104.1	104.4

TABLE 3

t_0	.45	.60	.75
R_1	16.50	17.76	18.72
R_2	16.76	18.10	19.14
$3.125/R_1$	.19	.18	.17
t_0 + above	.64	.78	.92

MATHEMATICAL FORMULAS

(All quantities in Figure 1 are to be taken as positive as drawn.)

Eq. (1) $R_2 - R_1 = \left(\frac{n^2 - 1}{n^2}\right) t_0$ to make the lens achromatic.

Eq. (2) $t_0 - t_y = \frac{cy^2}{2R_1^2}$ where $c = t_0 - (R_2 - R_1)$

Eq. (3) $F_1 = \left(\frac{n}{n-1}\right)^2 \frac{R_1 R_2}{t_0}$ is equivalent focal length of lens.

Eq. (4) $P = \frac{nR_2}{n - 1}$ gives equivalent position of lens.

Eq. (5) $F^3 = \dfrac{n^3 R_1^4}{4(1-k)(n^2-1)(n-1)t_0}$ eliminates spherical aberration of the "third order." *

Eq. (6) $k = \dfrac{P + E - F}{F_1}$ used in Eq. (5) and (7).

Eq. (7) $F_3 = F(1 + k)$ is equivalent focal length of mirror.

Eq. (8) $M = F_3\left(1 + \dfrac{F}{F_1}\right)$ gives position of final image.

* For very wide angle telescopes the best relation between R_1 and F should be determined by ray tracing methods rather than Eq. (5). (See "The Principles of Optics," Chapter II, by Hardy and Perrin).

The Design of Refractor Objectives by Ray Tracing

By James H. Wyld

The Ray Trace Method: The procedure ordinarily used by amateurs in designing refractor objectives is the simple one outlined in the articles by Ellison in ATM and by Haviland in ATMA. Briefly, this consists in establishing the focal lengths of the crown and flint elements by a simple approximation formula which leads to an achromatic combination of correct over-all focal length; the individual radii of the elements are then chosen by rule of thumb on the basis of experience. After constructing the lens elements, any spherical aberration remaining is removed by figuring one of the lens surfaces, testing the lens against a flat by auto-collimation.

This method leads to very satisfactory results in the case of small objectives of long focal ratios, such as, say, a 3-inch $f/15$ objective. However, for lenses of large numerical aperture, or of large diameter, it becomes increasingly unsatisfactory, especially if the lens is required to cover a considerable field, as in photographic work. Professional lens designers invariably employ a more refined design technic known as ray tracing, which it is the purpose of this chapter to discuss.

The ray-tracing method consists in calculating the exact path of two or more light rays through the lens system by accurate trigonometric methods. The intersection points of these rays with the central axis of the lens, or with one another, give precise information on the aberrations produced by the lens, and thus enable the lens designer to predict accurately its optical performance, and to make any desirable design changes on the basis of a rational picture of just what is happening to the ray pattern.

The average amateur is apt to think of ray tracing as a profound and mysterious subject, suitable only for learned professors and "long-hairs." Such an impression is altogether incorrect, and it is one of the purposes of this chapter to dispel the ill-deserved aura of mystery which has often surrounded the subject and to show how any TN possessed of a fair knowledge of ordinary high-school algebra and trigonometry can make practical use of ray tracing. In fact, even such training is not entirely essential, for the actual work of designing simple objectives largely consists of plain ordinary arithmetic, plus a little practice in the use of certain mathematical tables. It is only fair to add, however, that the method involves a very large amount of patient and accurate numerical computation, and is not adapted to impatient souls who want quick and easy results. The amateur telescope builder who takes real pride in exact workmanship, and who wishes to keep his theoretical design studies on the same high plane as his practical work with glass, pitch, and rouge, will find a great mental satisfaction in carrying out his designing by exact ray-trace methods; he will furthermore develop an invaluable insight into the whole subject of theoretical optics which no amount of book study can supply.

The essential tools of ray tracing are simple and cheap; they are merely a good set of logarithm tables and trigonometric tables. The author has found "Six-Place Tables" by E. S. Allen, (published by the McGraw-Hill Book Co., Inc., New York, price \$2.75 [1]) very satisfactory. You will also need plenty of common lined scratch paper and pencils; some graph paper (10 or 20 squares per inch) is often useful. A good 10-inch slide rule is likewise extremely handy. It costs only a few dollars, and you can easily learn to use it in a few evenings, if you don't know already. Another important (though invisible) ingredient is the ability to "figger" accurately and quickly; but cheer up, if you are not good at figures when starting such work, you certainly will be by the time you finish! There's nothing like just jumping in and learning how to swim; and if you get out of your depth in the mathematical quagmire, you don't need to drown—just put the stuff away and adjourn for a glass of beer or a smoke, and tackle it again later.

Professional lens designers invariably work with the aid of a good modern calculating machine, such as a Monroe, Marchant, or Friden calculator. Such machines cost from \$300 to \$900 [1], too expensive for the average amateur's pocketbook; but if you have the use of such a machine, or can borrow one, by all means do so, as the computing time is thus cut at least 50 percent and the mental wear and tear and chances of error are reduced even more. However, such old-time experts as Petzval, Steinheil, and Taylor did their work without such mechanical aid, and you can do the same if necessary.

The examples given here will be based on the use of log tables; those using a machine can readily alter the methods to suit. So-called "natural" trig tables are used for machine work; one of the best ones is "Seven-Place Values of Trigonometric Functions" by J. Peters (D. Van Nostrand Company, Inc., New York, N. Y., \$9.50 [1]). This table is made out in divisions of one thousandth of a degree, which greatly facilitates the addition and subtraction of angles which occurs in the course of the work, and also simplified the necessary interpolations. Another good table is Volume 2 of "Chambers's Six Figure Mathematical Tables," edited by L. J. Comrie (D. Van Nostrand Co., New York, N. Y.); the radian trig functions and inverse trig functions are very handy when interpolating. There is no fully satisfactory logarithmic trig table generally available that has decimal division of the degree or the radian, hence for log work you must "make do" with the old Babylonian degree-minute-second system. A six place table is best; the author has found "Six-Place Tables," by E. S. Allen (McGraw-Hill Book Co., New York, N. Y.) quite satisfactory.

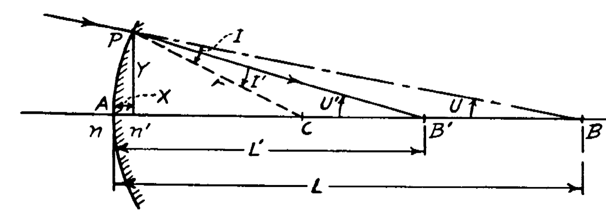
All ray-trace calculations are applied to spherical refracting surfaces, which are almost universal in commercial lens practice because of the difficulty of producing figured surfaces economically in mass production. (They can, however, be applied to figured surfaces by certain alterations in procedure, though this refinement will not be discussed here.) In the present chapter, their application to telescope objectives will be mainly stressed, as this is the application of most practical value to amateur designers.

[1] All prices quoted are as of 1950.

The amateur undertaking ray-trace work will find it worthwhile to supplement instructions given here by careful reading of a good introductory treatise on optical theory, such as Jacobs' "Fundamentals of Optical Engineering" (McGraw-Hill Book Company, New York, N. Y., price \$6.50 [1]). However, the present chapter includes enough theoretical discussion to clarify most of the practical problems arising in actual design work on telescope objectives, and to enable you to get on with the job.

The Equations of Ray Tracing: Before proceeding to the formulas used in ray tracing, the essential quantities used will be defined. The diagram (Figure 1) of a refracting surface will define these more graphically.

The ray is always assumed to start from the left. The solid line is the path of the ray. The dotted line CP is the "normal" or perpendicular to the



Drawings by the author

FIGURE 1

surface at the point P at which the ray enters; C is the center of curvature, and r the radius of curvature. L is the distance of the object point B from the vertex A of the lens. In the present case, the object B is virtual, located by the projection PB of the original ray (dash-and-dot line). Similarly, L' is the image distance AB'. L (or L') is given a positive sign if B (or B') falls to the right of the vertex A, otherwise a minus sign is applied. Likewise, r is taken as plus if C is to the right of A; otherwise, it is minus. The ray height Y is the vertical distance from the incidence point P to the axis, and is taken as plus if P falls above the axis.

The ray makes a slope angle U with the axis before refraction, and a slope angle U' after refraction. These angles are taken as plus if the axis can be swung into the path of the ray by a clockwise turn of less than 90°. The ray makes an angle of incidence I with the normal before refraction, and angle of refraction I' afterward. I and I' are plus when the ray can be swung into the normal by a clockwise turn of less than 90°. The figures n and n' refer to the refractive indices of the spaces before and after refraction, and are always plus. (If the space is simply air, use 1.0 for this figure.)

It is important to keep these plus and minus signs correct in the course of the calculation. In cases of doubt, it is a good idea to make a sketch of the ray path and compare it with the "all-plus" diagram, Figure 1, to clarify the results.

The sign conventions and symbols used here are the Conrady ones, also used in Jacobs, "Fundamentals of Optical Engineering." Some books use different conventions; watch out for this when you are studying them.

The ray path is traced through the lens, surface by surface, with the aid of the following formulas

$$\sin I = \frac{L - r}{r} \sin U \quad (1)$$

$$\sin I' = \frac{n}{n'} \sin I \quad (2)$$

$$U' = U + I - I' \quad (3)$$

$$L' = r\frac{\sin I'}{\sin U'} + r \quad (4)$$

After finally getting L', we start over again at the next surface using the transfer formulas:

$$L_2 = L'_1 - t_1 \quad (5)$$

$$U_2 = U'_1 \quad (6)$$

t_1 is the axial distance from surface 1 to surface 2. (See Figure 2.) The value of t is always taken as plus.

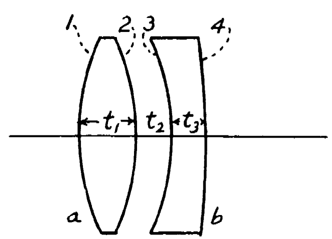


FIGURE 2

The various quantities L, L', U, U', etc., are given subscripts numbered 1, 2, 3, 4 according to the corresponding surfaces. The prime mark (′) is used for values after refraction at a surface, while unprimed letters refer to conditions before refraction.

With a telescope objective, the object distance L is infinite for the first surface, so we need an extra formula for this case. This is:

$$\sin I = \frac{Y}{r} \quad (7)$$

(For parallel incident ray only.)

Usually Y_1 is taken as half the clear aperture of the objective, that is, the ray is assumed to strike the very edge of the lens. This is called a marginal ray. For example, $Y = 3$ for a 6-inch objective.

Sometimes we may have a plane surface in the system. In this case, calculate:

$$I = -U \quad (8)$$

$$\sin U' = \frac{n}{n'} \sin U \quad (9)$$

$$I' = -U' \quad (10)$$

$$L' = L\frac{n'}{n}\frac{\cos U'}{\cos U} \quad (11)$$

(For plane surfaces only.)

All such calculations should be carried on to six decimal places, and all angles should be figured to the nearest one tenth second of arc. The reason for this high accuracy requirement is the fact that we have to compare some very small differences in image position for the various rays at the end of the calculation, and to get these differences correct the lengths and angles must be extremely accurate.

The calculations are best carried out by the aid of a standardized schedule sheet made up in advance, so that the insertion of the proper values becomes a largely mechanical operation. Examples of such schedules will be given later in this chapter. A supply of schedules of this sort may conveniently be made up in advance by mimeograph or "Ditto" stencils, to save the nuisance of writing out the marginal reference notations each time. Such a sheet should provide for three or four ray-trace columns (for an ordinary two element objective). Only two columns are generally used, but the others often come in handy for extra calculations.

It is possible to simplify the previous formulas very decidedly by considering rays which are close to the axis, in which case the slope and incidence angles become very small, so that the angles (expressed in *radians*) become practically identical to their sines. (One radian is equal to $180/\pi$ degrees, and represents an angle whose arc is equal to its radius.) Such a ray is called paraxial and we can trace it by the following simplified formulas, in which the small letters indicate that the ray is paraxial.

$$i = \frac{u(l - r)}{r} \quad (12)$$

$$i' = \frac{n}{n'} i \quad (13)$$

$$u' = u + i - i' \quad (14)$$

$$l' = r + \frac{i'r}{n'} \quad (15)$$

Transfer formulas:

$$l_2 = l'_1 - t_1 \quad (16)$$

$$u_2 = u'_1 \quad (17)$$

For plane surfaces, paraxial rays:

$$l' = l\frac{n'}{n} \quad (18)$$

$$u' = u\frac{n}{n'} \quad (19)$$

(Use same transfer formula as before.)

The equations (12) to (19) are easily derived from those for the trig rays, (1) to (11), by making all the sine values equal to the angles themselves (in radians) and making all cosines equal to 1.0.

Formulas (12) to (19) are best for paraxial ray tracing when logarithms are used. If you are using a calculating machine, a better set of paraxial equations are the following very simple ones, devised by Prof. R. Kingslake:

$$n'u' = nu + y\frac{(n' - n)}{r} \quad (20)$$

Formula (20) is a "universal" one applying to both curved and plane surfaces (the second term on the right becomes zero for a plane). Note that $u = 0$ for the first surface with infinite object distance.

Transfer by:

$$y_2 = y_1 - t_1 u'_1 \quad (21)$$

At the end of the last surface, we locate the final focus by the formula:

$$l' = \frac{y}{u'} \quad (22)$$

Curiously enough, equations (20) and (21) are not suited to logarithmic work, as they involve more logarithms than the regular formulas. (Try a numerical example if you doubt this.)

The effective focal length (f') of the whole lens system is given by

$$f' = \frac{y_1}{u'} \quad (23)$$

Note that (22) and (23) are identical, except that we use y from the *last* surface in (22) and from the *first* surface in (23); the u' value is for the last surface in both cases.

These computing equations provide all the necessary ingredients for a full ray trace of a refractor objective. We shall need some additional equations

later, to calculate the various aberrations and their corrections, but we shall put off the discussion of these for the moment.

Lens Aberrations: To investigate adequately the aberrations of a refractor objective, only two rays are needed. One of these is a marginal ray for the edge of the lens, traced by trigonometry; the other is a paraxial ray, which is also calculated for the edge of the lens (with $y_1 = Y_1$). This latter ray may be taken as representing the performance of the lens if the whole lens behaved like its central, gently curved sections, for it turns out that the paraxial equations always give the same values of l' and f' for any value of y. (If you are in doubt, try a simple numerical example.) The other (trigonometric) ray is used as a comparison, to establish the true conditions in the marginal ray; by

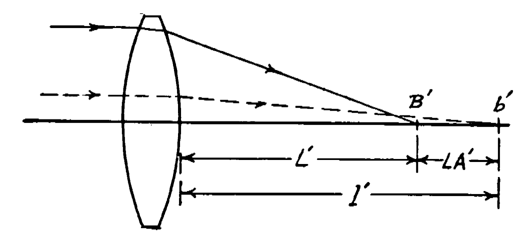


FIGURE 3

comparing the trig results and the paraxial ones, the aberrations can be worked out.

In refractor design, there are generally only three major aberrations to consider; these are (*a*) spherical aberration, (*b*) coma, (*c*) longitudinal chromatic aberration. These will be briefly discussed in the order named.

Spherical Aberration: Spherical aberration occurs when the marginal rays come to a different focus than the central ones (see Figure 3).

This aberration (LA', or "longitudinal spherical aberration") is measured by the difference of the marginal and paraxial focal distances of the last surface:

$$LA' = l' - L' \quad (24)$$

The lens designer, of course, attempts to adjust the proportions of the lens so as to make LA' as small as possible (or at least below certain limiting values, to be discussed later).

Coma and OSC': Coma is an aberration resulting from the fact that the effective focal lengths (F' and f') of the marginal and central rays may differ, even though their image distances (L' and l') are equal (i.e., zero spherical aberration). This may be clearer from Figure 4. (The lens shape is purposely exaggerated.)

The effective focal length of a ray is found by extending the emerging ray backward till it intersects the original entering ray, and measuring the distance along the ray from the focus to this intersection point. If this distance is not equal for the marginal and paraxial rays, we will have *coma*.

Coma manifests itself only in points of the image which are off the central axis. Owing to the different effective focal length of the rays from the marginal zones of the lens as compared with the center ones, an oblique pencil

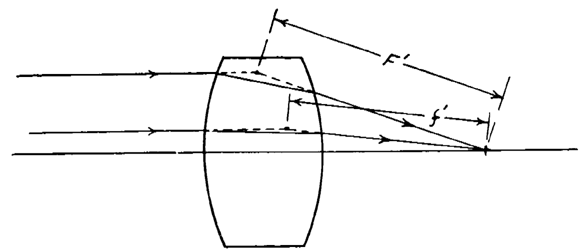


FIGURE 4

of light from these outer zones will "throw high" compared to the central light pencil, if "negative" coma is present. (Figure 5.)

