HOW TO MAKE A TELESCOPE

Second English Edition

BY JEAN TEXEREAU

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and adaptation of the present work will render an important service. We have extended our treatment beyond the frame of a simple description of mirror making, by explaining the physical reasons for a given precision to be attained, or that underlie given points of view. Frequently, in practical optics, the causes of a phenomenon are complex and inextricable. It is a mistake for beginners to believe that simple, improvised theories are always enough. A more penetrating view leads, no doubt, to development and elaboration in a degree that is foreign to writers satisfied with easy assertions and arguments on authority. The author feels, however, that the extra effort is worth while if it develops in the reader the judgment he needs to master technique, and trains him also to recognize the naïveté of inexperienced writers who propose new and amazing methods. The most effective instructions for the beginner are not those that are stripped to bare essentials. On the contrary! They must make good the beginner's lack of experience with an especially rich store of information—information that can be directly applied and is based firmly on physical fact.

To speak of a "good mirror" is to use a term of precise physical meaning. The amateur who takes the trouble to make a complete quantitative evaluation of his mirror has immediate, direct assurance of mirror quality that no amount of argument based on faith or authority can replace. We have attempted to show the reader how this can be done. The testimony of amateurs from many walks of life—accountants, carpenters, mechanics, teachers, engineers—proves that this indeed is the path of least resistance, and in the end the least expensive way for anyone determined to have, if but once, a telescope that is optically beyond reproach.

April 1957 JEAN TEXEREAU

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BASIC PRINCIPLES AND A PROPOSED TELESCOPE

I-1. "Geometric Optics" and the Astronomical Telescope

The reader is probably familiar with the optical diagrams of telescopes appearing in elementary physics tests and popular books on optics. These show how parallel rays, coming from a source which is presumably at infinity, pass through a lens (a refracting objective) or are reflected by a *mirror* (a reflecting objective), then converge to a *focus* to form an image. This image is then examined with a kind of composite magnifier which we call an *eyepiece* or *ocular*.

It is not usually made clear that these elements, objective and eyepiece, are by no means comparable in importance. The astronomer's hopes are almost wholly tied to the size and quality of the *objective*. The objective of even the smallest telescope, because of its larger dimensions, the severe optical requirements it must meet, and the difficulty of its construction, completely overshadows the eyepiece.

In certain large, modern photographic telescopes, the main mirror forms its image directly on the sensitive plate, entirely without the use of intermediate optics. How marvelous to contemplate that man explores the farthest reaches of space with the aid only of a single optical surface!

Studying the familiar diagrams of "geometric optics," which show light traveling simply in straight lines, one could easily conclude that the only advantage of a large-diameter objective is that it gathers more light and therefore can reveal fainter stars. This is not quite the whole truth. Assuming the objective is geometrically perfect, we should expect at the focus a perfect image of the star, that is, a mathematical point. It should therefore be possible always to separate or "resolve" any double star, no matter how close, even with the smallest telescope, since without great difficulty we could always further magnify the image. Actually, as we shall show, the smaller the telescope diameter, the poorer must be its "angular resolution." The larger telescope is superior, therefore, not only in light-gathering power but in the important respect of resolution also.

Thus, it was once believed that the perfection of a telescope image depended solely on how painstakingly the "artist" fashioned the objective. We now know that beyond a certain limit of image perfection no further skill is of avail, and that *this limit is set by the intrinsic nature of light rays.* The reason, as we shall see, is that radiant energy, strictly speaking, is *not* propagated in straight lines. Once a certain precision of optical surface is achieved, practically nothing is gained by perfecting it further.

For the telescope maker, therefore, who must know how precise to make his objective, or for the observer who wishes to know the limiting detail of which his instrument is capable, "geometric optics" is only a first, insufficient approximation. It is "physical optics" which defines the necessary final precision.

I-2. A Bit of Physical Optics[1]

Certain optical phenomena such as diffraction and interference can be explained only on the basis that light is *vibrational* in nature, and that,

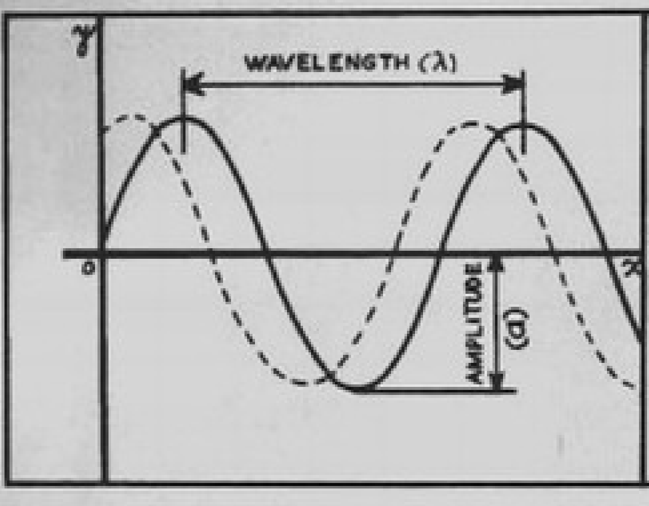


Fig. 1. Sinusoidal motion.

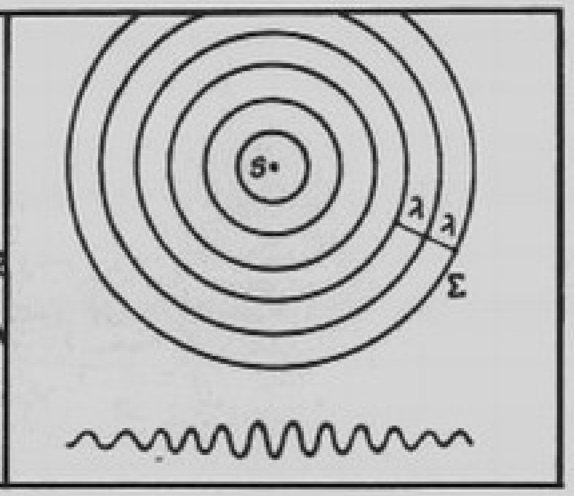


Fig. 2. Vibrational disturbance.

like other vibrations, it may be characterized by a particular *wavelength* and *amplitude*. The vibrational motion is in the nature of a sine wave (Fig. 1) of prodigious frequency: in a single second, transmitting undulations each $^1/_{50,000}$ inch long, it traverses a distance of over 186,000 miles.

In Fig. 1, a designates amplitude of vibration, and λ the wavelength. This wavy line is a mathematical device only—it has little in common with the physical "reality" that lies beyond the reach of our senses. However, it conveniently demonstrates some properties of light waves.

Assume that we have two light vibrations of similar amplitude and wavelength, and that they radiate in the same direction. We note at once that they do not necessarily coincide (Fig. 1, continuous and dotted lines).

[1] For a more complete treatment see E. Hecht and A. Zajac, *Optics* 1974, Addison-Wesley Publishing, Reading, MA

If, starting from the same source, one wave has traversed a path of different length, and the difference is other than a whole number of wavelengths, there is a "phase difference" or "relative phase displacement" between the two waves. Under suitable conditions, the two rays *interfere,* and if the phase difference is precisely a half wavelength, they may nullify each other completely. It was Fresnel who first demonstrated the effect and showed how under certain conditions the addition of one light beam to another can give total darkness.

Imagine now a source radiating light in all directions through a homogeneous medium. Any set of points located at an equal distance from the source are naturally *in phase*. A surface drawn through such a set of points is a *wavefront,* and in a supposedly homogeneous medium this can be only spherical in form. In the limit, as the source is very far removed, the wavefront closely approaches a plane.

A stone cast into a pond creates a somewhat similar wave disturbance (Fig. 2): point S emits a system of waves of constant wavelength. These waves, however, rapidly diminish in amplitude.

I-3. Definition of a Perfect Objective

The perfect objective should give a physically perfect image of a source located on the axis an infinite distance away. If we assume that the medium of propagation is homogeneous, the waves impinging on the objective are plane (Fig. 3). The function of the objective, whether refractor or reflector, is to reshape successive emerging wavefronts into concentric spheres whose centers lie at the focal point F.

If the wavelength of light were infinitesimally small, this picture would be quite accurate, and F would indeed be a mathematical point at which is concentrated all the light falling on the objective. But we know this is not the case. Actually, it is only when we move a certain small lateral distance FF' (Fig. 4) that we come upon total darkness. Image F is not a true point, but a *false disk* or *diffraction spot* of diameter $2FF'$.