The net result of this condition is that a luminous point (such as a star) is imaged as an arrow-shaped or comet-shaped blur of overlapping circles of light. (Figure 5, at right.)

This aberration gets proportionately worse as one gets further from the optical axis, so that it is very essential to clear up the coma effect in any ob-

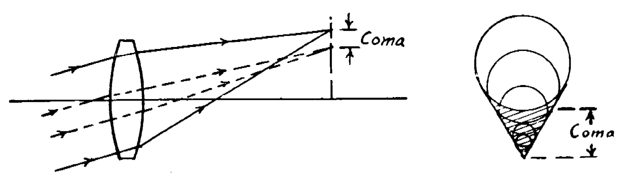


FIGURE 5

jective which is required to cover a large field, particularly a photographic telescope or an RFT visual telescope.

It can be shown mathematically that, in the absence of spherical aberration, coma will be practically eliminated if the ratio of the height Y_1 of the entering ray to the sine of the final slope angle U' is constant for all parts of the lens. (Abbe's sine theorem.) This condition is satisfied for the central and marginal zones if we trace the marginal and paraxial rays with the same initial ray height ($y_1 = Y_1$) and the ratio $u'/\sin U'$ at the last surface to be equal to unity. However, we must allow for any spherical aberration which might be present by applying a correction factor l'/L' to eliminate the effect of LA' on

the values of the slope angles. We finally have, as a measure for coma (if $y_1 = Y_1$):

$$OSC' = 1 - \frac{u'}{\sin U'} \cdot \frac{l'}{L'} \qquad (25)$$

(All data being for the last surface.)

The letters OSC' stand for "offense against sine condition"—the customary term for this coefficient, though a rather awkward one.

A lens in which both LA' and OSC' have been reduced to very low values is said to be *aplanatic*. In a refractor, this can be done by a proper choice of the surface radii. In a reflector, the problem is less simple, being soluble only by the use of special mirror curves (Ritchey-Chrétien, Schwarzschild) or special compensator lenses (Schmidt; Ross lens).

Chromatic Aberration: Chromatic aberration is the third major aberration involved in refractor design. As the name implies, this aberration results from differences in final image distance between rays of different colors. A lens which has been so designed that its final image distance remains nearly constant for a considerable range of different colors is called an *achromat*.

The basic cause of chromatic aberration is the fact that the refractive index of glass varies for different light wavelengths, being greatest for violet light and least for red light. This spread in the values of refractive index for different colors is called *dispersion*.

The refractive index of various types of optical glass is given in tables supplied by glass manufacturers. (Some examples of these are given on page 328 of Hardy and Perrin's "Principles of Optics," 1932.) Usually these are specified for various definite spectral lines, so that the completed lens can be conveniently tested with the aid of a suitable monochromatic light source producing one of these lines. For visual instruments such as telescope objectives, the index of refraction is usually specified for the yellow light of sodium vapor (so-called D spectral line) since this happens to fall in the part of the spectrum corresponding to maximum sensitivity of the human eye, and since monochromatic light of this color can be easily produced for lens testing by means of an alcohol lamp with common salt dissolved in the alcohol, or various other simple devices. This reference index (for D light) is symbolized as n_D.

To give a measure of dispersion, glass tables give the difference in refractive index between the value (n_C) for the red hydrogen line C, and the value (n_F) for the blue hydrogen line F. These colors are produced by using an electric glow tube containing hydrogen gas at low pressure. The letters C, D, F refer to an old indexing scheme for spectral lines, devised long ago by the famous physicist Josef Fraunhofer. It is customary to express dispersion by a derived quantity called *reciprocal dispersion* or simply the *V-value:*

$$V = \frac{n_D - 1}{n_F - n_C} \qquad (26)$$

This factor is used because of its convenience in various approximate formulas for correcting chromatic aberration.

Glass tables frequently give the refractive index differences between various other spectral lines throughout the spectrum. These are used in calculating various special types of color correction for lenses (in photographic work, for example) and they will not be discussed in detail here; the values of n_D and V are usually the only ones needed for visual refractor objectives, and many glass blanks are supplied with only these two constants specified.

It turns out that the effect of dispersion is such that a positive or converging lens has a longer focal distance for red (C) light than for blue (F) light, while the reverse is true for a negative or diverging lens. Thus, by combining a positive lens and a negative lens having different types of glass, we can balance their dispersion effects so that the lens becomes nearly achromatic, and still retain a positive power for the whole combination.

The proper powers for the two elements of the lens can be estimated by the following simple approximations (subscripts a and b refer to crown and flint respectively):

$$\frac{1}{f_a} = \frac{V_a}{f'(V_a - V_b)} \tag{27}$$

$$\frac{1}{f_b} = \frac{-V_b}{f'(V_a - V_b)} \tag{28}$$

For either a or b we have:

$$\frac{1}{f} = (n-1)\left[\frac{1}{r_1} - \frac{1}{r_2}\right] \tag{29}$$

Subscripts 1 and 2 refer here to the front and back surfaces of each lens. f' is the focal length of the whole system in the case of equations (27) and (28). The value of n is for D light.

The effect of these formulas is to make the overall focal length of the system equal for C light and F light (so-called C–F achromatism).

The equations fail to give definite values for the radii r_1 and r_2, as we could use any pair of values giving a correct value of f. In practice, we choose suitable values for r_1 and r_2 for each lens so as to reduce spherical aberration and coma as much as possible; this is done partly by experience and partly by trial ray tracing, as will be explained in detail later.

Before we get on to the methods of doing this, there are some further points to consider about chromatic aberration. These are illustrated in the following drawings.

If we plot the final paraxial focal distance l' (See **Figure** 6) of a good achromat against light wavelength, using an enlarged vertical scale, we get a flat, roughly parabolic curve, as shown. There is an appreciable difference in focal distance between the C–F focus and the focus corresponding to the yellow-green light to which the eye is most sensitive (labeled 555). This unwelcome left-over focal difference is called *secondary* color, and amounts to about 1/2000 of the whole focal length for usual types of glass. It becomes a quite serious source of aberration in large refractors. Unfortunately, not much can be done to reduce it, except by using very unusual types of glass. Such lenses with reduced secondary color are called *apochromats;* they are occasionally used for special purposes, but they are very expensive and, moreover, they usually lead to a considerable increase in other aberrations such as spherical aberration and coma; they are not suitable for the usual amateur refractor.

If we cannot eliminate secondary color, the next best thing is to have the flattest part of the focal curve fall in a position corresponding to maximum visibility, so that at least this important part of the spectrum will give sharp

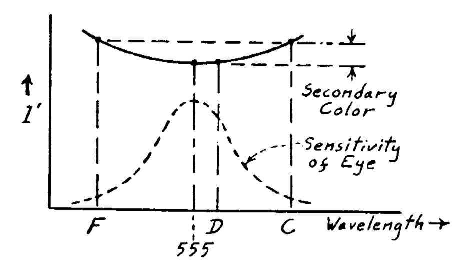


FIGURE 6

focus. Experience has shown that this is accomplished quite nicely by bringing the C and F light to a common focus, and this is the basis for the usual method of achromatizing. The flat minimum of the curve then falls close to the peak of visibility, at a wavelength of about 555 millimicrons (555 millionths of a millimeter, or 21.8 microinches).

The approximate formulas (27) to (29) are based on the assumption that the two lenses are very thin and very close together, which is not strictly true; moreover, they are based on paraxial rays, and fail to consider the effects of spherical aberration in the outer part of the lens. If this were taken into account, we would find that a lens which was properly color-corrected in the center would be seriously overcorrected at the margin, a condition known as sphero-chromatic aberration. Hence the formulas (27) to (29) are satisfactory only for obtaining a preliminary solution; we must employ a more refined scheme for the final correction, which will give us a good average correction for the whole lens. A great many methods have been proposed for doing this; most of them involve the tracing of special trig rays through an intermediate zone of the lens (usually at 70.7 percent of full aperture), which adds a great deal of extra computation. However, a method is recommended by modern authorities which is both rigorous and fairly simple, and requires no additional rays beyond the usual paraxial and marginal ones; this scheme, called the Conrady path-difference method, will now be briefly explained.

The Path-Difference Method: The path-difference method is based on the idea that a lens will be fully corrected if all the incoming waves of light arrive at the final focus at exactly the same moment. If some one of the waves arrives a bit too soon or too late it will cause an interference action with the other light waves, resulting in aberration. The situation will be clearer if we represent the incoming rays by a series of *wave fronts* (Figure 7). These wave fronts are perpendicular to the light rays.

The part of any ray inside the glass moves slower than the part in air, the refractive index (n) being the ratio of the speed in air to the speed in glass. Hence the distance (D) inside the glass is equivalent to a distance (Dn) in air.

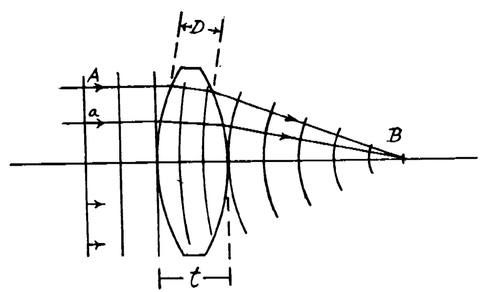


FIGURE 7

Now if two rays from points (A) and (a) on an incoming plane wave arrive at the focus B together, there is no aberration between them. This is equivalent to saying that they must have exactly equal optical path lengths (AB) and (aB), if we count the path in the glass (D) as an air path of length (n_D), and the path length t as an air path of length (nt).

If we have adjusted the lens shape by ray tracing to eliminate spherical aberration between the marginal and paraxial rays, the path difference of these rays is automatically brought to a very low figure, for the color used in the trace; but this equality may be upset if some other color is used. This is because the glass path length D for the marginal ray is different than the length t for the paraxial ray; this difference is equivalent to an air path difference of $n(t\text{-}D)$. The value of this difference varies, of course, as n varies; for example, we have a path difference between C and F light given by

$$PD = (t - D)(n_F - n_C) \tag{30}$$

This variation, of course, affects only the part of the rays inside the glass, as the refractive index of air remains nearly constant for all colors.

If we made a sketch similar to Figure 7 for a negative lens, the PD by equation (30) would be negative, because D would then be larger than t. Hence if we combine a positive and a negative lens, we can adjust the sum of their PD's to come out to zero; the lens will then be achromatic, for the changes in index between C and F light will not result in any change in effective air path difference between the paraxial and marginal rays. (We have neglected, of course, to account for any variation in PD due to difference in *position* of the actual ray paths for C light and for F light but these paths are so nearly alike that this causes no serious error.)

The calculation procedure for producing achromatism by the PD method is as follows:

1. For each lens, calculate the index (n_{555}) for "brightest light," which is given closely enough by:

$$n_{555} = n_D + 0.188\frac{(n_D - 1)}{V} \tag{31}$$

n_D may also be used directly, instead of n_{555}.

2. Trace a paraxial and marginal ray for this index through the first lens, and through the first surface of the second lens.

3. Calculate the sagittas X_1 and X_2 of the ray for the first lens (see Figure 8).

$$X = 2r \sin^2 \frac{U + I}{2} \tag{32}$$

4. Calculate distance D for first lens:

$$D_a = \frac{t + X_2 - X_1}{\cos U'_1} \tag{33}$$

(cos U'_1 is for the first surface of first lens.)

5. Calculate PD of first lens:

$$PD_a = (t_1 - D_a)(n_F - n_C)_a \tag{34}$$

where $(n_F - n_C) = (n_D - 1)/V$, by equation (26)

6. Calculate D required for second lens:

$$D_b = t_3 + \frac{PD_a}{(n_F - n_C)_b} \tag{34a}$$

7. Assuming the first radius of the second lens is known, calculate its first sagitta X_3 by formula (32).

8. Calculate second sagitta:

$$X_4 = X_3 - t_3 + D_b \cos U'_3 \tag{35}$$

(cos U'_3 being for first surface of the second lens.)

9. Calculate ray height Y_3 for first surface of 2nd lens:

$$Y_3 = r_3 \sin (U_3 + I_3) \tag{36}$$

10. Calculate ray height Y_4 at second surface of this lens:

$$Y_4 = Y_3 - D_b \sin U'_3 \tag{37}$$

11. Calculate radius of last surface:

$$r_4 = \frac{Y^2_4}{2X_4} + \frac{X_4}{2} \tag{38}$$

All this *PD* work should be done on a standardized schedule sheet, made up in advance, like the ones for the ray traces. An example will be given later.

We then continue the trace of the paraxial and marginal rays through the last surface, and check the results for LA' and OSC' by formulas (24) and (25). All the calculations for *PD* should be very accurately done, to six decimal places (or 1 microinch). A calculating machine is very desirable for the *PD* work, as log calculations for *PD* involve a lot of shifting from logs to antilogs, involving much additional labor.

The *PD* correction process establishes a good color correction between the central and marginal rays, leaving only some minor errors for intermediate zones (aside from the irreducible secondary color effect).

Having rendered the lens achromatic and calculated its OSC' and LA' values, we wish to determine whether the results are satisfactory. We use the following tolerance formulas, assuming the trace to be made using n_{555} light.

$$\text{Permissible } LA' = \frac{87 \times 10^{-6}}{(\sin U'_m)^2} \tag{39}$$

($87 \times 10^{-6} = 4$ wavelengths. Use 93×10^{-6} if *D* light is traced. U'_m is the slope angle behind the last surface.)

$$\text{Permissible } OSC' = .0025 \tag{40}$$

The LA' and OSC' should fall below the limits (which may be either plus or minus) set by equations (39) and (40). If they do not, we must alter the lens proportions and make a new calculation, as explained later. The *PD* calculations should also be carefully checked to make sure that the total *PD* does not exceed ½ wavelength, or about 11 microinches (that is, 11 one-millionths of an inch, or .000011 inch).

In equation (39), $1/(\sin U')^2$ is equal to 4 times the square of the *f* number of the objective. For example, for an *f*/15 objective, LA' should not exceed $4 \times (15)^2 \times 87 \times 10^{-6}$ or .078 inch.

The secondary color of an objective is usually not calculated directly; it is roughly allowed for by keeping the *f* number of the objective greater than 2.8 times the aperture in inches. Thus a 5-inch objective should not be built for a shorter focal ratio than $f/(2.8 \times 5)$ or *f*/14. In very large astronomical objectives, it is not practical to come anywhere near this limit, so that they usually have serious secondary color (a condition which seriously limits their effectiveness for some types of work). On the other hand, small objectives

(such as binoculars) often work down to as low as *f*/4 without any bad effects. It might be concluded from this that chromatic correction is a rather nebulous affair, and it may appear a bit questionable just how much effort should be spent in securing it, especially in long focus designs; there is not much sense in carefully tuning up the color correction if it is going to be spoiled by secondary color anyway. Although the matter has been argued over at great length by optical theorists, there is still surprisingly little agreement on it, and even less direct experimental evidence. The best answer that can be given to this is that it always pays to "tune up" the color correction by the path difference method to ensure that we have as good a design as possible,

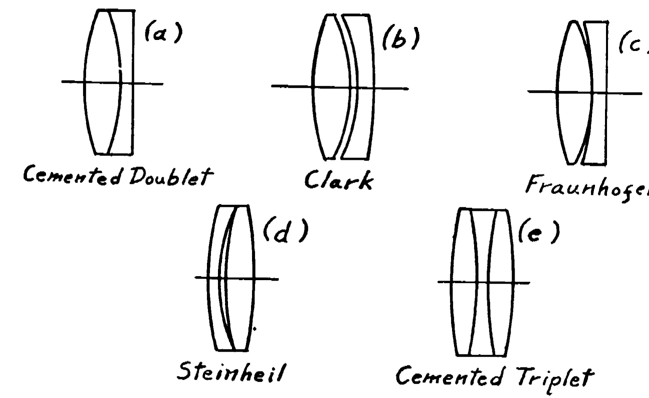


FIGURE 8

and to use a reasonable value for the focal ratio; we can then be safe in anticipating satisfaction from the finished lens, if its workmanship is good.

We are now about ready to take up the practical details of the ray trace; so, before we dive into this, take a well-earned rest for a while, and then "check yourself out" on the general methods explained in the previous discussion.

Ray Trace Design Procedure: Assuming that you are now sufficiently rested to cope with the terrors (not really very terrible) of slide rule, log table, and trig table, we will start right in with a practical design example.

To get a rough preliminary layout, one of the best procedures is to estimate the lens proportions from some previous design which is known to be satisfactory, and gradually alter the dimensions as the design proceeds. Mathematicians irreverently refer to this as "cooking a solution." Before we start the pot boiling, we have to decide on the general type of design. The sketch (Figure 8) shows several well-known layouts, schematically:

Type (*a*) is the usual simple cemented doublet, which is nearly always used for sizes up to about 2½-inch aperture. It is easy to construct and mount, and is the simplest to compute, as the rays can be taken through the

2nd and 3rd surfaces in a single operation. It has the disadvantage that we usually cannot get exact correction for both spherical aberration and coma, since the powers of the individual elements are fixed by the requirements for achromatizing and for over-all focal length, leaving the over-all shape of the whole lens as the only remaining major variable. If we use this to control the spherical aberration, the coma must be left to take care of itself and may turn out to be undesirably large. This procedure of changing the lens shape is called "bending," and is illustrated in Figure 9. The dotted lines indicate the effects of bending the lens, keeping the individual lens powers the same.

We can get better compensation for coma by a proper choice of glass; for example, making the elements of *BSC* crown 1.517/64.5 and dense flint 1.649/33.8 will often give a cemented combination that is nearly aplanatic. (The two

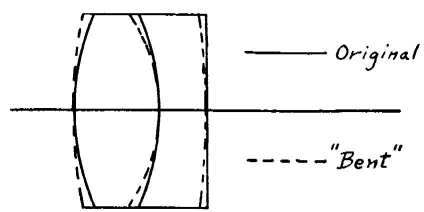


Figure 9

figures separated by the bar refer to n_D and V for the corresponding glasses; they are often abbreviated still further to 517/645, etc.) However, the amateur often has to "make do" with whatever optical glass he can get, so this idea often fails; moreover, it generally requires very tedious "cut and try" designing to select a good combination. Another plan is to design the lens to eliminate coma, and then take out any spherical aberration by figuring the finished lens, testing it against a flat by auto-collimation. This process will have only a slight effect on the coma correction. This method is rare in commercial work, owing to the expensive hand figuring needed, but is not a bad one for the amateur. A more commonly used scheme is to use a "broken-contact" lens with an airspace (type *b* Figure 8, known as the Clark type). The second and third surfaces match one another, just as in a cemented type, but the airspace gives a new variable to work with, so that by combining variation of airspace with bending of the whole assembly, we can control both coma and spherical aberration without resorting to figuring. This type is one of the best to use for large sizes (3 inches and up) especially if you are testing the lens elements against spherical test plates by interference fringes. The broken-contact also aids in eliminating warpage troubles caused by cement. However, this type requires very accurate construction of the mounting cell, as the spacer sleeve between the lenses must hold the airspace correct to a few thousandths of an inch, and also rigorously prevent any tipping or misalinement of either element. The individual elements must also be very accurately centered.

Types *c* and *d* are variants of the airspace idea, in which the airspace is "lens-shaped," surfaces 2 and 3 having different radii; type *c* has the crown in front; type *d* has flint in front. These types require more tools and test plates than types *a* and *b*, and are not recommended for amateur use. Type *e* is a triplet cemented lens in which coma is controlled by varying the relative power of the front and back crown elements; this type is hard to design and to construct, and is seldom used.

For our trial example, we will design a 4-inch $f/12$ objective of 48-inch focal length. The available glass will be assumed to be 1.5137/63.6 crown and 1.6164/36.7 flint.

We can estimate the proper proportions by cooking the following table of sample designs, which are all for an effective focal length of unity.

Table 1—*SAMPLE DESIGNS*

Design	1	2	3	4
r_1	.4645	.5814	.4462	.5935
r_2	−.4314	−.3585	−.4462	−.3394
r_3	−.4314	−.3585	−.4462	−.3394
r_4	−5.214	−1.6189	−7.541	−1.8928
t_1	.00697	.00693	.03771	.05075
t_2	cement	.00311	cement	.00217
t_3	.00498	.00495	.02514	.03045
Crown	1.5170/64.5	1.5170/64.5	1.5166/63.2	1.5407/59.4
Flint	1.6170/36.6	1.6170/36.6	1.6256/36.4	1.6225/36.0
Aperture Ratio	$f/15$	$f/15$	$f/3.98$	$f/3.94$

The first two examples are from Dimitroff and Baker's "Telescopes and Accessories;" the second two are based on data in Conrady's "Applied Optics."

As our proposed lens is a fair-sized one of moderate focal ratio, we will take Example 2 as a preliminary recipe. We will begin by a bit of slide-rule work to adapt this example to our own proposed layout. Equations (27) to (29) come in handy for this. We first calculate $V_a/(V_a - V_b)$ and $V_b/(V_a - V_b)$ for both our own lens and the sample design and calculate the ratios between the results. For our own crown lens, we find $V_a/(V_a - V_b) = 63.6/(63.6 - 36.7) = 63.6/26.9 = 2.367$, while the same figure for Example 2 comes out as 2.312, the ratio being $2.367/2.312 = 1.024$. Similarly, $V_b/(V_a - V_b)$ is 1.365 for our flint, and 1.311 for Example 2 (a ratio of $1.365/1.311 = 1.04$). This shows that the powers of both lens elements (for a given over-all focal length f') will have to be a little greater than those of Example 2, as will be seen by Equations (27) and (28). (The "power" of a lens is equal to $1/f$ where f is the focal length of the lens.) This indicates that we must use slightly deeper curves and shorter radii than Example 2. Also, we have a slightly different value of $n_D - 1$ than Example 2; this is 0.5137 for our crown and 0.517 for Example 2, which means we must again decrease our radius values somewhat to get the proper crown lens power for the lower index value (see Equation 29). The ratio 0.5137/0.517 is .993. In addition, we have a focal length of $12 \times 4 = 48$ inches instead of unity, so we must correct for this. The final correction factor for the crown radii in Example 2, including the dispersion correction, index correction, and focal length correction, is therefore $(.993/1.024) \times 48 = 46.5$, so we have $46.5 \times .5814 = 27.05$ inches for r_1, and $46.5 \times -.3585 = -16.68$ inches for r_2 (and also r_3, which is to fit r_2).

We really don't have to calculate r_4 as this will be established later during the path-difference calculation for achromatism. However, a preliminary r_4 value is of interest, and is readily found by Equation (29). We first find the "total curvature" (c) of the flint lens for the sample design. (Subscripts 3 and 4 refer to front and back of flint lens.)

$$C = \frac{1}{r_3} - \frac{1}{r_4} \quad (41)$$

This factor is $-1/.3585 + 1/1.6189 = -2.171$ for the design example. We must apply corrections for dispersion, index, and focal length. The index correction is $0.6164/0.617 = .999$; we have already calculated the dispersion correction to be 1.04 for the flint. Hence the corrected value of C is $(-2.171/48) \times (1.04/.999) = -.0471$. We have $1/r_3 = -1/16.68 = -.0599$. Hence, by Equation (41), $1/r_4 = -.0599 + .0471 = -.0128$, or $r_4 = -78.1$ inches.

The thicknesses of the lenses are corrected by applying the familiar approximate formula for the dip or sagitta (often abbreviated as "sag") of a circular arc:

$$X = \frac{Y^2}{2r} \quad (42)$$

For a given value of r, the sags will evidently vary in proportion to Y^2, and hence inversely to the square of the focal ratio or f number. They will also be proportional to the focal length. As the thicknesses ought to vary roughly in proportion to the sags, we find for our crown lens:

$$t_1 = .007 \times 48 \times \left(\frac{15}{12}\right)^2 = 0.525 \text{ inch,}$$

or say 0.52 inch; similarly, for the flint:

$$t_3 = .005 \times 48 \times \left(\frac{15}{12}\right)^2 = 0.375,$$

say 0.38 inch. Theoretically, we should also apply corrections for the index and dispersion, but these amount to only a few percent, and as the thicknesses are not very critical we will not bother with this refinement. In the case of short focus lenses, the above rule may give an inconveniently thick lens; in this case, the thickness should be somewhat less than the above rule would indicate. Make a scale drawing of the lens to check how much you can afford to shave off.

The airspace t_2 cannot be calculated accurately by any simple rule; however, we note from Table 1 that it varies only slightly with the focal ratio, tending to be a bit smaller for short focus types. As our ratio $f/12$ is a little shorter than the $f/15$ ratio of Example 2, we will take .00288 for the constant, so $t_2 = .00288 \times 48 = 0.138$-inch airspace.

We now have the following basic data for the preliminary design, (which should be sketched up to scale to see that it "looks right" and to check the edge thicknesses):

TABLE 2

$r_1 = 27.05$	$t_1 = 0.52$ (1.5137/63.6)
$r_2 = -16.68$	$t_2 = 0.138$ (air)
$r_3 = -16.68$	$t_3 = 0.38$ (1.6164/36.7)
$r_4 = -78.1$	

We will now proceed to a ray trace to check this preliminary estimate. Before we do this, review the whole cooking procedure just described, to make sure you understand it, checking the results with your own slide rule. (If you check Table 2 directly against Equations (27) to (29), you'll find some disagreement in the results, owing to the fact that we have used these formulas only for interpolation in the cooking process, not as direct solutions. This procedure gives a better approximation to the final results.) The cooking can be summarized as follows, where subscript s refers to a standard design, as in Table 1, and a and b refer to crown and flint respectively:

1. Calculate

$$Z_a = \frac{V_a}{V_a - V_b} \quad (43)$$

for crown, both standard and proposed.

2. Calculate

$$Z_b = \frac{V_b}{V_a - V_b} \quad (44)$$

for flint, both standard and proposed.

3. Calculate:

$$K_1 = Z_a/Z_{as} \quad (45)$$

$$K_2 = Z_b/Z_{bs} \quad (46)$$

4. Calculate:

$$K_3 = (n-1)a/(n-1)as \quad (47)$$

$$K_4 = (n-1)b/(n-1)bs \quad (48)$$

5. Multiply the standard values for r_1 and r_2 by $K_3f'/K_1f'_s$ (where f' and f'_s are the over-all effective focal lengths of the proposed design and of the standard design). Set $r_3 = r_2$ (for a cemented or Clark objective).

6. Calculate

$$C_{bs} = \left(\frac{1}{r_3} - \frac{1}{r_4}\right)_s \tag{49}$$

7. Calculate

$$C = C_{bs}\frac{f'_s}{f'}\frac{K_2}{K_4} \tag{49a}$$

8. Find $r_4 = 1/(1/r_3 - C)$ (50)
(using r_3 found in step 5)

9. Calculate

$$K_5 = \left(\frac{FR}{FR_s}\right)^2 \tag{51}$$

where FR is the focal ratio or f number (12, in our example).

10. Multiply the standard values for the lens thicknesses by K_3f'/f'_s.

11. Multiply the standard airspace value by f'/f'_s and apply a suitable empirical correction based on other designs, if available.

These operations look complicated, but require only a few minutes of slide-rule work, once you are used to them.

The next step in the lens design consists in tracing a trigonometric marginal ray and a paraxial marginal ray through the lens, using the preliminary values for radii and thicknesses. In the process of doing this, the lens will also be accurately achromatized by using the *PD* equations. The final results of the ray trace are then checked against the tolerance formulas (39) and (40) to determine whether the preliminary design is satisfactory, or whether a revision of the design is needed.

For general lens design, it is usually customary to use five-place log tables and work out all the angles to the nearest second; however, for refractor design it is preferable to work with six-place logs and angles taken to 0.1 second accuracy, because of the long focal distances and small angles involved. In the present calculation, the McGraw-Hill Six-Place Tables by Allen will be used. If you are not familiar with the use of logarithmic and trigonometric tables, study the explanatory examples in the preface to the tables till you understand the methods involved. The trig work involved in refractor design does not require any of the complicated formulas used in school courses in trigonometry; all you need to know is how to look up in tables certain mathematical values called the logarithmic sine and cosine of an angle, (abbreviated log sin and log cos), and how to interpolate between tabulated values (with the aid of a slide rule) to get the proper values for intermediate angles in between the tabulated ones. Logarithms are a little tougher, but if you have

trouble with them you can probably get some friend to help you out. All this, including the use of a slide rule, can be picked up in a week or so of evening study, so don't be worried if you know very little mathematics. If you have to start from scratch in these things, or have forgotten them for years, a hobby like lens design will offer a relatively painless and interesting way of learning them, and you will later find them useful for all sorts of other subjects.

Assuming that you have crammed a bit on the mathematical technic, you are ready to tackle the sample calculation shown in the work sheets given here. Go through them carefully item by item, referring to formulas (1) to (23) to see what is going on. In your own later work, you need not bother with the formulas, but just follow the mechanical operations of figuring out the work-sheet entries once you have a standard work sheet written out or mimeographed in advance. Expert lens computers eventually get so skillful at this that they can run a complete lens calculation like the one given here in about two or three hours, but when you first undertake such jobs, do them carefully and slowly—you'll probably find two or three weeks is closer to being right. Use separate sheets of scratch paper for working out interpolations and other miscellaneous calculations, and keep these neat and orderly so you can check them later if need be; be careful to write everything clearly and legibly; be *very* careful of plus and minus signs, and of interpolation corrections. Use pencil (not ink) and make any corrections in red or blue pencil.

You will note that each ray has its own vertical column in the table. The first entry indicates which surface you are using. In starting the calculation, skip items (1) to (5) and enter log Y_1 (in brackets) on line 6, corresponding to formula (7). Enter r on line 21 and log r on lines 7, 11, 26, and 30 (note signs), $-t_1$ on line 37, and log n/n' on line 9 (be very careful to get the sign and amount of this quantity correct). Now fill in entries (7) to (12), a mere matter of addition and subtraction. Notice that in doing these sums, wherever the characteristic of the log (the figure to the left of the decimal point) would come out greater than 9 or less than zero, we can (if we like) add or subtract 10 from one of the logs, to keep the answer convenient in size. This is equivalent to shifting the decimal point in the final result by ten places one way or the other. Theoretically we ought to keep track of these extra 10s as a separate item (as explained in books on logarithms) but in practice this is never needed, as it is always obvious where the decimal ought to go in the final result. Thus in getting item (8) we mentally add 10 to item (6), and in getting item (12) we mentally deduct 10 from the actual sum of items (10) and (11), and put the 10 back in getting item (14). You will quickly get the hang of this trick with a little practice.