If we assume for the moment that the objective is vignetted by a *square* aperture, it is easy to calculate the position of point F' as which darkness is complete:

Suppose point F' to be positioned in the focal plane a distance from F where it is closer to the upper edge P_3 of the wavefront by one wavelength. This is the same as saying that an imaginary wavefront Σ', traced with its center at F' and tangent to the upper edge P_3 of the actual wavefront Σ, would be displaced at its lower end from wavefront Σ by just one wavelength, or $PP_1 = \lambda$. The following interesting fact also becomes evident: the distance P_2F' measured from the middle of the wave Σ is longer by a half-wave than the distance P_3F', measured from the upper edge (by proportional displacement of the wave at P_2). However, according to a famous principle

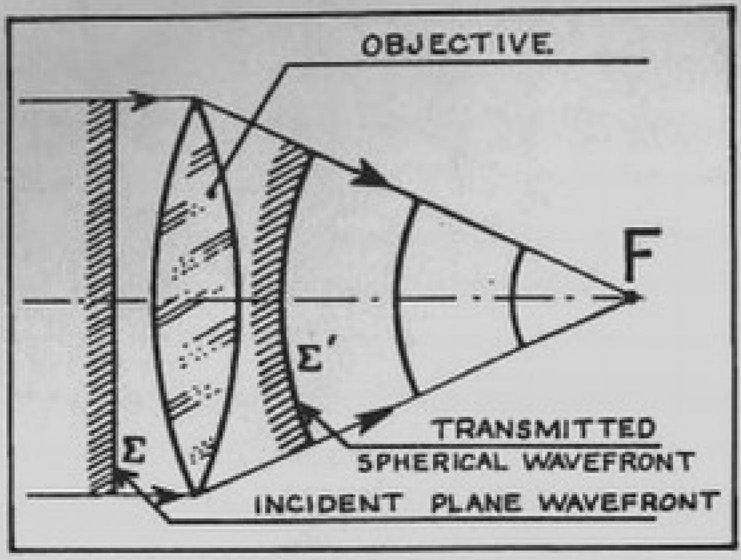


Fig. 3. Role of the objective.

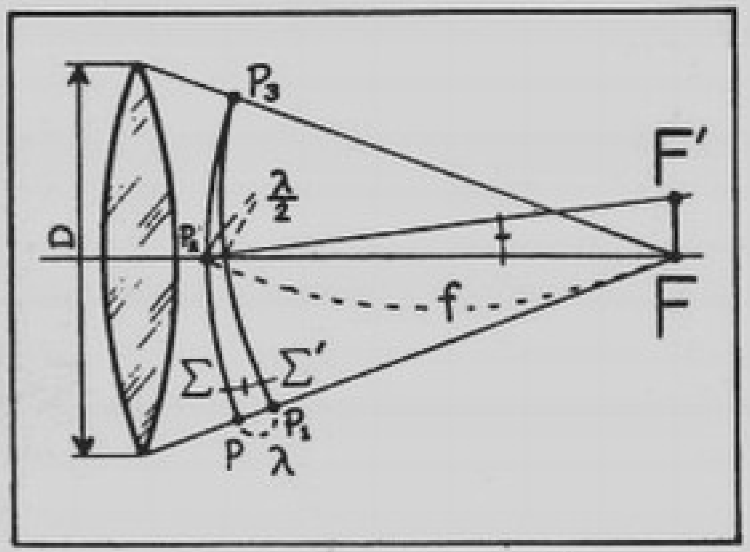


Fig. 4. Magnitude of the diffraction spot.

light source. It follows that rays P_2F' and P_3F', out of phase by a half-wavelength at point F', annul each other by interference, and therefore contribute no illumination to that point.

This property is true, however, for *all* points on the upper half of the wavefront Σ, because (remembering that its outline is a half-square) there exists for each point on the upper half of the wave a point on the lower half (a distance down the wavefront equal to P_3P_2) which likewise is a half-wavelength farther from F'. Considering then all points on the upper half of the wave down to point P_2, and points paired with these on the lower half down to point P, we conclude that *no* light starting from points distributed along wavefront Σ can illuminate F', since all the rays interfere completely at that point.

The "diffraction spot" therefore ends at F', and we can easily calculate the half-length FF' of one of its sides as follows (noting that the proportions

$$\angle FP_2F' = \angle PP_3P_1 \quad (1)$$

but
$$\angle FP_2F' = FF'/f, \text{ and } PP_3P_1 = \lambda/D; \quad (2)$$

therefore
$$FF' = \lambda f/D. \quad (3)$$

In practice, the objectives are *circular*, and we have therefore no complete point-by-point correspondence, in the upper and lower halves of the wavefront, of optical distances from an image point differing by $\lambda/2$. To calculate the *radius* of the diffraction spot (now apparently circular) is much more difficult. We shall content ourselves here with merely stating a relationship first derived by G. Airy: *the linear radius of the diffraction disk formed by an objective of diameter D and focal length f is given by*

$$\rho = 1.22\,\lambda\, f/D. \quad (4)$$

The ratio f/D is the "*f*" *number* or *focal ratio*. The wavelength λ of radiation to which the eye is most sensitive is 0.56 micron (1 micron = 0.001 millimeter or 0.000040 inch). For a typical telescope mirror, therefore, of $f/D = 6$, the radius of the diffraction spot measured in the focal plane is $\rho = 1.22 \times 0.56 \times 6 = 4.1$ microns. This then is the smallest possible image of a point source—the limit set by diffraction effect. The task of the optical worker is to retouch his mirror to the extent that all rays converge within a circle of this small radius.

All objectives of the same focal ratio give the same size of diffraction spot; however, the *angular* radius of the spot diminishes as the focal length f (and consequently also as diameter D) increases. Now, it is this *angular* radius that is of paramount interest to the astronomer. It defines the size of the smallest detail he can reliably detect with his instrument. This angle, in radians, is given by

$$\rho_{ang.} = 1.22\,\lambda/D. \quad (5)$$

To convert to seconds of arc, we multiply by 206,265.

Note that the angular diffraction disk diameter depends only on wavelength and objective diameter. If the astronomer tries to reduce the diffraction disk by using shorter wavelengths, he is confronted with difficulty. He is handicapped not so much by the limited sensitivity of photographic emulsions as by the radiation-absorption characteristics of the earth's atmosphere. This is a highly selective filter; the astronomer must accept whatever wavelengths remain once the starlight has traversed it. For greater resolution, then, the only recourse is to increase the diameter of the objective. Many an amateur has devoted his career to this quest for added power, advancing step by step with telescopes of increasing diameter. We shall later see why the amateur must in practice set a limit to this quest.

If we examine the diffraction image more closely, we see that the energy is not uniformly distributed: image intensity is very high at the center, then falls off rapidly to zero at the radius ρ calculated above. At certain larger radii, however, interference again is incomplete; we therefore see a succession of luminous rings, each weaker than the preceding, that fade rapidly into invisibility. If the star is not especially bright, we see only a first, and a barely visible second ring.

One should be familiar with this "ideal" star image, consisting of the "false disk" and surrounding rings, that is formed by the perfect objective and can be seen under very high power. A good criterion for perfect focus is that darkness of the first black ring is a maximum. The test can be used, of course, only with a good objective.

The pattern of the ideal diffraction image may be seen with a very simple apparatus: pierce a thin card with a needle about 0.020 inch in diameter. Set the card in front of a clear incandescent bulb, then back away a yard or two from the "artificial star" thus formed. As yet, we cannot see the pattern of false disk and rings; the objective of the eye under these conditions is too large to modify the appearance of the source visibly. Now, directly in front of the eye, place a second card, this time pierced by passing the needle point only about halfway into the card. If the "star" aperture is located in front of a portion of the filament, we now see a beautiful diffraction pattern resembling that shown in Fig. 5. By pushing the needle progressively farther into the card, we observe the diameter of the false disk becoming progressively smaller, the same as when we increase the diameter of a telescope objective.

I-4. The Rayleigh Criterion

It is of interest to ask how small a defect in the objective will visibly affect the diffraction image. Lord Rayleigh found that if the actual wavefront produced by an objective differs from the ideal, spherical wavefront by only a quarter-wavelength, the diffraction image is only slightly altered: peak intensity at the center is reduced 20 per cent below normal, and the first minimum is no longer quite zero.

Since the Rayleigh criterion is often specified, it is useful to determine what it represents in terms of tolerable error on the glass surface. A quarter-wavelength of the radiation to which the eye is most sensitive is 0.56/4 or 0.14 micron. If the objective is a *mirror* (Fig. 6*a*), and we assume a concave defect in its surface of depth δ, the defect represents an added distance that must be twice traversed by the light rays. The portion of the wave reflected at the defect therefore has a total *retardation* of 2δ. To satisfy the Rayleigh criterion, therefore, the defect on the glass surface may not exceed 0.14/2 micron or about three-millionths of an inch.

If the objective is a *lens* (Fig. 6*b*), and again we assume a concave defect of depth δ, the thickness of glass traversed by the beam is locally reduced. The wavefront impinging at the defect is therefore relatively *advanced,* in an amount given by $\epsilon = \delta (n - 1)$, where n is the refractive index

of the glass. Since $n - 1$ is approximately 0.5 for ordinary crown glass, we find a tolerable error in the glass surface of 0.28 micron, four times greater than for the mirror.