On reaching item (12), we have to start in on the trig tables. The angles are itemized in rows 15 to 19. Write down U (which is zero here) and look up I and I' in the trig table, using log sin of I and I' from items (8) and (10) and interpolating in table. You will probably need some practice in adding the angles—remember that you borrow or carry 60, not 10, between the minutes and seconds, or the degrees and minutes. A little practice will make

Sheet 1 — 4" f/12 Airspace Objective. Ray Trace — Crown Lens. 7/12/47 JHW

Crown: 1.5137/63.6. $\Delta n_a = \frac{.5137}{63.6} = .008077$

Flint: 1.6164/36.7. $\Delta n_b = \frac{.6164}{36.7} = .016796$

		Marginal Ray			Paraxial Ray	
	Surface	1	2		1	2
1	L	—	79.0900		Same as Marginal	79.1869
2	−r	—	16.68			16.68
3	L − r	—	95.7700			95.8669
4	log sin U	—	8.400329			8.399534
5	+ log (L − r)	—	1.981229			1.981669
6	log (L−r) sin U	.301030	10.381558			10.381203
7	− log r	−1.432167	−1.222196n			−1.222196n
8	log sin I	8.868863	9.159362n			9.159007n
9	+ log N/N′	−.180040	.180040			.180040
10	log sin I′	8.688823	9.339402n			9.339047n
11	+ log r	1.432167	1.222196n			1.222196n
12	log r sin I′	.120990	.561598		.120990	.561243
13	− log sin U′	−8.400329	−9.001666		−8.399534	−8.996400
14	log (L′ − r)	1.720661	1.559932		1.721456	1.564843
15	U	0	1−26−25.6		0	.0250919
16	+ I	4−14−24.6	−8−17−55.0		.0739372	−.1442140
17	U + I	4−14−24.6	−6−51−29.4		.0739372	−.1191221
18	− I′	−2−47−59.0	12−37−10.1		−.0488453	.2182965
19	U′	1−26−25.6	5−45−40.7		.0250919	.0991744
20	L′ − r	52.5607	36.3021		52.6570	36.7150
21	+ r	27.05	−16.68		27.05	−16.68
22	L′	79.6107	19.6221		79.7070	**20.0350**

Sheet 2 — 4" f/12 Airspace Objective. Checks and PD Work — Crown. 7/12/47 JHW

		Marginal 1	Marginal 2		Paraxial 1	Paraxial 2
23	½ (U + I)	2−7−12.3	−3−25−44.7	log l	—	1.898653
24	log sin ½(U+I)	8.568129	8.776793n	+ log u	—	8.399534
25	log sin²	7.136258	7.553586	log y	.301030	.298187
26	+ log r	1.432167	1.222196n	+ colog u′	1.600466	1.003600
27	+ log 2	.301030	.301030	log l′	1.901496	1.301787
28	log X	8.869455	9.076812n			
29	log sin(U+I)	8.868863	9.077048n			
30	+ log r	1.432167	1.222196n			
31	log Y	.301030	.299244			
32	+ log cot U′	11.599534	10.996134			
33	log Y cot U′	1.900564	1.295378			
34	Y cot U′	79.5360	19.7414			
35	+ X	+.0740381	−.1193472			
36	L′	79.6100?	19.6221?	l′	79.7069	20.0349?
37	−t	−.52	−.138	−t	−.52	−.138
38	Next L	79.0900	19.4841	Next l	79.1869	19.8969

PD Work:

39	$X_2 - X_1$	−.1933853	45	−D	−.3267180
40	+ t	.52	46	+ t	.52
41	ΔX + t	.3266147	47	t − D	.1932820
42	log(ΔX + t)	9.514036	48	log(t − D)	9.286192
43	colog cos U_1'	.000137	49	+ log Δn	7.907250
44	log D	9.514173	50	log PD	7.193442
			51	PD	.00156114

Sheet 3 — 4" f/12 Airspace Objective — Ray Trace for Flint; LA' & OSC. — 7/13/47 JHW

		Marginal Ray		Paraxial Ray	
	Surface	3	4	3	4
1	L	19.4841	121.4874	19.8969	121.1125
2	-r	16.68	78.2874	16.68	78.2874
3	L-r	36.1641	199.7748	36.5769	199.3999
4	log sin U	9.001666	8.209796	8.996400	8.210637
5	+log (L-r)	1.558278	2.300540	1.563207	2.299725
6	log (L-r) sin U	10.559944	10.510336	10.559607	10.510362
7	- log r	-1.222196n	-1.893692n	-1.222196n	-1.893692n
8	log sin I	9.337748n	8.616644n	9.337411n	8.616670n
9	+ log N/N'	-.208549	.208509	-.208549	.208549
10	log sin I'	9.129199n	8.825153n	9.128862n	8.825219n
11	+ log r	1.222196n	1.893692n	1.222196n	1.893692n
12	log r sin I'	10.351395	10.718845	10.351058	10.718911
13	- log sin U'	-8.209796	-8.620434	-8.210637	-8.620569
14	log (L'-r)	2.141599	2.098411	2.140421	2.098342
15	U	5-45-40.7	0-55-43.8	.0991744	.0162419
16	+ I	-12-34-14.6	-2-22-14.8	-.2174759	-.0413685
17	U + I	-6-48-33.9	-1-26-31.0	-.1183015	-.0251266
18	-I'	7-44-17.7	3-50-0.7	.1345434	.0668682
19	U'	0-55-43.8	2-23-29.7	.0162419	.0417416
20	L'-r	138.5475	125.4326	138.1723	125.4127
21	+r	-16.68	-78.2874	-16.68	-78.2874
22	L'	121.8675	47.1452	121.4923	47.1253

log u' = 8.620569
log l' = 1.673257
colog sin U' = 1.379566
colog L' = 8.326571
9.999963 = log .999914

OSC = 1-.999914 = .000086 (OK)
(Permissible OSC = ±.0025)
LA' = l' - L' = 47.1256 - 47.1442
= -.0186 (OK)
Permissible LA' = $4 \times 12^2 \times 92.6 \times 10^{-6}$
= ±.0534

(l' and L' values are from sheet 4, item 36)

Sheet 4 — 4" f/12 Airspace Objective — Checks and PD Work — Flint. — 7/14/47 JHW

		Marginal 1	Marginal 2		Paraxial 1	Paraxial 2
23	½ (U+I)	-3-24-17.0	-0-43-15.5	log l	1.298786	2.083189
24	log sin ½(U+I)	8.773702n	8.099784n	+ log u	8.996400	8.210637
25	log sin²	7.547404	6.199568	log y	.295186	.293826
26	+ log r	+1.222196n	1.893692n	+ colog u'	1.789363	1.379431
27	+ log 2	+.301030	.301030	log l'	2.084549	1.673257
28	log X	9.070630n	8.394290n			
29	log sin (U+I)	9.073964n	8.400780n			
30	+ log r	1.222196n	1.893692n			
31	log Y	.296160	.294472			
32	+ log cot U'	11.790147	11.379185			
33	log Y cot U'	2.086307	1.673657			
34	Y cot U'	121.9851	47.1690			
35	+X	-.1176604	-.0247907			
36	L'	121.8674?	47.1442?	l'	121.4925?	47.1256?
37	-t	-.38		-t	-.38	
38	Next L	121.4874		Next l	121.1125	

PD Work:

39	log PDa	7.193442
40	- log Δn	-8.225197
41	log PDa/Δn	8.968245
42	PDa/Δn	.0929317
43	+ t_3	.38
44	D_b	.4729317
45	log D_b	9.674798
46	+ log sin U'	8.209796
47	log D sin U'	7.884594
48	- D sin U'	-.007666
49	+ Y_3	1.977699
50	Y_4	1.970033

51	log D_b	9.674798
52	log cos U'	9.999943
53	log D cos U'	9.674741
54	D cos U'	.4728695
55	+ X_3	-.1176604
56	D cos U' + X_3	.3552091
57	- t_3	-.38
58	X_4	-.0247909
59	log Y_4	.294473
60	log Y_4^2	.588946
61	colog 2	9.698970
62	colog X_4	1.605707n

63	log $Y^2/2X$	1.893623n
64	$Y^2/2X$	-78.27500
65	$X_4/2$	-.01240
66	r_4	-78.28740

this easy. Note that the dashes between degrees and minutes, and between minutes and seconds, are just to separate the figures and don't mean "minus" —only the first dash at the extreme left, as in item 18, means "minus." If there is no special mark, the number is plus.

When you have U', look up log sin U' in the table, using interpolation, and enter the result on line 13; subtract item (13) from item (12), getting item (14); look up its antilog and enter it on line 20. By addition of r, we now have L', the marginal image distance for the first surface.

At this point, it is very desirable to check the results by an independent check formula, as it is very easy to make some error in the preceding work. The first thing to check is item (12), which should equal the sum of items (6) and (9)—it may differ by 10 in the characteristic, which does not count; if the difference is not 0 or 10, there is some error. (Use rough paper stencil if you like, to cover up intermediate items which confuse the eye.) Also, make certain log n/n' is correct. If these are OK, you can proceed to check L', which is done by the following formulas:

$$Y = r \sin(U' + I) \tag{52}$$

$$L' = Y \cot U' + X \tag{53}$$

The value of X is found by formula (32) given earlier in the chapter:

$$X = 2r \sin^2\left(\frac{U' + I}{2}\right) \tag{32}$$

We begin by calculating X (which we will need later anyway, for the PD work). We get item (23) by dividing item (17) by 2, and look up its log sin. This is multiplied by 2 to get item (25) (note that characteristic value 17 is written as 7 for convenience). Adding log r and log 2, we get log X as the final sum.

We then look up log sin $(U' + I)$ from item 17, enter it as item (29), add log r, giving log Y; we then look up log cot U' (taking U' from item 19); be careful in interpolating, as the correction for log cot or log cos is minus, not plus). Adding these logs and taking the antilog, we have Y cot U'; we look up X (from item 28) and add it to item (34), giving L', as item (36). This item should agree with item (22) within a few points in the last significant figure, i.e., to about 1 part in 200000; if it does not, there is probably some error. If the check seems good, we proceed to subtract t_1 from L'_1, to give L_2, the object distance of the next surface. Note that we use L' from item (36) as indicated by the exclamation point, instead of item (22), since item (36) is a little more accurate.

Note that the formulas do not give any check on whether n/n' is correct or not, simply because the formulas cannot tell whether you have (in effect) used an incorrect imaginary type of glass by inserting an incorrect value for item (9); that is why you must be very careful about this item. (A very small error of this sort actually occurs in item 49 of the trace from the first lens element.) Be careful about log r also, as this can also slip through the check formula if you used the wrong value all through the calculations.

Assuming that we have the object distance, item (38), we stop at this point and go back up to item (1) in Column 2, for the marginal ray at the second surface. Enter item (38) of Column 1 as item (1) of Column 2, and subtract the radius of the second surface; as this radius is −16.68, the minus sign reverses in subtraction and we actually add 16.68 to the object distance to get item (3). For item (4), we simply copy item (13) out of column 1, with reversed sign (see Equation (6) early in this chapter). Add items (4) and (5) to get item (6). From this point to item (38), the calculation proceeds in much the same way as Column 1, and you should be able to follow it fairly easily. The only novelty is the small letter n after items 7, 8, and some other items; this letter merely means that the original figure, to which the log refers, is negative or minus. This enables us to keep track of the signs of the various products. For example, item (8) is the log of a negative number, as it represents the product of a positive and a negative number, while item (31) is the log of a positive number, being given by the product of two negative numbers. (If you get into tangles over plus and minus signs, it is a very good idea to work out the whole problem roughly on a piece of scratch paper, by slide rule, so that you can see more clearly what is actually going on.) Notice that item (15) is just copied from item (19) in Column 1, while items (16) and (18) are found from items (8) and (10), using the trig tables; these are also used to get item (13) from item (19).

When Columns 1 and 2 are complete for the marginal ray, we start in on the PD calculation for the first lens element, starting with item (39), which is the difference of items (35) in Columns 1 and 2. Adding the lens thickness, we get item (41). (The triangular doodad, a Greek letter, "delta," means simply "difference of X values;" similarly, the figure "delta n" in item (49) is an abbreviation for $n'_F - n_C$). The log of item (41) is item (42). Item (43) is found by looking up log cos U' from item (19) of Column 1, and then subtracting this figure mentally from 10 to get colog cos U'. (Consult the introduction to the McGraw-Hill tables on the use of cologs, which are just a mathematical trick to simplify some of the calculations by adding a colog instead of subtracting a log.) The rest of the PD calculation requires no special comment, except for item (49), which is found from equation (26) as indicated by the little calculation at the top of Sheet 1. You can easily follow the other operations with the aid of equations (32), (33), and (34), given earlier in the chapter. Notice that we have not used "555" light, as called for in equation (31), but merely "D" light, using the regular n_D. This makes very little difference in the final result.

We complete the work for the first surface by tracing the paraxial ray. The original ray height for this ray is taken as $y = 2$, the same as for the marginal ray. It turns out that items (6) to (12) are exactly the same for both rays, so we start in at item (12), copying this from Column 1 in the marginal ray schedule. We calculate items (16) and (18) next, which are found by looking up the antilogs of items (8) and (10) in Column 1 for the marginal ray (since these items represent log i and log i' for the paraxial ray, as you will see by a little checking of the ray-trace equations). Item (19) is then easily found; we look up its log and enter it as item (13). After this, the calculation down to item (22) is very similar to that for the marginal ray. As a check, we recalculate l' by the following equation:

$$l' = y/u' \tag{54}$$

Items (23) to (27) in the paraxial column represent this equation. We use item (36) as the best value for the image distance.

If you have followed the work so far carefully, you will not have too much trouble in following the paraxial traces for surfaces 2 and 3, and the marginal trace for surface 3. At the end of surface 3, we have to resume the *PD* work, to calculate the proper radius for the last surface.[2] Items (39) to (66) on Sheet 4 represent the headache, which amounts to a workout (!) of steps 6 to 11 in the *PD* schedule given earlier in the chapter. Items (39) to (44) represent step 6. Items (45) to (50) represent equation (37); note that Y'_3 is just the antilog of item (31), so we don't need equation (36) in this particular calculation. Items (51) to (58) are based on equation (35) and, finally, items (59) to (65) come from equation (38). (Note that item (60) is found simply by multiplying items (59) by two.) All this section of the calculation is quite tricky, due to all the diving in and out of the log tables, so it is well to keep a running slide-rule check of the results to avoid getting lost—and be especially careful in your figuring. At any rate, we finally find that r_4 comes out quite close to the preliminary value from the cooking estimate, which is encouraging.

Now that we have r_4, the marginal and paraxial rays are traced through the last surface; see the Columns 4, which require no special comments. We finally arrive at the L' and l' values for the last surface, items (36).

The spherical aberration is now found by equation (24), and turns out to be −.0186 inch. The permissible value by equation (39), putting $1/(\sin U')^2$ equal to $4 \times (12)^2$, comes out to be .0534, so we are well inside the limit for LA'. Good so far!

The next step is to check the OSC' by equation (25). After a few bits of log work (adding logs of u' and l', subtracting logs of sin U' and L', and taking antilog of result) we find OSC' is 1–.999914 or .000086, which is much less than the limiting value of .0025 from equation (40). So we have again "rung the bell" and the lens design is proved to be a good one.

And please note the word "proved." You may be tempted to say, "Well, why all this trigonometric rigmarole, when the first figures turned out to be right anyhow?" The answer is that now you *know* they are right, instead of having only a strong suspicion. It might turn out, and very often does turn out, that the cooking was not done to a turn, and that the LA' or OSC' may fall outside the proper limits. This is not very likely in the case of a long focus design like the present one, but is quite apt to happen in a "tight" design like a small $f/4$ objective for binoculars. It is well to know what to do in such a fix.

[2] On Sheet 4, the four columns should have been numbered 3, 4, 3, 4, respectively, as in Sheet 3.

Generally the LA' is more apt to be wrong than the OSC'. The LA' of an airspaced objective is corrected by reducing the airspace slightly if the LA' has too high a "plus" value, or increasing the airspace if the LA' value is too "minus." A rough rule to apply is as follows:

$$\text{Required airspace change} = -LA' \times FR^2/80 \tag{55}$$

where FR is the focal ratio, or ratio of focal length to aperture, which is 12 in the present design. The correction would be an increase of about .033 inch in the airspace, for our present design. However, it is good enough "as is," so we will not bother with this final adjustment in the present case.

However, if we were making the full calculation, we would now make a new ray trace using the new airspace value, tracing through the third surface and calculating a new value for r_4 by *PD* work. Note that all the calculations for the crown element can be used all over again, just as they are. The result of this second approximation for the airspace will usually be a satisfactory LA', but you may occasionally have to find a third approximation and repeat the ray trace. Fortunately, airspace changes have only a slight effect on the OSC', so if this was good to start with, it will not "creep" much during LA' correction.

If the lens is a cemented type, we naturally cannot control the LA' by airspace shifts; in this case, we must bend the whole lens. There are several ways of going about this job; perhaps the most generally useful depends on the G-factors described in the chapter in this book by A. E. Gee on algebraic design of lenses. Most of you have already read this chapter; perhaps some of you are quite expert at the algebraic method by now, gee-whizzes with the G's, so to speak.

For our present purpose, we will use a modified form of the G-sum formula, giving the effect of a small change in lens curvature upon the LA'. The formula is as follows:

$$\frac{dLA'}{dc_1} = y^2 l_b'^2 (M_a + M_b) \tag{56}$$

in which M is defined as:

$$M = -G_2 c^2 + 2G_4 c c_1 - G_5 c/L \tag{57}$$

In equation (57), L is the object distance, c is the total curvature of the lens element, and c_1 is the curvature of the front of the element. M is worked out separately for the crown (M_a) and the flint (M_b). The various G-factors, which depend on the refractive index, are found from the table at the end of Gee's chapter.

We will illustrate the method using the data for our airspace design. By interpolation in the table of G-values, we find G_2, G_4, and G_5 to be 1.034, 0.596, 1.706 for the crown (n being 1.5137) and 1.304, 0.690, 1.995 for the flint (n being 1.6164). We get the curvature data from the radius values in Table II of this chapter; for the crown, we have $c = .0969$ and $c_1 = .0370$, and working out M_a we find: $-.00971 + .00427 = -.00544$. (The term involving L is zero because L is infinitely large.) For the flint, we have $c = -.0471$ and c_1 (actually c_3 here) $= -.0599$, also $L = 19.9$ from the paraxial trace; we find $M_b = -.00289 + .00389 + .00472 = .00572$. We now work out equation (56), with $y = 2$ and $l_b' = 47.1$ (from the ray trace) and find a value of 2.48 for the ratio dLA'/dc_1. (The letters d are an abbreviation for "small change in".) The desired change in LA' is .0186, so the change in curvature dc_1 is .0186/2.48 or .0075. The corrected value for c_1 is thus $.0370 + .0075 = .0445$, while the new value for c_2 (and c_3) is $-.0599 + .0075 = -.0524$. We find the corresponding radius values and make a new ray trace, finding r_4 "on the way" by *PD* work.

It happens that the ratio dLA'/dc_1 came out quite small for the present lens, showing that bending is not a very good control for LA' in this type of objective. Equation (56) doesn't work well in cases like this, where the required change in curvature is large. Fortunately, the method usually works better with cemented objectives, where bending is more essential—at least, if we stick to spherical surfaces.

However, we do not really have to stick to spherical surfaces, for as "hams" we do not have to grind out lenses by the hundreds or thousands on automatic machines, but can well afford to spend a little time on hand figuring. In this case, we can adopt the type of design mentioned earlier in the chapter, in which the coma (or OSC') is reduced to zero in the original design work, and the LA' is later controlled by figuring the completed lens against a flat by autocollimation. Such a cemented objective is excellently corrected for both OSC' and LA', and is quite easy to design. First, lay out an algebraic solution for a zero-OSC' design by the methods given in Gee's chapter, neglecting the LA' correction entirely. Test the results by a ray trace, solving for a corrected r_4 value by *PD* work in the course of the calculation. If the OSC' is OK, go ahead and build the lens, and forget the LA' till you come to Foucault knife-edge tests. If the OSC' is too far out, use the following simple correction formula:

$$dc_1 = 1.16\, f'\, dOSC'/y^2 \qquad (58)$$

in which f' is the over-all focal length of the objective. As a numerical example, try our airspace design, with $OSC' = .000116$. The required c_1 change is: $1.16 \times 48 \times (-.000086)/(2)^2$ or $-.0012$. So we have $c_1 = .0370 - .0012 = 0358$, and $c_2 = c_3 = -.0599 - .0012 = -.0611$. We find the corresponding radius values (27.93 and −16.37) and make a new ray trace to find r_4 (by *PD*) and check the OSC'. In the present design, of course, the OSC' is good enough already and no bending is really needed.

Sometimes we may have a short focus airspace design in which *both* the OSC' and the LA' must be corrected in the preliminary ray trace. This situation is handled by a combination of the preceding methods. First, we find dc_1 from equation (58) to eliminate the coma. We then use this dc_1 in equation (56) and solve for the resulting change in LA': this dLA' is then

added to the original LA' to find the LA' after bending. Then we use equation (55) to find the necessary airspace change to correct this new LA' value. Finally, we correct the curvatures by dc_1, calculate the new radius values and the new airspace, and check the new specifications (and find r_1) by a new ray trace. If the results are still not good enough, the process is repeated.

All the preceding methods, of course, apply just as well to a design arrived at by the algebraic G-sum method as to one found by the cruder cooking method. Either system usually gives a satisfactory trial design, but the algebraic method is safer and more scientific. In fact, it nearly always gives a satisfactory design for long focus objectives, as shown by the results of ray traces reported in Gee's chapter. For short focus designs, algebraic results are less reliable, especially in regard to color corrections, and a complete ray trace analysis, including *PD* work, is practically essential to short $f/4$ or $f/6$ jobs, such as those used in binoculars and small spotting scopes. For moderate focal ratios, something like $f/8$ or $f/10$, a compromise design method may be used, based on cooking to get the color correction and G-sums to find the radius values. Use equations (43) to (48) applied to some good standard design; after finding factors K_1 to K_4, find c_a and c_b from formulas (49) and (49*a*) applied to the crown and flint separately, using K_1/K_3 for the crown and K_2/K_4 for the flint. Then use these values of c_a and c_b in the G-sum formulas, instead of the values given by equations (1) and (2) in Gee's chapter. This procedure allows for sphero-chromatic aberration and other secondary color effects in a crude sort of way. It is often more accurate than the direct algebraic solution for color correction, if the standard example closely resembles the final design. The resulting design may be either used "as is," or subjected to ray-trace tests. You will recall that in our example the "cooked" r_1 differed from the true one (by *PD*) by only 0.2 inch, though this was partly just luck.

"And in Conclusion, My Friends. . . .": The present chapter, together with the companion chapter by A. E. Gee on algebraic design, serves as a practical introduction to the problems of scientifically laying out refractor objectives of high correction and efficient performance. It also illustrates some of the basic methods used by professional lens designers in working out more elaborate optical systems, such as photographic objectives, microscope objectives, and projection systems. After reading it you may have some idea of the immense amount of patient and accurate work involved in such designs. For example, the humble but subtle triplet anastigmat lens, used in many moderate priced cameras, involves only three pieces of glass, yet its design probably cost weeks of work for some lens expert who was a master of his art, and who had earlier designs of this type to guide him. You can easily see the reason when you consider that the designer not only had to consider coma, spherical aberration, and longitudinal color, as we have done, but also had to take into account four more aberrations: astigmatism, field curvature, transverse color, and distortion. Moreover, he had to analyze all of these for various intermediate zones of both the lens aperture and the image field. He probably arrived at a preliminary layout by algebraic methods similar to the G-sum equations, but much more involved; then he tested this solution very

thoroughly by ray tracing, using several different rays, with elaborate cross checks of the results to work out the various aberrations. Then he went back to analytical work to decide what should be done in the way of bending, changing lens powers, and airspace corrections. And then came more ray-trace checks, more analytical work, a third round of ray traces, and so on till he arrived at a good compromise design. Of course, he might have had to repeat some of the work using other types of glass, or make checks to find out the effects of manufacturing tolerances, or variations between different lots of the same general grade of glass. . . . Bearing all this in mind, you might make a slight bow of admiration when you see a fine Sonnar or Ektar lens in some optician's window; it is a real jewel, even if it is only glass. It is the product of a tricky and exacting craftsmanship in mathematics which exceeds by far even the delicate workmanship in its actual construction.

There may be a few readers of this chapter who will feel bold enough to sink their teeth in more difficult phases of optical design, such as projection lenses, microscope objectives, and photographic lenses. A few concluding remarks are therefore added for the benefit of such venturesome characters.

The first thing to remember is that you are letting yourself in for a whole lot of work—dozens of pages of slow, painstaking, and accurate calculations. You will find Edison's saying about "one percent inspiration, ninety-nine percent perspiration" was probably a low estimate of the sweat involved. Merely reading up on all the optical principles involved is quite a job all by itself. The second thing to remember is that every optical expert was once a beginner, and that you, too, can follow in the footsteps of the old masters if you stay with it long enough and realize that there's no royal road to success in optical design, which requires more patience and dogged persistance than almost any other technical subject.

You should start by soaking yourself in the elementary optical books, the more the merrier. Some obvious possibilities are: the two companion volumes to the present book, "Amateur Telescope Making" and "Amateur Telescope Making, Advanced" (both published by *Scientific American*, New York, N. Y.), L. Bell's "The Telescope," Jenkins and White's "Fundamentals of Optics," D. H. Jacobs' "Fundamentals of Optical Engineering," Hardy and Perrin's "Principles of Optics." (These last four all published by McGraw-Hill Book Co., Inc., New York, N. Y.) J. P. C. Southall's "Mirrors, Prisms, and Lenses" (The Macmillan Co., New York, N. Y.), and "Telescopes and Accessories," by Dimitroff and Baker (Harvard University Press, Cambridge, Mass.) A particularly complete general text is L. C. Martin's two-volume "Technical Optics" (Pitman Publishing Corp., New York 36, N. Y.)

You should build up your general understanding of optical theory by carefully reading and re-reading *several* of these books. After a fair amount of this preliminary study, you should get "Optical Design and Lens Computation" by B. K. Johnson, which gives a good summary of both analytical and ray-trace methods of design for a wide variety of optical systems, together with a number of practical examples. (Published by The Chilton Co., 100 E. 42nd St., New York, N. Y.) Careful reading of Johnson's book, together with

plenty of practice with actual design examples, should soon give you a good "feel" for the basic technics of optical design, and the practical examples in the book will suggest many projects for you to work on.

For a deeper understanding of the theory of optical design, it is a good idea to devote some study to A. E. Conrady's "Applied Optics and Optical Design," a basic work from which many of the methods of Johnson's book are taken, as well as those of the present chapter and the one by Gee in this book. This big, heavy, old-fashioned book—Conrady—is notoriously difficult reading (one of the chapters is no less than 120 pages long, all brass-bound solid math) and is expensive and hard to obtain. It is, however, unrivalled in its thorough treatment of basic theory. There is also a valuable article by Conrady on "Microscope Objectives" in Vol. IV of Glazebrook's "Dictionary of Applied Physics" (reprint edition, Peter Smith, 20 Railroad Ave., Gloucester, Mass.) much of which deals with general design methods applicable to numerous optical problems. Those who can read German will find some useful material in Berek's "Grundlagen der praktischen Optik" (Edwards Brothers, Inc., Ann Arbor, Mich.) which deals with highly refined algebraic methods of lens design.

If you pursue the subject more deeply still and attempt complex problems such as highly corrected anastigmat objectives, you will soon get quite off the beaten track and be forced to invent many, if not most, of your design technics. Really high-grade optical design is essentially a craft or art rather than a definite science; it depends very largely on accumulated "know-how" and technical judgment acquired by years of practical design experience, plus all kinds of hunches, tricks, and specialized numerical and graphical doodling that would defy any clear explanation in print. Every skilled optical designer invariably develops his own personal and highly individual methods of doing things, like any other artist. Alan R. Kirkham once said of elaborate optical systems: "They are *invented*, not merely calculated. After you've traced rays through 100 or more sets of lenses you learn about what to expect, but you couldn't tell anybody how, any more than you can tell why you like the little redhead on the end better than the blonde in the middle."

The only way to learn such an art is by constant, endless practice. However, if you have access to a large technical library you can find many useful ideas and "leads" by carefully combing through various books and periodicals on optics, such as the *Journal of the Optical Society of America*, the *Transactions of the Optical Society* (British, since 1932 included in *Proceedings of the Physical Society*), the *Revue d'Optique*, and other scientific journals. There is also considerable material in the patent literature (a useful lead here is the chapter on photographic objectives in Neblette's "Photography: Its Materials and Practice," which gives patent references for about a hundred different types of camera lenses). Efficient library research is quite an art in itself, which we can't take time to discuss here.

Perhaps most readers will feel thoroughly frightened of the whole subject by now. There will always be a minority, however, who will feel challenged by its sheer difficulty. To these, I say in conclusion: Start right in, boys—sharpen up your pencils—and happy landings!

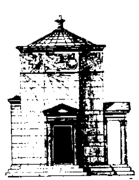
Zephyr, the West Wind

(Editor's Chapter)

I owe a debt to the many TNs who gave technical advice during the editing of this book. In editor's notes here and there I have often passed along their wisdom as my own, following one of the time-honored traditions of the editorial trade.

The contributors were invited to use the imperative when giving precise procedures, also to use the natural "I" of oral speech in place of circumlocutions like "the writer"; the writer promised them an alibi if they would and this is it. Modern spellings such as aline, diaphram, etc., are not the contributors' fault but were forced upon them by editorial rape. Without higher authority f.l. was also cut to fl, and e.f.l. to efl, to conform with modern styles like rpm (cf. Am. Standards Assn., "Abbrevs. for Scientific and Engineering Terms").

Hank Paul named this book when he learned that a title was being sought retaining "ATM" but adding a specific term. He suggested simply ATM Book 1, ATM Book 2, ATM Book 3 (ATM3). Another little problem was to find a heading for this chapter that would place it alphabetically at the end of the book. Dictionary search yielded only zephyr. Now a zephyr is a gentle, balmy breeze, and that is what will presently blow on the contributors in the informal biographies that follow—informal because telescope making is an amateur sport, its addicts a fraternity, in which even the amateur turned professional forever remains an amateur (lover), and we don't have to be solemn in our books; biographies because you're naturally curious about these people, many of them graduates of ATM. It further proved that in Greek mythology Zephyr, or *Ζέφυρος*, was a personification of the warm west wind of Greece. In Athens there is a well-preserved octagonal Tower of the Winds shown below,[1] built about 100 B.C., with sculptures on its frieze. The one shown



on the right, for the western face, depicts Zephyros the West Wind floating softly in the warm air, with the fold of his mantle filled with bouquets to be showered on people.

---

[1] From Gayley, "Classic Myths in English Literature and in Art," by permission of Ginn and Co.

James G. Baker was born in Louisville, Ky., in 1914, studied manual arts and general courses in high school, made a 3-inch $f/40$ lens from a glass bathroom shelf to view the moon, graduated valedictorian of boys' high school later to marry the valedictorian of the girls' high school, majored in mathematics at the University of Louisville, following astronomy on the side, and graduated in '35. He worked in a bank, banked his earnings, wrote Harvard College Observatory he wanted to become an astronomer. His earnest letter led the H.C.O. to investigate: findings excellent, a fellowship granted. Baker's first work was in theoretical astrophysics and was of "exceptionally high caliber," an H.C.O. astronomer states, adding, "At end of the year we recognized that here was a man of exceptional ability and originality." He was granted a fellowship that gave full freedom from ordinary academic routine. He designed new types of spectrographs. Unable to obtain needed parabolic cylinders he figured them himself. He soon developed revolutionary methods in optical design.

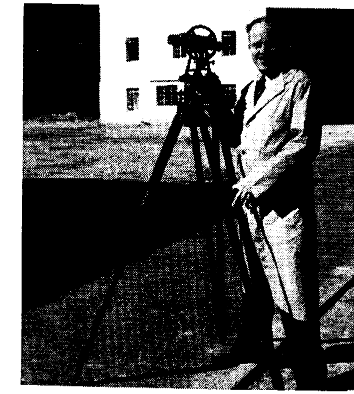
Baker preferred astrophysics, optics an adjunct, but war dictated otherwise. He began developing new and completely original designs far beyond anything ever developed before. Learning of this the military, in '41, Aug., set up the Harvard Observatory Optical Project with Baker at its head, to design and manufacture aerial camera lenses (and in '42 Harvard gave its Ph.D.). "Jim *was* the group, a TN member of it writes. "He carried the load of designing, superintending optical and machine shops. A majority of his opticians were TNs. At first, funds were very limited but when his 40-inch $f/5$ telephoto camera was tried by the military, unlimited NRDC funds were his and the little shop at H.C.O. basement was moved to far larger quarters. Here he carried on for 3 years with more than 100 optical projects. One camera was over 100 inched f.l., and when the war ended we were making lenses of 12-inch diameter." [*Continued on p. 620*]

Earle Brown was born at Newburyport, Mass., in 1909. He trained for the accounting profession, becoming a CPA in '38. He knew nothing of telescope nuts until '35 when he joined the Amateur Astronomers Association of New York and became a charter member of the Optical Division at the Hayden Planetarium. Operations by such doctors as Frank Varela, Wally Everest, Lew Lojas and other vips left the disease incurable, so he returned to school (New York University) to learn mathematics and physics, and was soon teaching astronomy and optics in the AAA classes and conducting the "Gleanings for ATMs" department in *Sky* magazine, later *Sky and Telescope*.

It was inevitable that he should make of optics his vocation, and he accordingly left the accounting profession in '41 to become general manager for the optical firm of Wm. Mogey and Sons. This work was interrupted in '42 by the Draft Board, and he became a GI and served for 3½ years in the Ordnance Department, mainly as an instructor in instrument repair, optics, and optical coating, at Aberdeen, Md. and Santa Anita, Cal., where he alternated his work in the classroom with writing technical manuals and developing teaching methods. He was one of the group who inaugurated the Army's program of optical coating, and was in charge of the training program for coating-machine operators. While in service he wrote a textbook, "Optical Instruments," (1945, Chemical Pub. Co., New York). A second book "Basic Optics for the Sportsman," appeared in '49 (Stoeger Arms Corp., New York).

After World War II he was a free lance consulting engineer on optical design and high-vacuum processes and then joined the Farrand Optical Co., where he became Chief Project Engineer on military instrument development.

He is a member of the Optical Society of America and of the American Astronomical Society. He is married, has a son and a daughter, and lives in suburban New Jersey.



C. Fred Clarke was born in Corcoran, California, while his parents were vacationing there in 1905, but was reared in Michigan. He says he knows nothing about telescopes or telescope making. From '24 to '31 he was an engineer in radio broadcasting and used also to operate amateur radio W8AZ.

He took his master's degree in physics under Dr. C. Duane Hause at Michigan State College in '35, at which time he chose as his problem the construction of a grating spectrograph around a replica grating that was available at the College. Thus he outdid the man who was given a button and sewed a coat on it. The object was to adapt an Eagle mounting to the use of undergraduate students specializing in optics. The adaptations of the mounting proved very flexible, and provided an instrument that was easily reset.

Upon completion of this work in '31 Clarke left for South Africa where he has been teaching science and mathematics in a private school whose primary object is the training of European missionaries for work among the natives of Central Africa.