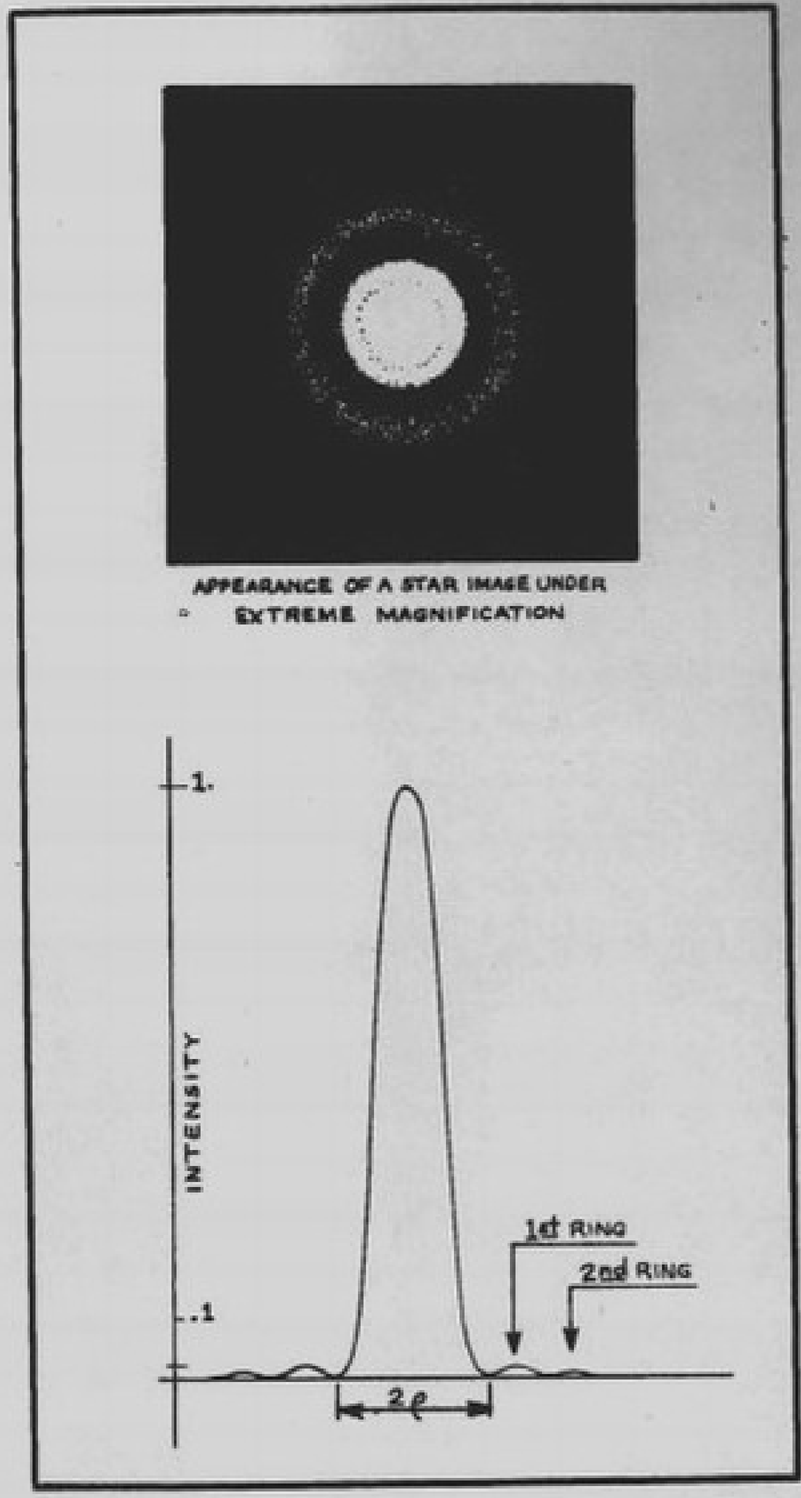


Fig. 5. Distribution of light intensity in the diffraction image.

It would be wrong to assume, however, that an objective satisfying the Rayleigh criterion must be beyond reproach. Several qualifications must be kept in mind as the amateur approaches final testing of his objective:

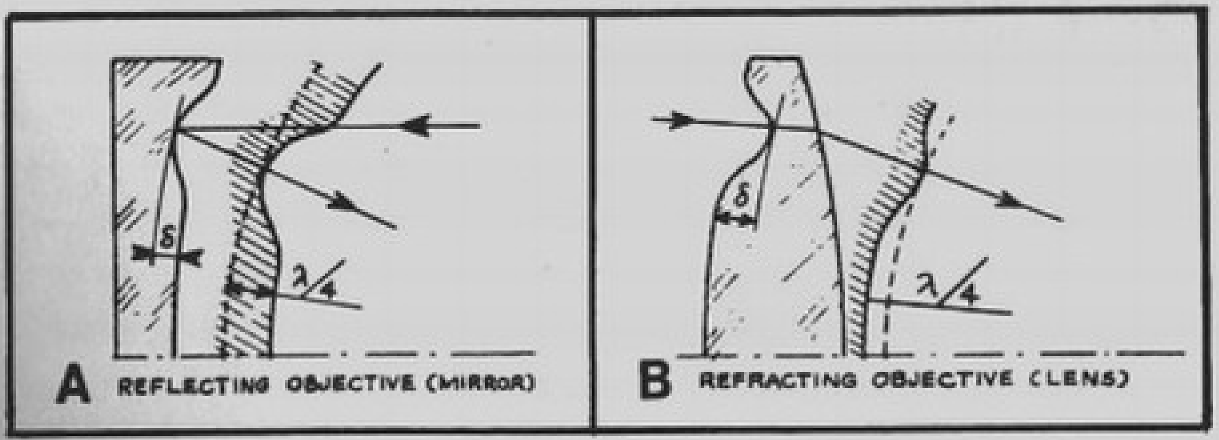


Fig. 6. Maximum tolerable defects in mirror-type and refractor-type objectives.

1. A. Danjon has pointed out[2] that under actual conditions it is the *total* wavefront imperfection we must consider; that we must take account of atmospheric disturbances superimposed on the defects of the objective. The effective sum of these exceeds the Rayleigh tolerance much more frequently if the objective itself has defects approaching a quarter-wave. Such an objective is therefore much more sensitive to atmospheric disturbance than an otherwise similar perfect objective. Such sensitivity is no asset, unless, perhaps, it were atmospheric turbulence itself that we were studying.

2. A. Couder[3] has shown that the form and number of the defects of an objective are very important. If, for example, there are many small defects of abrupt slope, then though these be only of slight depth, they may deflect a substantial fraction of the light outside the diffraction disk. Instances have been described[4] in which this occurred to a serious extent.

3. The Rayleigh criterion must be qualified for low-contrast images. The situation here is much less favorable than in viewing a star. Francon,[5] studying planetary detail of minimum visible contrast, found that a wavefront defect of $^1/_{16}\,\lambda$ begins to be objectionable. This implies a maximum tolerable error in the mirror surface of 0.02 micron. The difficulty here is not in making the mirror to this precision, but rather in obtaining a wavefront of this quality from the sky. Anyone who has studied faint planetary detail knows how quickly that detail vanishes when definition suffers even slightly.

I-5. Principal Types of Telescopes

The *refractor* (Fig. 7) employs an achromatic objective lens mounted

[2] A. Danjon, *Réunions Institut d'Optique*, 1933, 2e réunion. Editions de la Revue d'optique théorique et instrumentale, Paris, 1934.
[3] A. Couder, *Cahiers phys.*, No. 26, 50–62 (Dec., 1944).
[4] A. Couder, *L'Astronomie*, 50, 66 (Feb., 1936).
[5] [illegible]

at the end of a long tube. The objective usually comprises two lens elements of different types of glass which must meet severe standards of homogeneity, refractive index, and curvature. The other end of the telescope provides an eyepiece tube into which eyepieces can be fitted interchangeably and adjusted for focusing.

The *reflector* uses an objective in the form of a concave mirror. The thick glass mirror disk is not an optical medium in this case, but merely a