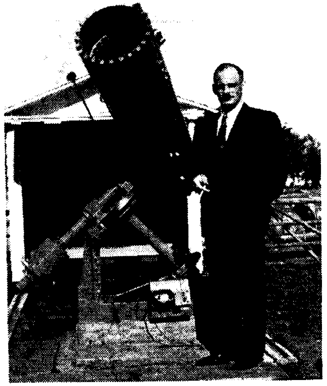
During his furlough in '45 he completed his doctorate in education.

He enjoys his work immensely. One of his aims is to make his boys self-sufficient in their mechanical problems when they find themselves miles from nowhere, in their mission work. Together with some of his students he attempts to oversee the mechanical maintenance of the institution.

He has in the department of science where he teaches an 8-inch reflector but thus far he has had but little time to get it working.

He is especially interested in photography, yet he found it hard to furnish the requested informal photograph of himself because his photographic enthusiasm usually places him at the other end of the camera.

He is a member of the American Physical Society.



Strathmore R. B. Cooke was born in Wanganui, New Zealand, in 1907. After taking degrees in chemistry and metallurgical engineering at Otago University and the University of New Zealand in '28 and '29, he came to the Missouri School of Mines as a graduate student. After obtaining his doctorate he was research metallurgist in the Missouri State Mining Experiment Station. From '36 to '39 he was assistant professor of metallurgy in Missouri. From '39 to '46 he was research professor of mineral dressing at the Montana School of Mines, Butte, since when he has been professor of metallurgy and mineral dressing at the School of Mines at the University of Minnesota.

In New Zealand, long before he became a "mining man," astronomy, and in particular selenography, was his hobby. He used the 9½-inch Cooke refractor at the Wanganui Observatory and contributed his observations to *English Mechanics*. At Missouri he built a 10½-inch reflector and with it made crisp contrasty lunar drawings, using India ink, charcoal and stumps on white paper, an example of these being reproduced above. These were published in *The Journal of the British Astronomical Association* and in the same association's memoirs of the Lunar Section, he being a member of the association.

The fundamental research that he conducted at Missouri, on the separation of ore particles in mineral dressing (see Hanna, chapter on abrasives, footnote 1) pertains equally well to abrasives such as he had used in mirror making; telescope making ties into practically everything.

He has taught courses in astronomy at the University of Minnesota and has been president of the Minneapolis Astronomy Club.

Robert A. Wilson, junior author of the Cooke-Wilson chapter, graduated from Montana School of Mines in '38, worked at several metallurgical and engineering jobs, and returned to Montana School of Mines for an advanced degree in metallurgical engineering in '41. Since then he has followed the mining and metallurgical fields, with emphasis on [*Continued on p. 626*]

Horace E. Dall was born in Chelmsford, England, in 1901. He lived during his formative years and had his schooling in London and in Luton, Bedfordshire, 30 miles north of London. He trained for engineering and specialized eventually in instruments and methods of flow measurement, and has sat on National and International Committees on this subject.

His astronomical interests developed at the age of 16 and he made spectacle lens and other rigged up telescopes. Three years later he acquired an 8½-inch Calver reflector. His telescoptics proper started a few years later from following Ellison's articles in *English Mechanics*. Since then he has made many mirrors, object glasses and complete instruments, with hundreds of eyepieces now distributed in various parts of the world. His other hobbies include microscopy (making, designing and repairing their optics) and photography. He was married in '34. Has no children.

Prior to marriage he made a hobby of cycling in many countries including Iraq, a "first ever" crossing of Iceland's interior wilderness via Askja, and another first ever of the African High Atlas in southern Morocco bordering the Sahara. "When, after dodging the French," he once wrote, "I rolled down the mule trail into Sous it was the first bike ever seen there. I spent a night in a wonderful old caid's castle and had to demonstrate on the bicycle in the courtyard to the great glee of many Negro slaves." While snooping through a keyhole Zeph once overheard a neighbor of Dall's say that on these cycling adventures he stripped all nonessentials from his kit, then stripped off nonessential parts from these essentials, and carried it all in his pockets. In later years he built the 3½-inch, × 80 Cassegrainian shown above (and in detail in S. Am. '47 Dec.). Stripped to a bare 8 oz. it fits the weskit pocket.

R. E. English, whose likeness appears in his chapter, was twice urged to forget modesty and tattle about himself and finally broke down and furnished the following. "I was the manager of a food processing plant. Before World War II I had made several telescopes. I was in the wartime roof prism program of Scientific American and had started to set up equipment when approached by a precision gage manufacturer who was trying to obtain optical flats. I was handed an order for "all the flats you can make." Three other amateurs went in with me and together we worked out a technic. We made more than 3000 flats, within tolerances of either 0.000001 inch or 0.000002 inch. Some were checked by the National Bureau of Standards as being within 1/100 wave. While this was going on a local manufacturer was having trouble in procuring a Pyrex filter that went into the gunsights of the B-29. We came to his rescue and supplied him with 22,000 at the rate of 1000 per week. On VJ Day *we* cancelled the balance of his order for 30,000. All this was done in addition to our regular vocations. We thought we were through when the war ended but orders continued to come in and in December 1951 Harold J. Watson and I set up a shop, the E & W Optical Company, at 2406 East Hennepin Avenue, Minneapolis, Minn., to manufacture optical flats and special optics with very close tolerances."

In '44 Baker was named Director of the Optical Research Laboratory at Harvard and in '46 Associate Professor at H.C.O.

He has worked on photographic instruments large and small, new types of telescopes, meteor cameras, television projectors, photographic reflectors, movie lenses, also classified and instrumental developments. In '48 he received the Presidential Award of Merit for wartime work, and an honorary doctorate from his Louisville alma mater. Since '48 he has been Research Associate of both Harvard and Lick Observatories to maintain astronomical interests, while breadwinner as consultant to the Air Forces, Perkin-Elmer and others. He introduced the reflector-corrector to astronomers. As ATM3 went to press in '53 he had started construction of a 29-inch apochromatic telescope of 1200 inches fl for Sacremento Peak as a telescope for his astronomical research. He received Magellanic Medal, '52, for conception and design of "Super-schmidt" meteor camera. He has three sons, one daughter, aged in '53 respectively, 13, 11, 8, 4.

Fred B. Ferson was born in 1897 on a farm near Delaware, Ohio, and grew up with a violin bow and a pitchfork in his hands. In 1912 his family moved to southern Mississippi. He studied mechanical engineering at Tulane University and in '19 went into newspaper advertising work, becoming manager of the display advertising department of *The New Orleans States* in '23. In '26 he moved to Biloxi and till '39 was in the real estate, fire and casualty insurance business. In '33 he made a 6-inch reflector, followed by the Springfield telescope shown in ATMA, with a side hobby of molding and casting Springfield parts, replicas of Russell Porter's sculptures, and of the dome of the 200-inch.

Foreseeing World War II he planned to enter optics. Investigation revealed that one of the hardest things to make was Amici roof prisms, so he reasoned these would be the scarcest and taught himself to make them. He led the way in the amateurs' roof prism program, passing to other TNs the methods he had learned or devised. His garage was his workshop. From this beginning he has developed a large optical business, his two plants having many times its area. His hobby is sailboat racing and golf. One daughter (ATMA 360).

Peter Lenart, Jr., a director and production manager of Ferson Optical Co., Inc., was born in 1918, reared in Wisconsin, attended college there, and in '36 began making telescopes as an amateur. He enlisted in the Air Corps for pilot training but his optical inclinations were discovered and he was trained to maintain artillery sights and sent into Normandy with the invasion. He served in front lines and later in Berlin. In '46 he resumed his love of optical production with the Ferson Optical Co. His hobbies are sailboat racing and golf.

Irvine C. Gardner was born in 1889 at Idaville, Ind., graduated from DePauw University in '10 and earned a Ph.D. from Harvard in '15. He instructed in physics 2 years at Harvard and did research in the extreme ultraviolet. In World War I he was a civilian employee of Army Ordnance, visiting manufacturers of optical fire control apparatus, conferring and assisting scientifically and otherwise to facilitate their production, then was transferred to Frankford Arsenal to develop fire control instruments. There he wrote "Elementary Optics and Application to Fire Control Instruments," a Government publication that went through many editions, was reprinted and used widely in World War I but is now out of print. He was a member of the Army Ordnance Technical Staff that inaugurated and authorized development projects.

In '21 he became chief of the Optical Instruments Section at the National Bureau of Standards. The work of the section includes research on optical design, research on methods of testing optical systems and optical materials, the certification of airplane camera lenses, and the testing of optical instruments and optical glass. In order that the section may produce prototypes of the optical designs which it develops and research optical parts for the work of the Bureau, the Optical Instruments Section has a thoroughly modern optical shop. At present the section has 33 employees. Dr. Gardner has been especially interested in the construction of solar eclipse apparatus including 2 spectrographs with 21-foot gratings, and two smaller corona cameras; participation in 4 successful eclipse expeditions; the development of long focus and wide angle camera lenses for airplane photography; design and construction of an installation for testing large range and height finders at all temperatures; the use of T-stops on cameras to compensate for variations in transmission, and the development of many minor optical instruments and optical systems. [*Continued on p. 632*]

Alan Gee (pronounced as in McGee) was born in Jacksonville, Florida, in 1916. He joined the ranks of the TNs at the tender age of 13 years, when his first 6-inch reflecting telescope was completed and turned upon the stars. The bug bit deep and the disease became incurable, instrument following instrument year after year.

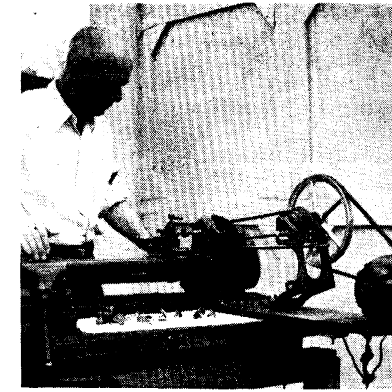
In '36 Gee entered the U. S. Military Academy at West Point, N. Y., as a cadet. Even the stern discipline of that institution failed to defeat the bug, so that time was found to build two telescope mountings, and many pleasant hours were spent at the eyepiece of the 12-inch Clark refractor of the Academy.

The year 1940 brought graduation with honors (No. 2 man in his class) and a commission in the Corps of Engineers as second lieutenant. An assignment to Vancouver Barracks, Wash., and acquaintance with A. E. McIntosh of Portland, Oregon, provided opportunity for collaboration in the construction of the rather elaborate 20-inch telescope described in *Scientific American*, '48 April.

After the war Gee, now a Lt. Col. in the Ordnance Dept., was sent to the University of Rochester for two years' postgraduate work in optics and optical design. He was later assigned as Chief of the Fire Control Division, Frankford Arsenal, Pa., which includes the best of the Army's optical shops and laboratories. He still finds time to turn out refracting telescopes of professional quality in his well-equipped basement workshop. Col. Gee is a member of the Society of the Sigma Xi, national honorary scientific society, and of the Optical Society of America, also of the Armed Forces–National Research Council Vision Committee.

The informal snapshot, such as were sought from all the contributors because they are all human beings behind the official jobs they hold, shows Gee in typical position contemplating the beauties of Matsushima Bay, Honshu, Japan, though he claims he didn't catch any fish.

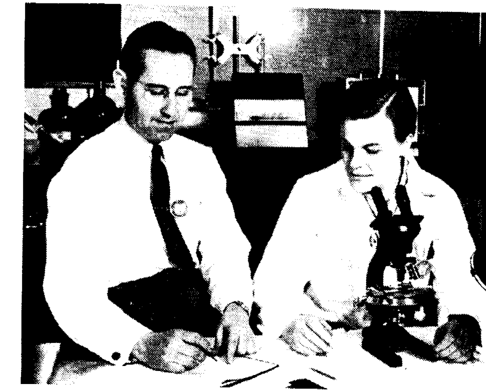
G. Dallas Hanna was born in Arkansas in 1887, graduated from the University of Kansas and earned a Ph.D. at George Washington University. "American Men of Science," the "Who's Who" of science, shows that since '19 he has been curator of paleontology at the California Academy of Sciences, San Francisco, an institution that includes a large museum of natural history, an aquarium and a planetarium. Since '42 he has been administrative assistant to the director. Collaterally, for 25 years he did field exploration for a petroleum producer, especially in Alaska where he was bitten by $9^{(9^9)}$ mosquitoes. His interests center around geology, conchology, zoology, microscopy, and scientific instruments. The photograph shows him in the field in Alaska with a pack on his back, taking samples from oil seepages. He does unusually interesting things: expeditions to tropical isles or to sea on a vessel equipped to bite rock specimens out of the Pacific's bottom a mile down. He spent 7 years on the remote furseal islands in the center of Bering Sea, and found there, of all odd places, a complete bound set of *Scientific American Supplement*. He virtually committed them to memory. In wartime he and his TN friends made a few hundreds of roof prisms but were discovered by the Navy which shoved battered binoculars at him so fast that he shifted the museum's fossil collection aside, installed long tables, 50 assistants, and rejuvenated 6000 binoculars, also hundreds of precision instruments each a special headache. Later he spent 4 years supervising the design and construction of the Academy's Morrison Planetarium, its projector built on the spot at great saving, Zeiss in basic type but extensively modified. Noting that planetarium stars were unnaturally round, his inspiration was to lay 3800 irregular Alundum grains, each of correct size, on the flat surfaces of the 30 Aero-Ektar *f*/2.5 projection lenses, aluminize condenser lenses behind the 30 Aero-Ektar f/2.5 projection lenses, aluminize the surfaces and brush away the grains. For this prolonged ordeal (performed by Frances M. Greeby) he designed a traversing microscope to spot each grain.



C. R. Hartshorn, author of the chapter on the Barlow lens, is an auditor employed by a major oil company at Los Angeles, California. His qualifications as a telescope maker are based on 16 years of intensive spare-time lens and mirror work, and two and one half years at Pomona College, in California, where he acquired a lifelong interest in mathematics and the physical sciences. Other hobbies have included shop work, violin making, surf fishing, and mountain hiking. Hartshorn has given a considerable amount of time to home study, having worked through several textbooks on technical subjects for the fun of it. He has also completed two correspondence courses and one night school course on business subjects. In '41 and '42 he was a member of the group of roof prism workers sponsored by Scientific American, and succeeded in making acceptable prisms, but not early enough to qualify for an Army production quota. Hartshorn was born in 1895, is married, and has two grown daughters.

While an engineering student at the University of Wisconsin Gerald E. Kron, whose photograph, after special urging, is included in his chapter, built a 6-inch reflector, working from ATM. Graduating at 20 in '33 as an engineer, he shortly met Dr. Joel Stebbins, Director of the University's Washburn Observatory, world authority on photoelectric photometry, and turned to astronomy. In '38 he earned his doctorate at Lick Observatory of the University of California and the same year qualified as junior astronomer. During World War II he became acquainted with Russell Porter at Inyokern in the Mojave Desert where both worked on the same project. "His position there," Porter wrote, "was a very responsible one." At Inyokern Porter kept Kron's workers cool by sketching polar bears and igloos on a blackboard while temperatures daily hit 105. Kron gives credit to Mrs. Kron for the final fine grind and polish on his chapters.

mechanical engineering and manufacture of machinery used in this industry with Ingersoll-Rand Co. of Phillipsburg, N. J. and The Galigher Co. of Salt Lake City, where he holds the position of chief engineer. Member A.I.M.E.



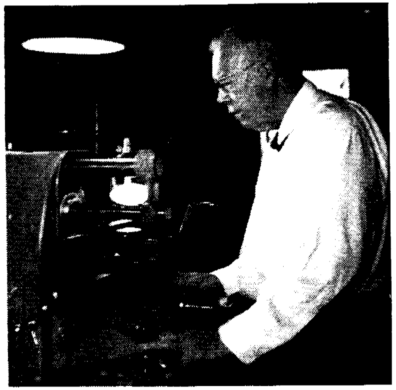
Henry Paul is occupied primarily with the development of new medicinals, and works as Assistant Research Director of the Norwich Pharmacal Company and Eaton Laboratories, Inc., at Norwich, N. Y. His optical instrument hobby is not as distantly unrelated to his profession as may appear, since in modern methods of research specialized optical instruments such as spectrographs, ultraviolet and infrared spectrophotometers, polarizing and phase microscopes, all serve as essential tools in solving basic problems that arise.

His wife, Dr. Mary Frances Paul, is Chief of the Division of Biology and works directly with him in the research laboratory, as the photograph shows, and he cannot comprehend, despite his Ph.D., why with only three children and a full-time job as research chemist she cannot find much time to join him in telescoptics.