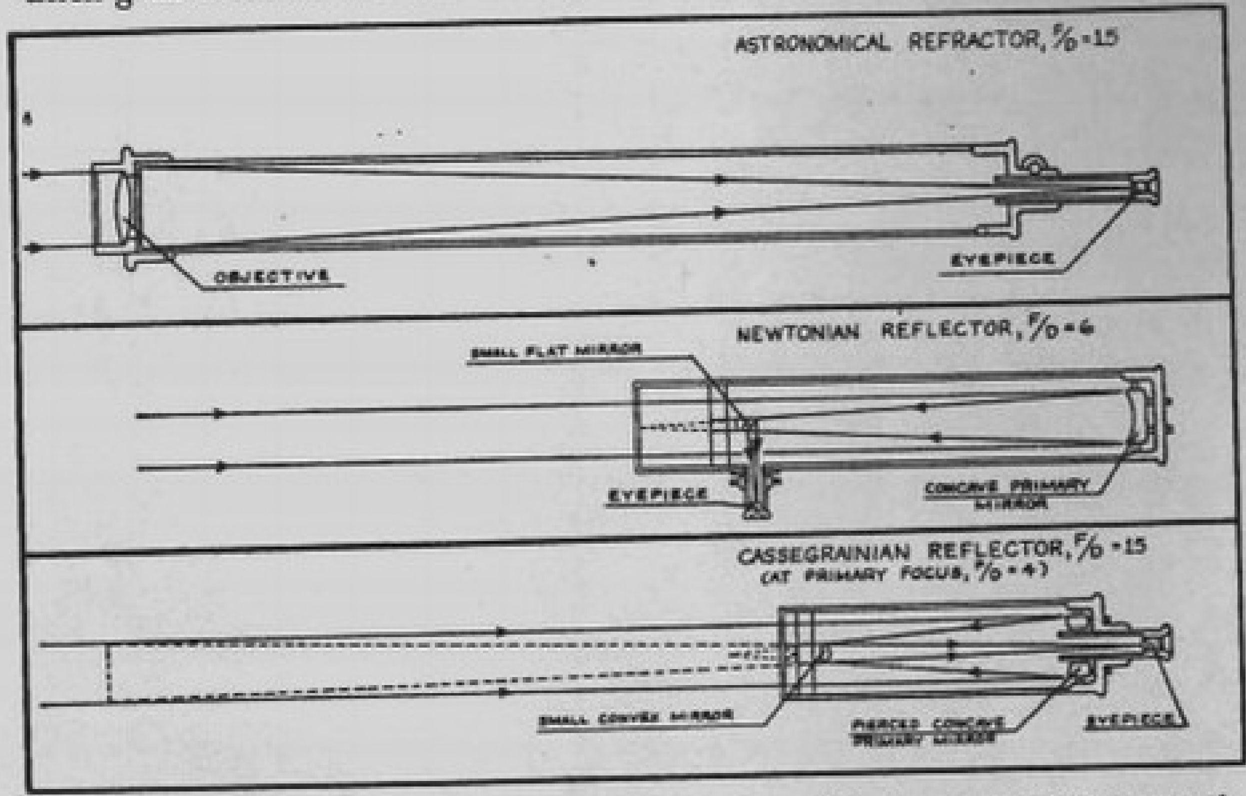


Fig. 7. Optical layout and relative overall dimensions of various types of telescopes of equal power.

support for the reflecting surface. Therefore it need not be free of internal defects. The polished concave face is of such slight curvature, it would almost escape the notice of an uninformed viewer (being about $^1/_{12}$ inch deep at the center for an 8-inch diameter mirror). This surface is made highly reflective either by a chemically deposited silver film or by a very thin aluminum film evaporated onto the glass under vacuum (an aluminum layer $^1/_{10}$ micron or 0.000004 inch thick is sufficiently opaque). Since the mirror at the bottom of the telescope projects the image back toward the incoming beam, means must be provided for diverting the image; otherwise in a small telescope the observer's head would seriously obstruct the incoming rays. In the *Newtonian* arrangement (Fig. 7), the converging rays are deflected toward one side to a convenient observing position. In the *Cassegrainian* (Fig. 7), the main mirror is centrally perforated, and the light from the main mirror is directed first to a small convex mirror (which reduces its convergence), then back through the main mirror aperture.

No single kind of telescope is fully adaptable to every kind of telescopic work. Even the modest amateur, curious merely to see some of the wonders of the night sky, must choose a suitable telescope type, dimensions, and mounting. He must consider (*1*) whether he will do more specialized work later; (*2*) the observing site available (and viewing conditions at the site); and (*3*) his budget, skill, and available mechanical facilities.

I-6. Refractor vs. Reflector as the Amateur's Telescope

This question has often been debated. The refractor has been more popular among amateurs on the continent, and the reflector the preferred form in England and America. We shall confine our remarks here to the important practical factors that must be weighed in making a decision. We have seen (Section I-3) that the angular radius of the diffraction image depends only on wavelength and objective diameter. Reflector and refractor are therefore equivalent so far as ultimate available detail is concerned. The two are nearly equal also in respect to light losses: assuming a typical 8-inch instrument in each case, and considering mainly the wavelengths to which the eye is most sensitive, the light lost on reflection from two well-silvered or aluminized mirrors about equals that lost in traversing a two-element refractor objective.

But let us consider carefully the *differences* that may affect our choice.

Refractor. The *advantages* of a refractor are as follows:

Steadiness of image. Convection currents are eliminated since the tube is closed by the lens at the upper end.

Stability of focal length. This is an asset in certain micrometric measurements and in photography.

Reduced deformation effects. Flexure and expansion of the objective are less damaging to image quality than in a mirror.

Coma correction. The possibility of easily correcting "coma" increases the useful field angle for photographic work.

Minimum maintenance. The objectives are permanent; unlike a mirror, they do not deteriorate optically and therefore require no upkeep. Thus, in a small instrument, the objective lenses may be installed and permanently centered by the maker (though the telescopist should be competent to make the adjustment if necessary).

Its *disadvantages* include the following:

Imperfect achromatism. Assuming the objective is designed for visual use, radiation of medium wavelengths (yellow), to which the eye is relatively sensitive, converges at one focus, and radiation of other wavelengths, especially the shorter (e.g., violet), converges at a quite different focus (Fig. 8). The instrument therefore acts as a selective, yellow filter. The best corrective measures introduce other disadvantages: they require strongly curved surfaces and a third lens element, and are difficult to apply to objectives over 8 inches in diameter.

Inconvenient dimensions. To reduce chromatism sufficiently requires

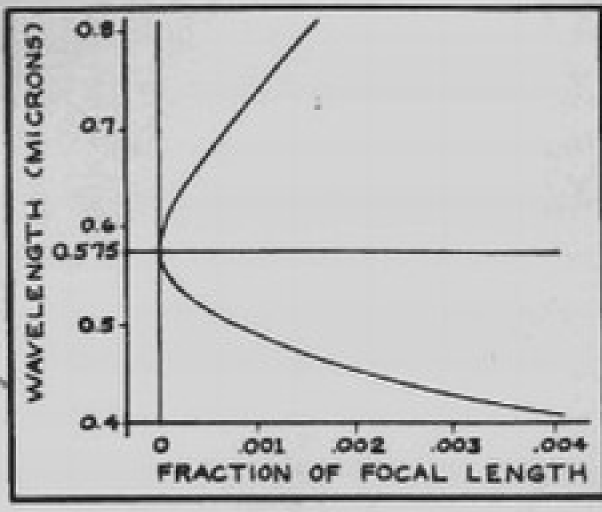


Fig. 8. Longitudinal chromatic aberration of a refractor objective lens.

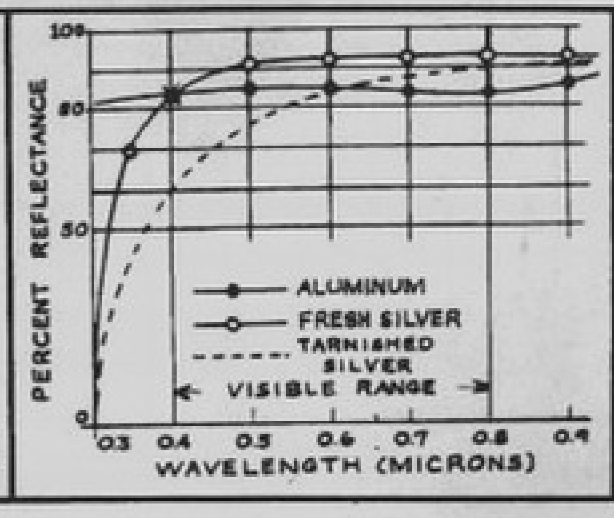


Fig. 9. Reflectivity of aluminized and silvered mirrors.

a long focal length, approximately 15 times the objective aperture. For objectives over 8 inches in diameter (requiring a 10-foot tube) this is quite impractical as an amateur undertaking.

Difficulty of construction. Glass used for the objective must be of the highest optical quality. This becomes very expensive for diameters exceeding 6 inches. Power equipment is required, and testing during "figuring" requires high-precision optical reference elements. Though the necessary surface precision is only one-fourth that of the corresponding reflector, the investment required cannot be justified by the beginner.

High cost. Total instrument cost is always much higher than for the equivalent reflector.

Reflector. The *advantages* of a reflector are the following:

Perfect achromatism. Focal length is inherently identical for all wavelengths, and reflectance of the mirror coatings (aluminum or a good silver film) is high and nearly uniform for the entire visible spectrum (Fig. 9).

Smaller dimensions (Fig. 7). Tube length is smaller by at least a factor of two compared with the refractor of equal aperture. Hence the mounting is steadier, installation is simpler, and tube movement is more easily controlled.

Low cost. The amateur himself can make the cardinal element, the mirror (by far the most expensive part if purchased), at very low cost. This brings within his reach large-aperture objectives, at least to 20 inches, that are otherwise absolutely inaccessible.

Its *disadvantages* are as follows:

Obstruction of beam by secondary mirror. Loss of light attributable to the diagonal mirror is usually unimportant; however, the obstruction does alter the diffraction figure slightly. Assuming the secondary mirror is one-fourth the diameter of the primary, the intensity of the first diffraction ring is doubled at the expense of the central disk, the intensity of which is reduced 15 per cent.[6] Also, the three or four blades which support the secondary mirror produce, respectively, six or four fine, flare lines radiating from the bright star images. The change in diffraction pattern is not altogether negligible, especially in planetary observation; on the other hand, it need not be exaggerated. The detractors of reflecting telescopes often rely themselves on refractors with a residual spherical aberration that intensifies the first ring even more. At any rate the effect in the Newtonian reflector almost disappears if we make the focal ratio 8 or 10 and the diagonal mirror only large enough to accommodate the incident light cone. These proportions are quite satisfactory for planetary work, and reduce secondary mirror obstruction to about one-eighth the large mirror diameter. It is pointless, therefore, to consider eliminating the obstruction by such crude measures as directing the image off-axis.