Henry was born in Los Angeles in 1908, but grew up on a farm near Guthrie, Oklahoma, where he says he became allergic to farm work; as there was *no* mechanized equipment. While in high school at Guthrie he built his first reflector (other photograph), working from the "cracker thin" first edition of ATM borrowed from the Guthrie Carnegie library. He says, "The thrill of looking for the first time through a precision high power telescope I had built mainly myself (big brother Bill helped), made from plate glass, an old buggy axle, with one-gallon molasses cans soldered for the tube, has not yet been equalled though far more elegant instruments have been built since."

Dr. Paul received the B.S. degree in chemical engineering from Oklahoma A. and M. and his Ph.D. from Cornell University in '38, majoring in nutrition and biochemistry. While at Cornell he took special work in spectroscopy and microscopy as an aid in future use of the instruments in research.

He admits a liking for fishing, speed boating, amateur photography. Occasionally and as a last resort for entertainment he even uses his telescopes but says he hardly knows where to look for what, not being an astronomer.



Edison Pettit was born in Peru, Nebraska, in 1890. At the age of 14 he worked as a college laboratory assistant there and at 15 was given the keys to the observatory. He followed Mars through the apparitions of '07 and '09 and Halley's Comet in '10 when at the Nebraska State Normal School where he earned a B.E. degree in '11. Between '14 and '17 he was measuring double stars and in World War I he made the filters for the ultraviolet telegraph instruments used in signaling at night. In '18 he went to Yerkes Observatory where he studied solar prominences with a spectroheliograph. In '20 he moved to the Mt. Wilson Observatory.

While he has done much astrophysical work, such as the measurement of Nova Puppis and T Coronae, using a wedge photometer that he revised for more accurate work, he is best known for his work on the sun and the planets. For this he designed and built his own apparatus. Examples of this work are researches on the radiation and temperature of Mars, Mercury, the eclipsed moon and the dark side of Venus, using vacuum thermopiles and thermocouples he built beginning in '20. He used the same instruments in measuring the solar corona and ultraviolet solar spectrum.

In '40 he built the monochromator he described in this book and with it obtained the first life history of a coronal cloud prominence. He also made a refrigerated photomultiplier photoelectric photometer with which the light curve of Zeta Aurigae was measured.

In World War II he made the thermopiles with which the atomic bomb explosions were measured.

His is one of several dozen bleak offices of the Mt. Wilson and Palomar Observatories in Pasadena but a visit to his private observatory-den-shop in his own back yard nearby reveals the man. The observatory is shown in his chapter. Behind it is the cozy den. Attached to this is the shop in which the above photograph was taken. He used to drive his ma- [*Continued on p. 629*]

Irvin Schroader was born in Louisville, Ky., 1918. At the susceptible age of 12 he was bitten by the TN bug when extensive use of a friend's 20× mail order telescope stimulated a desire for one of his own. Through a combination of influences—articles in *Scientific American*, ATM, and the advice of Ward deWitt—he was guided through to completion of a crudely figured but usable 6-inch reflector. A second attempt, a 10-inch, started a search for a test more satisfactory than Foucault's, ending in the adoption of Gaviola's caustic test.

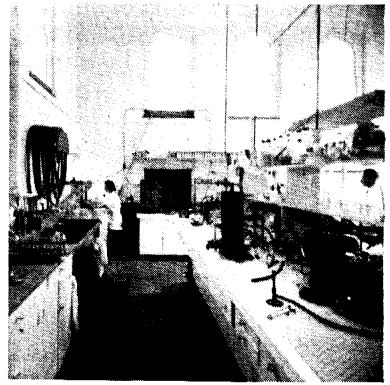
Extracurricular activity in college consisted of assisting in the physics laboratory, figuring two mirrors for the college observatory, photographing and courting his wife to be (she says he did it with mirrors). Graduated B.A. in physics '42.

Following two months in the optic shop of the Gaertner Scientific Corporation, 3 years were spent as instructor in the Army Electronics Training Center at Harvard. He is now (1953) at the Applied Physics Laboratory, Johns Hopkins, as a senior physicist. Member of the American Physical Society.

Driven by the continual lashing of ye ed's blacksnake whip (formerly cracked by the late Mr. Simon Legree), he wrote up the caustic test while playing hookey from graduate school. Present optical equipment consists of a 6-inch reflector mounted with circles and motor drive, and a temporarily mounted 12-inch, with a 16-inch telescope being slowly worked up. He admits piddling at photography, amateur radio (ex W3MFP) and with young sons Jimmy and Bobby.

chine tools with a steam engine he built. Before me is a note that Russell Porter once scribbled: "Pettit makes his gadgets himself with his two hands. I've heard that if some tool was missing at the Mt. Wilson shop or on the Mountain they'd say 'Go find Pettit; he's probably got it.'"

His wife and daughter are also professional astronomers.



Horace H. Selby was born in Redkey, Indiana, in 1906, grew up in Sheridan, Wyoming, and later went to California where he has lived since '26. As a youth he was an eager beaver with the books. Reading of Charles Steinmetz he determined to become an electrical engineer but accounts of Pasteur's researches and those of Koch made him want to be a chemist-bacteriologist-physician. However, he thought, math and optics had much in their favor as careers when you pored over the biographies of Descartes and Newton.

When 16 he began learning the rudiments of clinical laboratory work, instructed by his surgeon father who found in him such an apt pupil that after two years he was given much of the actual routine work to do. This work made necessary the frequent use of the microscope, so its innards had to be understood, even to the curves and types of glass employed—naturally, since he's Selby.

He has studied at the University of Wyoming, the University of California, Caltech, and San Diego State College, and has taken courses from several schools including the Army's Chemical Warfare Service School.

He's a regular member of the Optical Society of America and has maintained memberships in the American Chemical Society and the Society of American Bacteriologists for many years. As a member of our prism gang he made roof prisms for the Army during World War II. He's designer for an optical company, has been consultant in optical design for another firm and, during the war, for the Navy.

Chemistry has been his official profession since 1928. He is chief chemist and an officer of a chemical firm that makes agar-agar, a substance widely used in bacteriology.

What does Mrs. Selby do? She's also a chemist—in charge of the control laboratory of the same company. That's her, in one of the pictures.

James W. Shean (pronounced shane) is a native of Minneapolis. He received the Bausch & Lomb Science Award at his local school. He had made several telescopes before he was 18. Then he organized and was first president of the Minneapolis Astronomy Club. A check of the annals of the A.A.A.S. shows that when 17 he was made an Honorary Junior Member of that organization on the recommendation of the Minnesota Academy of Sciences. He attended Swarthmore College and later obtained his bachelor's degree in mathematics, physics and astronomy at the University of Minnesota.

In '42 he was temporarily a member of the wartime amateurs' roof prism program and later did optical engineering for the Minneapolis-Honeywell Regulator Co., one of many organizations that undertook wartime work outside their commercial fields. In '43 he joined the Navy where he spent three years as a flight instructor and transport pilot. In '46 he engineered for the Clarus Camera Mfg. Co. and then did graduate work in optics at the University of Rochester. In '47 he joined the Photographic Section, Scientific Bureau, Bausch & Lomb Optical Co., his principal work being lens design. A month before Korea he joined Gee's group at Frankford Arsenal where he became responsible (engineeringwise) for all optics involved in the Ordnance Corps' fire-control instruments that are in production.

When an undergraduate in college Shean, with a friend Ben Benjamin, purchased for one dollar the abandoned 22-foot dome of the old observatory on the campus of the University of Minnesota. With their bare hands they razed it for its 500-pound curved steel rails, its 200-pound building stones and other valued salvage. With these materials the amateur Minneapolis Astronomy Club would build a permanent headquarters and observatory when they found a suitable site. Alas, when the two wreckers took their eyes from the stacked up parts of the old dome and returned, they found only the site where these had been. An enterprising junkman had carted off every smidgen.

Franklin B. Wright was born in Philadelphia in 1891, educated in Lansdowne, Pa., public schools and graduated at the University of Pennsylvania with the degree of B.S. in Electrical Engineering in '13. He spent 3 years with the New York Telephone Co., then did graduate work in physics at the University of Pennsylvania, followed by a short time in the Army in '17. He spent 3 years with the Philadelphia Electric Company in distribution engineering work. He was an instructor in physics at the University of Pennsylvania '20–'23 and was granted the degree of Master of Science in Physics in '23. He was in the General Plant Department of the Pacific Telephone and Telegraph Co., in San Francisco, from '23 to '51 and retired in '51 as a Plant Staff Supervisor who specialized more or less in the statistical measurement of plant results.

He became greatly interested in an article in *Scientific American* about '28, made several mirrors and a few telescopes and, as he states it, "has 'played around' with the optical and mathematical problems of telescope design and methods of testing off and on ever since." He is also an enthusiastic advocate of the proposed adoption of "The World Calendar" and contributed an article on this subject to the *Journal of Calendar Reform* in '38 December.

In '45 he was in Germany 3 months representing Army Ordnance, making a complete survey of the German optical industry.

He has published numerous papers dealing with optical design, optical instruments, and eclipse coronal measurements. His "Applications of the Algebraic Aberration Equation to Optical Design," Scientific Paper of the National Bureau of Standards No. 550, is one of the more extensive publications dealing with optical design.

He has a sly sense of humor.

James H. Wyld is Research Specialist of Reaction Motors, Inc., and a well-known pioneer in the development of the modern liquid-propellant rocket. Born in 1912, he is a high honors graduate of Princeton University, class of '35. His interests in telescope making and rockets both began in his college days. A leader in the early rocket experiments of the American Rocket Society (of which he was president in '44–'46), he was one of the founders of Reaction Motors, Inc., early in '42. The rocket power plants of the Air Force X-1 and Navy D-558 supersonic airplanes and Navy "Viking" altitude rocket were based on his inventions. One of his early rocket motors of '38 is now in the Smithsonian Institution Aviation Museum. In more recent years he has also worked in the field of nuclear energy power plants.

"Prior to my present work as a full-time rocket racketeer," Wyld says, "I worked in such diverse fields as oxy-acetylene equipment, high speed aerodynamics, and medical electronics. My most lasting interests, next to rockets, have been astronomy and telescopes, gradually evolving later into lens design theory. For the rest, I am a lover of sea food, a mountain climber, an enthusiastic but unskilful accordionist, and the happy occupant of a small country home which I can mess up all I like with home shop projects. My wife is as great a potterer, tinkerer, and lover of hobbies as I am, and my two small children seem likely to carry on the tradition."

Optical Glass Procurement: Odd lots of glass picked up by middlemen and sold at retail are often dependable but mainly the amateur will buy his glass directly from the manufacturer. The manufacturer goes as far as he can to accommodate the amateur though he does not actually solicit such retail trade. I have listened to the reasons, which make sense businesswise. First, the manufacturer is not at all disturbed about the loss of the sale of the things we amateurs make. Next, he chuckles and says he can't quite figure out why people turn to his work for their fun; he relaxes in saner ways. However, he admires the amateur's enthusiasm. The company staff, *as individuals*, want to be helpful but the company is not set up for our retail trade in glass and is afraid it will grow. First, he tells you the worst and then, *if he sees you understand,* he may go out of his way to help you. The worst is that the clerical costs—and clerical costs are not to be sneezed at—for an order for half a pound of glass are as large as those for a ton that goes to the optical industry; and, second, that amateurs tend to get literary and write long letters to firms, full of questions calling for answer by highly paid men. Occasionally an amateur will even ask for shop help in working the glass he has bought. You can imagine the effect of a few such letters on a manufacturer's attitude toward amateurs. Some manufacturers solve this problem without much financial loss (or gain) by stocking a retail sideline of blanks in several sizes and one or two general types. This takes care of most of the retail trade and shows existing good will. If now in addition an advanced and experienced amateur wants special types and *knows what he wants* and is doing, results will depend largely on his letter and are not unlikely to be good. Largely, the recipient wishes to know that his trouble will not be for nothing.

The following, which did not originate with me, are pared-down forms of inquiry to optical glass manufacturers for ascertaining availability or non-availability of desired types [2] of glass. These forms will be understood as inquiries even without covering letters. They are only examples; nobody wants regimentation.

EXAMPLE 1

Name..........................Address...............Date..........

The following annealed optical glass is desired:

Item No.	Glass type	No. of disks	Minimum Diameter of disks	Thickness of disks	Grade
			(dimensions in inches)		
1	572574	1	4.25″	0.6″ or more	B
2	621362	1	2.25″	0.5″ or more	B
3	513605	1	4.25″	0.6″ or more	B

See enclosed return form.

[2] All glass manufacturers have adopted or are adopting a universal designation for optical glass types, in which 6 digits are used. Even those who have not will readily understand such designations and thus glass may safely be specified by this method. Examples: The 6 digits 605436 represent N_D = 1.6050 and Γ = 43.6. The 1 is omitted, being common to all glasses, and the 6050 is rounded off to 605, while the decimal point drops out of the Γ value. Thus a barium crown N_D = 1.57250, with Γ = 57.4, is specified simply 573574. A light flint N_D = 1.57950 and Γ = 41.0 becomes 580410. The desirability of accuracy is obvious and the figure sent to the manufacturer should be checked all the way back to the original specifications instead of taken from transcribed notes.

With these compact inquiries a self-addressed postal card should be enclosed, filled out thus:

Manufacturer's name...
Glass will be made available (   ) Check.
Glass not available (   ) Check.
Remarks:
Price quotation $.......... Estimate $..........

Suppose one were interested in making a Kellner eyepiece, say to the specifications in ATMA 181. It is doubtful whether the finished optical components of this eyepiece would weigh even one ounce. To order an ounce of glass would surpass absurdity. Such an order would be filled very reluctantly, the costs involved being measured in pennies, while the connected clerical cost to the manufacturer would be measured in dollars. Perhaps, therefore, no order less than $5 should be sent to a manufacturer of glass.

Such an order might read as follows:

EXAMPLE 2

Name....................Address....................Date.........

The following fine annealed optical glass is desired:

Item No.	Glass type	Approximate minimum weight	Minimum thickness	Minimum dimension	Grade
			(dimensions in inches)		
1	572577	1 lb.	0.20 inch	.75 inch	C
2	605380	1 lb.	0.50 inch	.75 inch	C
3	517641	3 lb.	0.25 inch	1.5 inch	C

Enclose the same postal card as in Example 1.

(NOTE: The glass types in Example 2 are taken from the Chance catalog. If ordered from Bausch & Lomb the types specified would be 573574, 605379, 517645, etc.)

Before placing his order the inquirer should ascertain the price in the above manner. If then the quotation or estimate received is acceptable to him he should remit cash with an order (the above was not an order but an inquiry, or exploratory feeler) and restate his requirements.

Such inquiries and orders—simple, direct, to the point—can be sandwiched in with a plant's routine on larger business without loss of step and thus the welcome of the amateur will not wear out.

Delivery may run from one to six months after acknowledgement of order, according to stock on hand and scheduling of manufacture. A point to remember is that in fair-sized pieces of good glass, annealing alone will consume considerable time. Nagging follow-up letters may not help—may even tend to work in reverse. A practical expedient, especially if the glass desired is some uncommon type, is to order it, and forget it, and start some other job. "Watched pot never boils."

It has been said that nothing is more discouraging to a manufacturer than a flood of requests for costly literature. It would be expedient if requests for glass catalogs came from groups and the catalogs were used in common. As lively reading matter they do not rank with whodunits but are more like a table of logarithms.

When ordering glass from one manufacturer, the Bausch & Lomb Optical Company, Rochester, N. Y., it is suggested that some simple, easy-to-answer form as the one outlined above be used, listing what is desired and asking what can be offered. Bausch & Lomb generally has available in stock slabs of glass from which optical elements can be made, and if the amateur is willing to accept whatever size and thickness of slab that B. & L. may have on hand, provided of course it is large enough for his purposes, B. & L. can generally supply glass. When, however, the amateur insists on some specific size and thickness it would be necessary for B. & L. to take a slab and cut it to size and that is where the headaches begin.

Optical glass can cost as little as 25 cents a pound for certain low silica types, depending on striae grade, annealing and bubble quality and size. Though prices vary widely you should not be jolted too badly by the price charged if you estimate at roughly $5 a pound (1953) for good slab glass in ordinary types. As a guesstimate the amateur's glass will more probably cost him $2 to $1 a pound. Before ordering it might be prudent to gain an approximate idea of the cost by figuring out the weight from volume and density.

Of the hundreds of optical specifications in the literature, many contain unusual or odd-index glasses. A glass manufacturer cannot determine the suitability of substituting one of his near catalog glasses for some odd type. That choice will necessarily rest on the user. Trouble will be saved if it can be ascertained that a given manufacturer makes the type of glass desired before placing an inquiry. Consult a glass catalog if one is available.

How far one can depart from specified values in a given design depends on the design itself and what will satisfy the user, neither of which can be determined by the glass supplier. Therefore it is best that the amateur himself determine if possible that a specific catalog glass meets his requirements in index and dispersion. He should then order the catalog glass, not the odd glass type, thus not forcing the manufacturer to inquire whether the catalog glass is suitable as a substitute, since this would involve further costs and headaches. Trouble will be saved if, before an inquiry is placed, the seeker can ascertain that the given manufacturer actually makes the type desired. It is therefore best to consult the glass catalogs if such are available. Furthermore, manufacturers sometimes drop, add, or slightly change glasses in their lists. Therefore glasses contained in specifications that may be ten years old may no longer be duplicated exactly.

One should not be perfectionist by specifying extreme qualities in the glass desired, since Grade C, or even Grade D, is still good glass. For illustration, note the large numbers of eyepieces that are hacked out of plate glass (Grade Z) that nevertheless give satisfaction. To specify Grade A glass having superb annealing is rarely a requirement. Notable exceptions are objective lenses and systems where the optical path in glass are long or critical, *e.g.*, interferometers. Eyepieces in general stand at the other extreme; here lehr annealing is generally sufficient and a lower grade of glass is expedient. For most optical systems the prudent choice lies between the stated extremes. Prisms, however, deserve good glass since the light passes through them in several directions and heavy striae are intolerable. How then should the quality of annealing be specified? Unless you have very special needs don't try. Generally, all optical glass is well annealed when so requested. The specification 'fine annealed' will provide sufficient annealing commensurate with the glass quality.

Regarding the exact index of the glass received, it is not customary for manufacturers to provide melt sheets listing the exact index with all small pieces of lower grades of glass. One should not, however, be concerned about the exact value of his indices until he has all the other variables—radii and thicknesses—under control to fine limits. A poor design or execution will mask any small variation—say plus or minus 2 in the third decimal—in the *D* index of his glass from the nominal value. The situation is helped by the fact that when the *D* index in a given piece of glass departs slightly from the catalog values, the dispersion of the glass remains essentially the same. There is more likelihood that a system will perform poorly for the amateur because of errors in radius and thickness and because the design of the lens system is not up to par than that a *small* variation in the *D* index of his glass will be the cause of his trouble. If you can use glass with index tolerance ±.004 instead of ±.002, and so indicate, your chances of getting the glass will be increased. Unfortunately the novice has little means of knowing what tolerance he can accept. He should not, however, be unreasonably exacting.

In '48 Bausch & Lomb, "with the idea of being of service to the amateur telescope maker," made special pressings of telescope pairs: Borosilicate Crown 517645 and Dense Flint 617366 in 3½-inch pairs at $11 postpaid (tool blank of plain glass optional at $3.25), and in 4½-inch pairs at $21.75 postpaid (tool optional, $4.25)—prices that may change. The disks may be ordered in pairs or separately. They are made of "our regular instrument glass such as we use in all our instruments, due regard being given to the quality demanded for astronomical objectives of this size." These are molded blanks approximately the shape of the lens elements and are not in slab form.

In Dimitroff and Baker, "Telescopes and Accessories" ('45) pages 28–29, are specifications for four visual telescope objectives designed by Dr. James G. Baker. Concerning these he wrote in a personal communication, "I had my tongue in my cheek, back in '44, when I put the refractor designs in the book on telescopes with Dimitroff, for the separated doublet offers a correction within a very small fraction of the Rayleigh limit, both for spherical aberration and coma, and is as good as can be done short of special glasses not available to amateurs in general. I wonder how many amateurs took the design seriously. We made up a 6-inch of the kind during the war and had excellent luck. The design can be carried even to $f/3.5$ before departing from the Rayleigh limit." The B. & L. pairs described above were chosen because they were the ones specified for the separated doublet of Baker, just referred to, also because they are two of the most active glasses in the market.

The types of optical glass used in the triplet designs of the Baker chapter of the present book may be obtained from B. & L. For apertures of 3 inches or so, Baker states, one can specify Grade B, or even C. For apertures of 6 inches or so one should specify grade A, precision annealed, he continues. He points out that a 6-inch $f/7$ lens will have a front element of clear aperture 8.0 inches.

Bausch & Lomb and others describe glass, not by method of manufacture but by grades. Thus: Grade A contains no visible striae, streaks or cords when viewed through two opposite ends by means of a striascope. Grade B contains striae that are scattered when viewed through two opposite ends with a striascope. Grade C contains striae that are light when viewed through two opposite ends with a naked eye. Striae will be approximately parallel to the surface of the plate and will be invisible when examined through the faces with the unaided eye.

Some other glass sources are named below, but the picture is that of the year '53 and may change. It is difficult to describe glass availability in terms that will stay put to the extent implied by their inclusion in so permanent a form as a book. Nevertheless, some of these data should remain useful over a period of years.

Concerning the glasses used in his reflector-corrector design Baker states: "The requisite crown and flint glasses made use of in this particular design are manufactured by most large glass companies. Anyone interested in procuring the specified glasses might try the Pittsburgh Plate Glass Company, Grant Building, Pittsburgh, Pa. The correcting lens is so near the photographic plate that optical glass of low quality annealing is acceptible. Moreover, the beam striking the lens for any single star is only a few inches in diameter. The glass can be purchased in the form of squares to the nearest standard thickness in excess of what is required. Glass costs will not exceed a few dollars for even fairly large systems. The correcting plate shown in Figure 5 can also be made of Pittsburgh ophthalmic crown, code 523586. Specify Grade C, lehr annealed. Even plate glass can be used for the correcting plate."

The Pittsburgh Plate Glass Company supplies glass cut into squares for several standard thicknesses, for all the glass types needed, with the exception of 513605. Such Pittsburgh glass is rolled from the melt and lehr annealed.

For the best results in critical systems the glass should be fine annealed, though the Pittsburgh Company, unable to foresee the future, cannot undertake at all times to fine anneal it for the amateur. Pittsburgh usually makes its glasses on special order for the trade and does not stock them. Often, however, it has small quantities left over from quantity orders, which become free stock and can be used to fill small orders. In 1953 it also has in stock $3\frac{1}{2}$-inch and $4\frac{1}{2}$-inch refractor blanks in pairs, types 517645 and 617366, with plate glass tools. It will entertain any request for optical glass.

In '53 the Fish-Schurman Corporation, New Rochelle, N. Y., offered Schott-Jena objective blanks of BK-7 (516640) and F-2 (62363) in 2 to 8-inch apertures, listed in a circular. These and other glasses were being made in Schott-Jena branch factories in the western part of Germany.

Britain's largest, oldest (1848) optical glass manufacturer is Chance Brothers, Ltd. (see ATM 107, 108, 110, 112), Smethwick 40, Birmingham, England. Their U. S. agency, named on page 226 of printings of ATMA prior to '48, was withdrawn but Chance Brothers wrote: "We are anxious to supply telescope blanks to anyone in the United States wishing to buy them and in these days of air mail can deal with the enquirer directly from England." In '52 they listed two special types for retail trade, hard crown 519604 and dense flint 620361, or borosilicate crown 518641 and the same flint, in pairs, postpaid, exclusive of import duty, 3.3-inch \$6.33, 3.8-inch \$9.33, 4.3-inch \$14, 5.4-inch \$23.33, 6.4-inch \$38.66, for respective clear apertures 3, $3\frac{1}{2}$, 4, 5, and 6 inches. Glasses first quality, a term with a specific meaning in optical glass: completely free from striae, and accompanied by melt number and optical readings. Since the value of money may change, it is well to check on current prices. For the first combination Dall suggests three equal radii and a plane, "with freedom to a high degree from spherical and chromatic errors." He advises $f/15$ and triple radii 22.0 inches for the $3\frac{1}{2}$-inch and $28\frac{1}{4}$-inches for the $4\frac{1}{2}$-inch. He adds, "Slight departure from the radii is of no importance provided all three are alike. The near plane of the flint need not be plane to the accuracy of a flat; even a ten-fringe departure will have negligible effect on performance. Of greater importance is regularity of figure." Gee points out that "the first combination gives a secondary spectrum $f/3200$, the second $f/2500$ and, since the average criterion in professional work is about $f/2400$, the first combination is damn good." (Dist. C and F focus to D focus = $\frac{1}{2400}$ fl.)

In 1953 imported optical glass was still dutiable at 50 percent of the value, under paragraph 227 of the Tariff Act of 1930, as modified, which reads: "Optical glass or glass used in the manufacture of lenses or prisms for spectacles, or for optical parts, scientific or commercial, in any and all forms." Reluctance to buy glass from abroad probably stems largely from uncertainty about procedure and fear of red tape. Here is the procedure, as verified by the Bureau of Customs, U. S. Treasury Dept. Buy a draft at your bank or a foreign money order at your P.O., which always knows current exchange rates. Mail remittance with order to manufacturer; if sent by air there's practically no delay. Glass is shipped, U. S. Customs Office at New York intercepts parcel, opens it, assesses duty, forwards parcel to your P.O. billing it, not you, for duty. Your letter carrier punches your doorbell, collects the duty in cash, hands you the parcel. It's that simple.

Narrow-band Filters for Solar Observation: As Menzel has pointed out in "Our Sun," (Harvard University Press, Cambridge, Mass.) common glass filters would transmit much too wide a band of the sun's colors for the observation of fine solar details in the narrow lines of hydrogen and calcium. In '53, as the present book went to press, narrow-band filters working on other than absorption principles and much more highly refined than the best glass filters of that kind would be, were well under development. Of these there were two generic types: (1) Birefringent filters of several varieties—quartz, calcite, PN. (2) Frustrated total reflexion filters of several varieties. This book leans heavily on type 1, including the chapter by Pettit (originally published in '41 but now revised and greatly extended) because in '53 type 1 is still the only practical type for the amateur to build. Since this situation may change, the following fragmentary notes, mainly about type 2, are included for general orientation of the tyro. While the physicist would find the notes naive, they may help fill in small areas in the gap between the average non-physicist's initial knowledge of the subject, and that of the physicist whose specialty is filters and whose articles in the scientific periodicals, largely the *Journal of the Optical Society of America,* are written for other physicists and may seem abstruse to some.

Type I: Birefringent filters. On birefringence, see texts on optics such as Hardy and Perrin, or Jacobs. Hold a quartz or calcite crystal against an illuminated pinhole and note double image. Read Pettit, this book, on special application of this principle. Names prominently connected with development of this type: "Ohman, Lyot, Evans, Pettit, Wood, Billings, others.

Pettit chapter deals only with quartz filters but others of type 1 employ calcite and PN. In response to a specific request for very elementary data assuming no previous knowledge of this subject on the part of the reader Elizabeth Menzel replied: "PN crystals are ammonium dihydrogen phosphate, artificially grown. Size, up to 7 or 8 inches and larger. Properties, birefringence; electrooptic (quasi quartz and calcite). Obtainable Brush Development Co., Cleveland, Ohio. Can amateur work it? *a:* Orientation of crystal axes requiring some kind of optical device for testing. *b:* The softness and sensitivity to most liquids presents special problems: 1. Grinding and polishing vehicle: toluene; ethylene glycol—*i.e.,* one type of anti-freeze). 2. Figuring (pitch lap and rouge too harsh. HCF over pitch with Barnesite is satisfactory. 3. Protection from atmosphere (mounting requires non-corrosive, organic cement, and perhaps inclosure in oil. Clarite dissolved in toluene is O.K. for cement.) 4. Time required in working PN extensive, since technic is still undeveloped. 5. Calcite very expensive, hard to get, impractically small."

Comments by others: By a professional, former amateur: "The technic of polishing PN is not yet, in '53, at a stage where amateurs should undertake it except on a martyrdom basis." By an astronomer, former TN: "The views of the prominences with Pettit's birefringent monochromator are enough to make a spectrohelioscope-educated man feel that his life had been wasted." Comment on preceding comment, by another astronomer: "An understatement."

Type II: Frustrated total reflexion filters. Several dielectric layers between hypotenuse faces of paired prisms. Cryolite, zinc sulfide, or magnesium fluoride. Working principle based upon Fabry-Pérot interferometer, but use frustrated total reflexion, in textbooks sometimes referred to as "partial total reflexion," in a prism in place of the usual silver partial reflector of the Fabry-Pérot. ZnS as spacer layer instead of air as in the Fabry-Pérot, otherwise the same. Now available commercially.

What Turner frustrated total-reflexion filters are and how they work is explained in the following composite of replies by Evans, Gee. When total reflexion occurs in an ordinary right-angle prism the light penetrates into the air behind the reflecting surface a distance of one or two waves. If, in this distance, the light meets any obstacle it is not totally reflected. In fact, under some circumstances the reflexion may be killed altogether. Turner's filter is based on a carefully controlled frustration of the total reflexion. He simply takes two prisms and places them with their hypotenuse faces nearly in contact, separated by a sandwich of one high index film between two low index films. The low index films provide the "frustration" of the total internal reflexion, permitting the leakage of a very small percentage of the light into the high index or "spacer" film, where it bounces back and forth thousands of times. At each bounce some of the light escapes in the same direction as the original beam, but with a different path length. The result is a series of beams coming out of the instrument with definite steps of retardation, like the successive beams from grooves in a diffraction grating. When the retardation is an integral number of wavelengths, that wavelength will be transmitted very strongly, but if the retardation is the slightest bit off an integral number of wavelengths practically no light is transmitted. It will be obvious that the retardation will depend very strongly on the direction of the incident light. This results in a very small field of view. The sandwiched films are usually magnesium fluoride-zinc sulfide-magnesium fluoride.

(The second sentence in the preceding paragraph may interest those who mount prisms as diagonals in telescopes with hypotenuse face in contact with a backing.)

Comment by a former TN who has made frustrated total reflexion filters: "Will never replace birefringent type and never do all that type will do. Definitely not an amateur job unless TN has shekels plus access to good lab equipment. Vacuum set-up $1,000 plus accessories."

See mention of these filters in chapter by Earle Brown.

Comment by Gee, who has made these filters for solar work and applied them successfully to a prominence telescope: "Frustrated total-reflexion filters, or Turner filters, were devised by Dr. A. F. Turner and Paul Luergens at the Bausch & Lomb Optical Co. They can be made with pass bands as narrow as 5A with sufficient transmission for use on the solar prominences. They have three definite advantages over the birefringent polarizing monochromator. They are much cheaper to produce (assuming access to the necessary equipment), they are considerably less bulky, and they do not need to be thermostatically controlled. Unfortunately, there is writing on the other side of the ledger. The Turner filters are extremely sensitive to the angle of incidence of the incoming light—much more so than the birefringent type. As a consequence, the field of view through a Turner filter is seriously restricted if very narrow pass bands are required. In addition, expensive and elaborate vacuum equipment as well as photoelectric monitoring equipment is required to make the Turner filters. The first of these objections can be largely overcome for operations on the amateur level but the last one is a tough one. Certainly the Turner filter will do a pleasing job on the prominences but who has the necessary equipment and know-how to make them! Further, there may be questions of patent rights, as in the case of any special devices or optical systems."

Flats: There is a common impression that expert flat figurers use occult methods, generally behind doubly barred doors. Actually their methods are essentially no different from those available to the tyro. Their "secret" is the provision of the best possible conditions. They use fused quartz; use it thick to minimize flexure; use (as many do not) correct methods of viewing the fringes in the test, thus avoiding self-deception; and deal with the residue of flexure with the clear understanding that this is a must for going beyond a millionth of an inch in precision. This last factor is dealt with more as a science and less as an art than ever before in a meaty 7-page paper by Walter B. Emerson of the National Bureau of Standards titled "Determination of Planeness and Bending of Optical Flats," Research Paper 2359, reprinted 1952 October from Vol. 49, No. 4 of the *Journal of Research of the National Bureau of Standards*, obtainable from the Supt. of Documents, Gov't. Printing Office, Washington 25 D. C., for a thin dime.

In making better than tenth-wave flats the key problem is to ascertain the true shape of the disk—the shape if it did not bend. Emerson accomplishes this by supporting the flat first at the edge, then at the center, pairing it with a flat of a different thickness and working out equations; otherwise you can't tell whether both flats aren't sagging equal amounts and leaving the fringes unaltered. After studying this paper one wonders how many determinations of flatness previously made with master flats were correct, and what were the true contours of the flats so measured.

The best flat described in the paper is designated as No. 3 and is shown by a graph to have a maximum error of less than one fortieth of a fringe, or less than 1/4,000,000 inch. This flat is now the Bureau's standard for testing other flats, supplanting earlier masters, that are submitted to it for calibration often by industries which use them for control of the accuracy of gage blocks. Thus this one flat in final analysis controls the flatness and straightness of practically every product manufactured by American industry. It was made by Fred B. Ferson and chief optician Peter Lenart Jr. of the Ferson Optical Co., Biloxi, Miss., who nevertheless say they began as amateurs and continue to think as amateurs.

INDEX