Reduced field. In the classic reflecting telescope the image is perfect only on the axis. For visual work the useful field is nevertheless always wide enough so that this is of no consequence. In photographic work, it must be taken into account.

Eyepiece requirements. For an *f*/6 mirror, eyepieces of very short focal length must be used for high magnifying power. Furthermore, the kind of correction that can be applied to simple eyepieces is insufficient for a cone of rays of this angular width. For optimum performance one must therefore buy relatively expensive orthoscopic eyepieces. Both disadvantages are removed by the Cassegrainian arrangement; unfortunately, this design is a difficult undertaking for the beginner.

Convection effects. This is the most serious, if not the only significant, practical disadvantage. Convection within the tube is very difficult to eliminate completely. Therefore, it is much more difficult to see the ideal diffraction image of a star than with a refractor of equal diameter. The observation of planets is also more difficult because the moments of optimum visibility occur less frequently. Nevertheless, an 8-inch reflector does perform quite satisfactorily, provided the amateur does not copy the mistakes of certain classic models or adopt an open framework like that of the giant telescopes. A more radical remedy, justifiable mainly on an instrument of 10-inch or greater aperture, consists of closing the tube hermetically with a parallel-faced optical window. See Chapter X.

Mirror distortion effects. Mechanical and thermal distortion may shift the focal point slightly and introduce spherical aberration. But in the small telescope the effect is hardly perceptible. For example, in a Cassegrainian telescope 10 inches in aperture and 216 inches in effective focal length, the angular reading of a micrometer screw used to check focal length changed less than 1/100 second of arc in an entire year (and daily variation was smaller still).

[6] These effects are discussed in detail by Theodore Dunham in *J. Opt. Soc. Amer.*, 41, 290 (1951).

Resilvering requirements. If the mirror is silvered and is used in the city without some protection, it may have to be resilvered every six months (Fig. 9). Nowadays the common practice of *aluminizing* mirrors eliminates this inconvenience; a good aluminum deposit normally lasts five years, maintaining high reflectivity throughout the entire period.

I-7. Practical Conclusion: The "Standard" Telescope

For a general survey of the heaven's curiosities, observers are often content with a telescope under 4 inches in aperture. Such an instrument presents a minimum of problems for the user, and in this case the refractor is no doubt the instrument of choice. The fact remains, however, that even a novice's 6-inch reflector surpasses a commercial 4-inch refractor and costs much less.

For certain work, moreover, a more powerful instrument is needed than the small refractor, for example, for observing interesting planetary detail, studying weak variable stars, resolving the closer double stars, and enjoying good views of the nebulae. To make a substantially larger refractor, say 8 inches in diameter, becomes very difficult indeed. Possibly for measuring the separation of double stars, the larger refractor might nevertheless be preferred, not because it has a more stable focal length but because the diffraction image is seen more easily. For all other uses, the choice by all odds is the much less costly, more easily mounted reflecting telescope. The relative ease of making a powerful mirror up to 20 inches in diameter in a way even constitutes a danger. The amateur must remember: whereas an 8-inch mirror can be fully exploited in a simple altazimuth mounting weighing a total of 40 pounds or less, a 20-inch telescope, properly mounted, requires a sturdy equatorial support weighing a total of 2 tons!

In considering larger diameters, the amateur must remember too the severe limitations imposed on image quality by atmospheric conditions at the observing site. For example, it is not possible to use effectively a telescope of over 6-inch aperture through the window of a dwelling. On a balcony, an 8-inch is the practical maximum. Attics adapted to provide a large opening and roll-away cover have been used for a 10-inch, but do not often permit the optimum performance of such an instrument. A broad terrace is better, if it affords a stable support for the telescope and is shielded from the sun's heat during the day by straw matting or the like. Better still is an open, grass-covered space separated from any structure, though this raises the difficult problem of shelter for the instrument. A lightweight metal dome, unless sufficiently large, will not prevent excessive daytime heating. A double-wall construction is very helpful in this respect, but expensive. The telescope shed with roll-away roof is comparatively less troubled by convection currents but gives poorer protection against wind. The difficulties, in a word, that attend full exploitation of a telescope larger than a 12-inch are great, and the remarks we have made here only begin to touch upon them.

Due consideration of the facts now permits us to specify the desirable features of the "standard" amateur telescope:

It shall be a reflector, much easier ot construct, and of smaller overall dimensions than the refractor of equal diameter.

It shall be of the Newtonian type, easier for the beginner to make than the Cassegrainian.

It shall be an 8-inch, a good overall compromise between high power and the difficulties of making and using larger sizes.

It shall be $f/6$ or $f/8$, depending on space available at the observing site for the telescope tube.

It shall employ an altazimuth mounting, of the form conceived by A. Couder, this being the easiest for the nonprofessional to build well, and low in cost.

Fig. 10. The first "standard" telescope, diameter 20 cm., $f/6$, made by members of the Instrument Group at the Society Observatory, 1946–47.

Fig. 10 illustrates a telescope of the "standard" type.

Chapters II, III, IV, and V relate particularly to this model. However, everything relating to mirror-making and testing is applicable without change to mirrors 6- to 12-inch in diameter, and in any case represents an "indispensable apprenticeship" before undertaking the more difficult projects described in chapters VI, VII, VIII, IX, and X.

MAKING THE MAIN MIRROR

II-1. Form of the Main Mirror in the Newtonian Telescope

From the elementary laws of reflection we can predict that a concave spherical mirror will produce a perfect image of an object positioned close to the center of curvature. To form an image of a star, however, which for our purposes we may consider infinitely far away, we require that a bundle of incident rays, all parallel to the axis (Fig. 11), be reflected from the

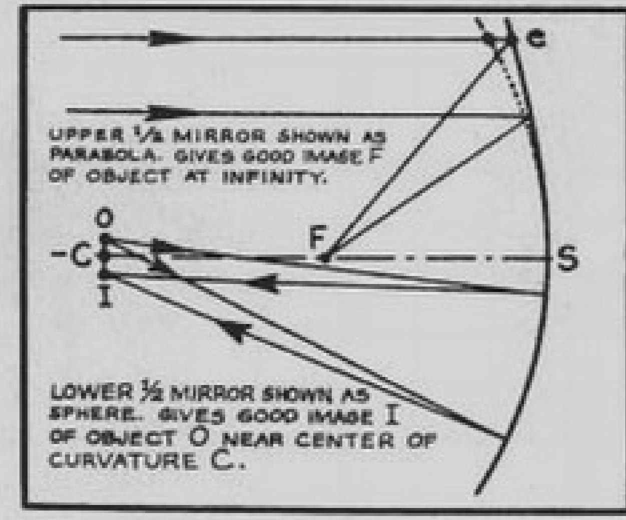


Fig. 11. Illustrating the need for a parabolic mirror surface.

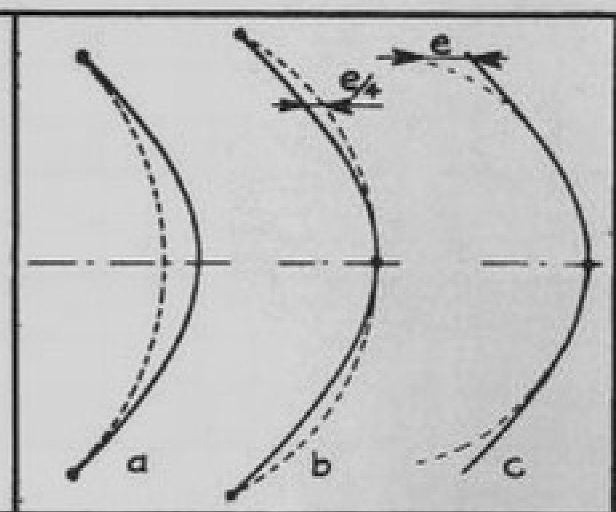


Fig. 12. Comparison of a parabolic surface with three spheres of decreasing radius.

mirror at such angles as to converge at a single point F on the axis CS (within the limits set by diffraction, of course, see Section I-3). It may be shown that the surface cross section that uniquely satisfies this condition is a *parabola*. The three-dimensional surface is of course a "figure of revolution," generated by rotating the parabola about its axis, and properly speaking is *paraboloidal*. By a curiously persistent misusage, however, paraboloidal mirrors are almost always described as "parabolic."

Our description of a paraboloidal surface need not frighten the mathematically untrained reader, nor need it suggest that the curve is necessarily difficult to obtain. We shall see later that polishing a mirror, *if procedure is correct,* tends naturally to form a *sphere.* If, then, we compare sphere and paraboloid, we can judge how difficult the task is. The curves may be compared several different ways, depending on the relative radius of curvature of the "reference" sphere we choose (Fig. 12). In Fig. 12*a* we compare the paraboloidal mirror with a sphere that is tangent to the paraboloid at the edges. In Fig. 12*b* we compare it with a sphere that is tangent at the center and intersects the paraboloid at the edges. In Fig. 12*c*, sphere and paraboloid are again tangent at the center, but the radius of curvature of the sphere is selected to equal the curvature of the middle portion of the paraboloid. In every case, maximum separation of the curves is very small for the standard amateur mirror. For the case of Fig. 12*c*, since the paraboloid is less curved toward the edge, the separation e is greatest at the edge and has the value given by the formula

$$e = \frac{1}{64} \cdot \frac{h^4}{f^3}, \tag{6}$$

where h is "height" (distance from the mirror center) or "radius of incidence" at the point considered and f is focal length.

For our standard telescope mirror, taking the focal ratio f/D as 6 and h equal to 4 inches, we find that f is 48 inches; therefore

$$e = \frac{1}{64} \cdot \frac{4^4}{48^3} = 0.000036 \text{ inch}, \tag{7}$$

namely, the maximum separation is 36 millionths of an inch, or about 0.9 micron.

In the case of Fig. 12*b*, where the curves are tangent at the center and intersect at the edge, maximum separation is only one-fourth as large—about 9 millionths of an inch. This is approximately the size of the errors in sphericity that occur naturally when one carefully polishes a disk of standard size. Contrary to the usual opinion, therefore, we are as likely to produce a parabola at the outset of "figuring" as a sphere. For larger mirrors, or for mirrors of smaller f number, this will not be true.

It is amusing to hear industrial workers talking smugly of the difficulties of parabolizing, when the surfaces they accept as accurately finished spheres already have errors as large as the parabolic correction (about 1 wavelength). Unfortunately these errors are quite haphazard. For the telescopic mirror, a precision at least ten times as great is necessary.

If the f number is large enough, i.e., if the mirror is relatively shallow, the difference between the parabola and sphere becomes very small; in fact the uncorrected spherical mirror may satisfy Rayleigh's rule (Section I-4) *and give a practically perfect star image.* A. Couder[1] has given a formula

[1] A. Danjon and A. Couder, *Lunettes et Télescopes,* Editions de la Revue d'optique théorique et instrumentale, Paris, 1935.

for the minimum required focal length f of any mirror of given diameter D that is to satisfy this condition:

$$f^3 = 34.9D^4 \tag{8}$$

where f and D are measured in *centimeters.* To determine f in *inches* (taking D in inches also) the equation is written

$$f^3 = 88.6D^4. \tag{9}$$

Table I gives examples applicable to amateur mirrors. In practical terms the table is carried too far. It would be foolish to make the last mirror of

TABLE I
MINIMUM FOCAL LENGTH FOR SPHERICAL MIRRORS SATISFYING RAYLEIGH'S CRITERION

D (in.)	f minimum (in.)	f/D
3	19	6.3
4	28	7.0
5	39	7.8
6	49	8.2
7	60	8.6
8	72	9.0
10	96	9.6
12	123	10.4

the series, short of a special need for so high a focal ratio, in the hope merely of automatically obtaining a perfect sphere. The chance that this will occur spontaneously in a disk as large as 12 inches is vanishingly small. On the other hand, if the beginner wishes to simplify his task to the maximum and perhaps dispense with testing, he has a fair chance of success with a mirror under 6 inches in diameter and of the prescribed focal length. We shall return to this in detail later.

II-2. Working of Optical Surfaces and Theories Concerning Polishing

It often surprises the beginner that some of the most precise surfaces man has made are fashioned by hand, using no machinery whatever, and by a procedure that is almost childishly simple. So-called common sense in this technological age has become so conditioned to complexity that it requires an act of will to think clearly about the simple processes involved. The shaping of high-precision surfaces is governed by two basic principles, and these have been applied consciously or otherwise ever since the stone age: (*1*) the principle of abrasive action, and (*2*) the law of averages.

The grinding of an optical surface requires a "tool," that is, a companion work-piece of comparable surface area. The abrasive, comprising small cutting grains of a material harder than that being worked, is dispersed between the tool and the optical blank. The combination of pressure and movement, with the pressure distributed over many hard abrasive points (Fig. 13), produces on a brittle material such as glass a multitude of minute chips and fractures. These occur mainly at the relatively high areas, which tend therefore to disappear gradually. If on the average the pattern of motion subjects the two pieces everywhere to the same pressure, irregularities are automatically planed down to a precision better than the abrasive grain diameter. If, moreover, relative motion between the pieces occurs in every possible direction, the surfaces necessarily assume the shape of a sphere (or, as a special limiting case, become plane), since only this figure permits unbroken contact for all relative positions of the pieces. The depth of the individual fractures or pits themselves approaches the abrasive grain size.

If there is a small, though sustained, unevenness of pressure, for example, an abnormal pressure applied always at the same part of each stroke, then invariably a noticeable distortion of the surface results. To avoid this,

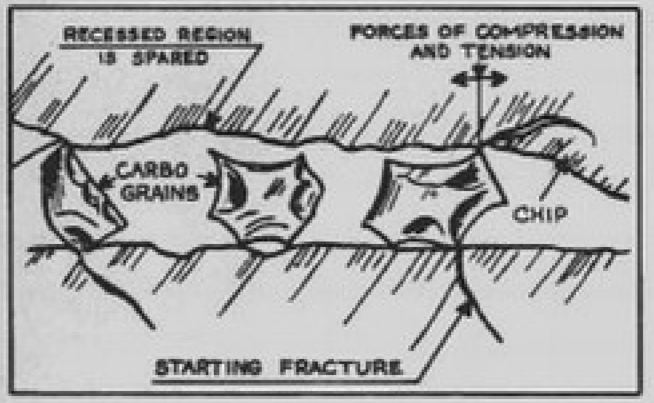


Fig. 13. Mechanism of abrasion (J. Strong).

we make it *improbable* for such repetition to occur. For this, we apply the law of averages. The work requires at least several thousand strokes; therefore if the motion is applied by hand, and the operator makes each stroke length only *approximately* correct, then in the long run the errors of individual strokes are compensated to an astonishing degree. We can state, in fact, that the more numerous and varied the operator's errors, the better he will succeed.

The shaping of a large mirror, say 3 feet or more in diameter, demands more power than a single man, or even several, can muster. The use of a machine becomes mandatory. The problem then becomes one of obliterating the "personality" of the machine, that is, of eliminating any regular tendency, and of making its action as truly random as possible. Even with the best measures, however, the machine-made mirror must always be finished locally by hand.

Shaping of an optical mirror surface takes place in three main stages:

1. Rough grinding. The circular glass blank, approximately flat on both sides at the start, is made concave on one side by grinding against an-

other glass disk (the tool) of the same diameter. The abrasive is a very hard and relatively coarse material (carborundum, grain size about 0.004 inch) and the grinding stroke at this stage is such that it localizes pressure almost completely at the center of the mirror disk. This gives rapidly and *roughly* the desired concave shape.

2. Fine grinding and smoothing. This serves the double purpose of improving the general surface form and ultimately reducing pitting to the point where polishing is practicable. Unlike rough grinding, these operations call for several grades of abrasive, successively finer in size (the last grains being only a few microns in diameter), and a "normal" grinding stroke that tends to act uniformly on the whole surface.

When the pits are finally only a few microns deep, it becomes difficult to reduce them further simultaneously and in a regular manner everywhere on the surface. The logical notion that one should be able to pass imperceptibly from the fine grinding operation to polishing is contradicted by experience; a distinct discontinuity exists between the two processes. It is as though a limit existed on how minutely a glass surface could be fractured. Here, what we call "common sense" or intuition seems to fail us.

3. Polishing. The process is a very distinctive one. The agent is polishing rouge, a powder of very uniform particle size (about a half-micron). Figure 14 compares the rouge particle size with a coarse grain of Carborundum and with a fine grade of emery (M303). The tool is no longer the hard disk of the preceding operations; this would produce only a kind of smoothed surface, not a polished one. Instead, the tool is covered with a substance such as pitch, able to mold itself slowly to precisely the shape of the mirror, yet acting, in shorter intervals such as the duration of a polishing stroke, as a substantially rigid body.[2] The rouge grains lodged in the surface of this pliant medium give the tool its polishing action.

It is difficult to know precisely what occurs in polishing. Newton and Herschel, perhaps the most celebrated of amateur mirror makers, believed that polishing was merely a fine kind of abrasion and that pits left in the surface became progressively smaller until a continuous surface of desired smoothness resulted. Elihu Thompson,[3] pursuing a similar logic, believed that the rouge particles adjusted themselves automatically to a common level in the pitch during pressing and working, and acted by producing a network of ultramicroscopic scratches. Similarly, John Strong[4] has described the polishing tool as a kind of complex scraper, in which crystalline faces of the abrasive are aligned identically by forces parallel to the surface, and exert a very fine cutting action. B. Lyot, who has studied the polishing process painstakingly in relation to coronograph lens making, apparently confirms this. He has stated that by illuminating the surface powerfully with a

[2] A. Couder, *Lunettes et Télescopes*, Section 45, p. 145.
[3] E. Thompson, *J. Opt. Soc. Amer.*, 6, 843–847 (1922).
[4] John Strong, *Procedures in Experimental Physics*, p. 32. Prentice-Hall, New York, 1943.

Fig. 14. Photomicrographs of abrasives and rouge (magnification 1070×). (A) Fragment of single Carborundum grain, No. 120. (B) Grains of smoothing emery, M303. (C) Grains of polishing rouge (calcined ferrous oxalate).

projected image of an electric arc crater, he could observe innumerable fine scratches crossing in every direction even on surfaces polished with the greatest care. Still, the theory generally believed to be the most satisfactory is that proposed by Lord Rayleigh.[5] (See Fig. 15.) It postulates that even at the beginning of polishing the peaks of all irregularities are leveled off with perfect finish (we note that even under the ultramicroscope nothing can be seen on these leveled areas). The plateaus so formed increase in area until finally even the deepest pits are removed. Meanwhile, imperfections in the polished area remain always of *molecular* dimensions only, like those of the free surface of a liquid. This molecular process (so fine that it is difficult to

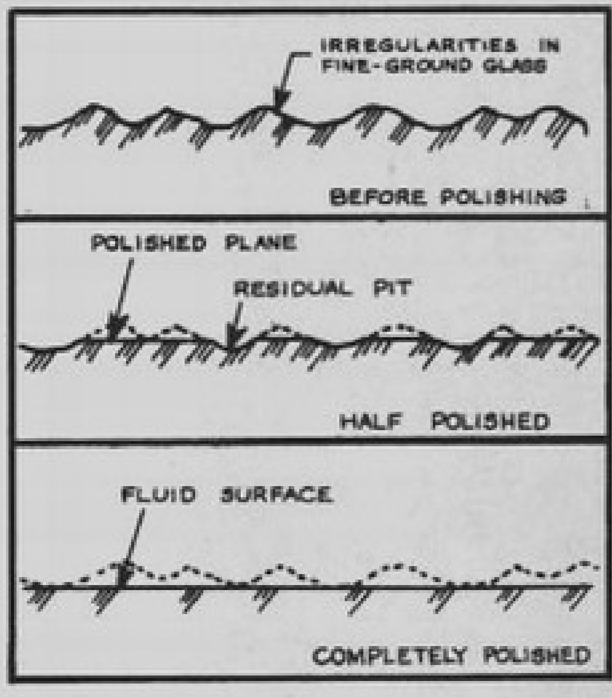


Fig. 15. Rayleigh theory of optical polishing.

detect any change of weight during the operation) differs radically from the action of abrasives, which invariably remove chips of enormous size compared with molecules.

Judging from the ingenious experiments of Motz[6] and Selby[7] it is not at all certain that polishing is merely fine-scale removal of glass. These experiments seem to show that in polishing there exists a so-called Beilby layer,[8] of the kind well known in metal polishing. Given the poor thermal conductivity of glass and pitch, and the large amount of mechanical work transformed into heat during polishing, it is easy, say these writers, to account for the softening of a very thin layer of glass. This layer is immediately spread across the surface, much the way butter is spread on a slice of bread. The theory is surprising, but it does help account for the mysterious reappearance of pits when a surface, polished by typical industrial

[5] Lord Rayleigh, *Nature*, 64, 385 (1901); *Scientific Papers*, IV, 542 (1903)
[6] L. Motz "On the nature of a polished surface," *J. Opt. Sci. American*, 32, 147 (1942)
[7] H. H. Selby, *Sci. American*, Vol. 161, p. 378 (Dec. 1939)
[8] Sir G. G. Thomas Beilby, *Aggregation and Flow of Solids*, MacMillan, London, 1921

"brute force" methods, is repolished by gentler techniques. Without abandoning the picture advanced by Rayleigh, one might well admit that flow does play a role, though perhaps a minor one, in the finishing of precision optical surfaces.

The optical microscope easily shows us the individual rouge grains; their size (about 0.5 micron) remains almost unchanged even after a period of very harsh use (Fig. 14*C*). It is difficult to say, however, how they lodge themselves in the pitch. Any valid picture of their action, it seems, must take into account the enormous surface tension and molecular forces acting at the freshly exposed, nearly dry glass surface. But if the mechanism remains mysterious, the results nevertheless appear quite controllable and reliable. The electron microscope will no doubt in time disclose the finer detail of the polished surface that is now inaccessible. We should mention, however, the beautiful method perfected by B. Lyot[9] which reveals (Fig. 41), within highly polished areas a few millimeters square, the presence of defects of molecular height, i.e., only several Angstroms high!

We return, however, to the defects of "figure," that is, the broad surface errors that affect the general mirror form. We know quantitatively what precision we must have (Section I-4). If the mirror is small and we use the surface-finishing techniques already described, it is possible to obtain automatically a spherical surface of the desired precision, *provided no cause of error intervenes.* We cannot, however, expect this to occur systematically. In any case, in a mirror as large as 8 inches in diameter, this is virtually impossible.

Fortunately, Léon Foucault has given us a remarkable test method which lets us *see* departures from sphericity as vividly as though they were molded in high relief on the glass surface. The test is widely used. It permits us under optimum conditions to see surface differences at least a tenth as small as the least error that would affect mirror performance. Yet the apparatus is of the utmost simplicity. Knowing the position and size of the defect, we can correct it by suitable local action with an adapted polishing tool or special stroke. However, it is not easy to keep this process fully under control; our senses are not closely enough in touch with what takes place at the surface. We must strive therefore for optimum form at the start in order to reduce "localizing" to a minimum. The optical worker's skill is measured at least as much by his mastery of broad figure control with the full size tool as by his ability to remove without trace a last protruding local zone.

All that we have said in this section comprises a warning: the reader must be wary of intuition or "common sense," for in this domain they are not reliable guides. If he must theorize, let him do so freely as he circles his mirror; conditions then are excellent for the stimulation of gray matter. We have given little consideration to the *why* of mirror-figuring processes; for present purposes we shall content ourselves mainly with the *how*—the methods that give results. The reader who accepts the work on these terms

[9] B. Lyot, *Compt. rend.*, 222, 765–768 (1946).

will finish his mirror without difficulty. The others, unless they have an infinity of time, are urged to follow instructions and finish the mirror first. Let the theorizing come afterward.

II-3. The Mirror Blank and Tool

The primary mirror is a relatively massive and therefore rigid body. We must be certain, however, that its precise surface resists mechanical deformation when in use and that it also resists the effects of inevitable temperature changes. Table II lists for several different mirror materials some of the

TABLE II
PHYSICAL PROPERTIES OF VARIOUS MIRROR MATERIALS

Substance	Density (δ)	Specific Heat 25°C, cal/gm°C (c)	Thermal Conductivity cal cm/cm² sec°C 25°C (m)	Expan. Coeff. $\alpha \times 10^7$	$\frac{\alpha\delta c}{m} \times 10^7$
Speculum Metal	8.6	0.079	0.20	186	630
Steel	7.8	0.109	0.20	110	468
Plate Glass	2.5	0.20	0.0018	75	21,000
Duran 50®	2.2	0.18	0.0028	32	4,500
Pyrex® (80% SiO_2)	2.3	0.20	0.0027	33	5,600
Fused Silica	2.2	0.17	0.0032	5.6	650
ULE™ Titanium Silica	2.2	0.17	0.0031	0.2	24
Cervit®/Zerodur® Crystallized Glass-Ceramics	2.5	0.22	0.004	0.2	27

physical properties that determine thermal deformation. A. Couder[10] has proposed as a criterion for thermal deformability the quantity $\alpha\delta c/m$ derived from these properties, the value of which appears in the last column. It represents the relative deformation shown at any moment by mirrors of the various materials, assuming equal size and equal temperature change.

The properties of speculum metal and steel are shown only as a matter of curiosity. No known metal or alloy has the homogeneity or stability necessary to qualify seriously for an astronomical mirror. Foucault and Steinheil, by replacing speculum metal with glass in 1856, opened a new era in the history of reflecting telescopes.

Fused silica and other materials of very low expansion coefficient, developed especially for space research and particularly by Corning Glass Works and Owens-Illinois, may tempt the experienced amateur perfectionist planning a large mirror. However, aside from the higher cost, he should know that rough grinding, polishing and figuring these very hard materials will exact a substantially greater effort.

[10] A. Couder, Thesis, "Recherches sur les déformations des grands miroirs employés aux observations astronomiques," p. 59. Faculté des sciences de Paris, 1932. Reproduced also in *Bull. Astron.*, 7, sections VI, VII, and VIII, 1932. Gauthier-Villars, Paris.

For the amateur, whose modest mirrors are not seriously influenced by temperature change, the remaining practical materials are Pyrex and plate glass. Pyrex is the more widely used by American amateurs. Its thermal properties are quite interesting, and in hardness and resistance to chemical attack it is superior to plate glass. On the other hand, it is much more difficult to cast without internal inhomogeneities and bubbles. Such defects, brought to the surface during finishing, could to a slight degree affect optical performance. However, the Pyrex telescope disks normally supplied by the manufacturer are inspected against serious defects of this type. Plate glass, though much less attractive in thermal behavior than Pyrex, is nevertheless widely used by European amateurs. In part, this stems from the difficulty of obtaining Pyrex in Europe, even in small disks. A good plate glass does have the advantage of taking a beautiful optical polish. Moreover, the thermal distortion effects are almost imperceptible in reflectors under 10 inches in diameter. Invariably, air currents in the telescope tube are the larger, more troublesome factor. In France, the plate glass used almost exclusively is St. Gobain,[11] especially cut and annealed for telescope work, and available in thicknesses up to $1^3/_4$ inches. Sometimes maritime porthole disks are used, available up to $1^3/_8$ inches thick in polished glass plate, which even without special annealing seem to take and maintain a fine surface figure.

We require, of course, two disks, equal in diameter, to make the mirror. The *tool* disk may be a quite ordinary glass (even inexpensive translucent paving block is sometimes used); and if one is making a Pyrex mirror, the tool may be of plate glass. The mirror disk, however, should be selected with some care.

To be assured a desired optically useful mirror diameter, one would ideally select a mirror blank slightly larger in diameter, say larger by $^3/_8$ inch or $^1/_2$ inch. This would allow for the necessary chamfer and permit masking the extreme edge where optical defects cannot always be fully corrected. In practice, however, one is usually limited to diameters regularly available from suppliers; and so for the standard mirror, for example, one normally uses a disk 8 inches in outside diameter. Pyrex blanks in this and other diameters are available from the Corning Glass Works.[12]

The disk *thickness* must not be left to chance. Since we can mount the mirror best by supporting it on three equally spaced points near the edge, we must be certain that flexure resulting from the weight of the disk is not excessive. A. Couder[13] has given a formula for the minimum thickness necessary to preserve image quality when the mirror is supported in this way in a horizontal position:

$$R^4/e^2 \leq 1000, \qquad (10)$$

[11] Cie. de St. Gobain (Service Optique), 6 rue Cambacères, Paris 8.

[12] See Appendix E.

[13] A. Couder, cited thesis (ref. 10).

where R and e are, respectively, the mirror radius and thickness measured in centimeters. For dimensions in *inches* the relationship becomes

$$6.45R^4/e^2 \leq 1000. \qquad (11)$$

Table III gives examples of minimum required thickness and includes a slight compensation for loss of thickness incurred during grinding. These thickness requirements are met by the standard Pyrex mirror blanks.

TABLE III
MINIMUM REQUIRED MIRROR THICKNESS

Diameter (2*R*), inches	Thickness (*e*), inches	Weight, pounds
6	0.90	2.3
7	1.00	3.5
8	1.35	6.1
9	1.70	9.3
10	2.10	14.9

The weight of a telescope increases very rapidly with weight of the mirror. Excessive thickness therefore imposes a much greater burden on a telescope than would offhand appear. Another disadvantage is that thicker mirrors take longer to reach thermal equilibrium. For mirrors larger than 10 inches in diameter it is better to build a more elaborate support[14] than to increase thickness to the extent shown by the formula; otherwise the thickness rapidly becomes prohibitive.

Thickness of the *tool* may be less than that of the mirror. Being the lighter of the pieces, it may then be conveniently manipulated on *top* of the mirror, where, with less pressure on the surfaces, control of the figure becomes easier. A plate glass tool 1 inch thick may be used for mirrors up to 8 inches in diameter; a $1^1/_4$-inch plate may be used for mirrors up to 12 inches.

II-4. Abrasives[15]

Carborundum (silicon carbide, SiC) is a widely used blue-black or greenish abrasive produced in the electric furnace. It is supplied in a wide range of grain sizes that are graded by sifting through wire mesh, and bear a commercial designation representing the mesh (apertures per linear inch) that will pass a specified proportion of the grains. The extreme hardness of silicon carbide permits appreciable saving of time in rough grinding, especially when a substantial depth of glass must be removed, compared with the use of emery alone. It does, however, leave deeper pits and scratches that are subsequently harder to remove. No. 80 "carbo" is often used by amateurs for rough grinding; but unless the mirror is over 8 inches in diameter and

[14] Details are given in the cited A. Couder thesis (ref. 10).

[15] See Appendix for suppliers.

more than 1/16 inch deep, it is better to use No. 120. The final pits are then smaller and easier to eliminate. The quantities of abrasive required are indicated in Section II-6 below.

Emery remains the better abrasive for finer stages of grinding and in the final smoothing operation produces a superior surface. Emery is a natural form of aluminum oxide, found in association with various impurities, among them oxides of iron which impart a brown or reddish color. After pulverizing, it is often still graded by the classical "elutriation" process, i.e., by selective settling in water. Since amateurs have often done this themselves to improve a relatively poor grade of emery, we should say a little more about the process.

The larger the grains, the faster they settle in water. If we mix a quantity of the powder thoroughly in a sufficiently tall vessel of water, then after a specified time (measured in minutes, whence the designation of fineness often used) only particles of a certain minimum fineness remain suspended. By siphoning off the water and allowing its suspended matter to settle in turn, we obtain the specified "minute" grade of emery. Theoretically, grading by elutriation requires settling in a meter of water. In practice, emeries of equal "minute" designation supplied by various makers may differ considerably in fineness.[16] But this is not the worst fault of some of these products. They are often sold in bulk, being dispensed in paper sacks of dubious cleanliness, and are sometimes contaminated with coarser particles. Besides, the manufacturer of nonoptical abrasives removes none of the debris *finer* than the nominal grade. For example, in a batch of very fine particle size, say 40 to 60 min., we would obtain not only grains traversing a meter of water in 40 to 60 minutes but particles of every *smaller* size. The smaller particles form a kind of meal or mud that is *most objectionable* for proper grinding, behaving much like a spent emery that is loaded with glass particles. A useful fraction of such emery can be recovered by repeated washing in the following procedure: a maximum of 2 pounds of abrasive is mixed with water in a 10-quart pail. After several minutes of stirring the slurry is allowed to settle. Surface mud and fine suspended matter are then *discarded* with the bulk of the water. Fresh water is added and the process repeated until the abrasive settles freely in a dark or blackish mass that leaves only clear water above.

The American and British markets fortunately offer excellent "white" grades of emery—chemically purer products that are sometimes also designated as corundum.[17] These are sold in tins, and may be relied on fully without further processing. The number designations are unrelated to any water-settling procedure. Equivalence of the various products in terms of their abrasive action is indicated in Table IV. The best abrasives for precision smoothing are those showing minimum dispersion in their grain-size distribution curve. On this score, we should mention particularly Microgrit

[16] In the European market, fineness is usually overestimated. Thus commercial "40 M" emery may be barely a 20-minute grade.

[17] See Appendix E for Suppliers.

WCA, product of Micro Abrasives Corporation[18], comprising pure aluminum oxide.

TABLE IV
ABRASIVE AND POLISHING QUANTITIES FOR 8-INCH MIRROR

Operation	Quantity lbs	Silicon Carbide (Grit)	Emery (min)	A-O *Emery*[a]	B&L *Corundum*[b]	Microgrit WCA (microns)
Roughing	2	60–120				
Fining	½	220	1			
	½	320	2			35
	¼	500	5	M 302	600	25
Smoothing	¼		10	M 302½	750	20
	¼		20	M 303	1200	15
	¼		40	M 303½	1600	9
Optional Final	¼		60	M 304	2100	
Polishing						
Pitch	1 to 2					
Red Rouge	¼					
or						
Ferrous Oxalate						
for Calcining	500g					
or						
Cerium Oxide	¼					

[a] American Optical Co. The corresponding emeries (*BM* series) of British American Co. Ltd., 39 Hatton Garden, London are designated by similar numbers for equivalent grades.

[b] Bausch and Lomb

II-5. Polishing Materials

Polishing Pitch. The preferred product is Swedish or Norwegian pitch, a pine-wood derivative melting at about 140° F. This is shipped from the point of origin in barrels, but when sold by the retailer in 2-pound or kilogram loaves has often been heated carelessly and lost some of its valuable properties. The quality may be judged by warming a fragment in the mouth for a few minutes. If it can then be chewed and stretched like chewing gum, its quality is very good.* If it breaks when bitten, it can be improved by addition of turpentine, though this will not of course replace all the original natural solvents.

A satisfactory substitute material is coal tar pitch (softening point 170°-180° F.), which is very often used for this purpose in the United States.[19] This material is mixed as follows: one part of tar (flooring flux), two parts of rosin; all tempered to the proper hardness by the addition of Hercolyn® (Hercules Powder Co.).

* See Appendix J for a description of a pitch tester.

[18] Micro Abrasives Corp. Westfield, Mass 01085.

[19] See Appendix A.

Though solid in appearance, pitch is in fact a liquid of very high viscosity. Even at room temperature it will mold itself slowly to the shape of any object pressed against it. This viscosity of pitch is probably its most important property in optical work, and must not be carelessly impaired by the addition of beeswax or other materials.

To minimize the possibility of scratching, the pitch tool is often covered with a thin layer of beeswax. We shall refer to this technique in some detail later.

*Polishing Rouge.** Although materials such as titanium dioxide (a white powder) and cerium oxide (a rose-colored material) are widely used in industry for polishing glass, they are not recommended for large precision surfaces such as that of a telescope objective (see Fig. 41). For this, *polishing rouge* is preferred, though it is not nearly as clean to handle. This is a form of ferric oxide obtained by heating ("calcining") pure ferrous oxalate in air (thus is distinct from industrial rouges such as colcothar, which are formed from ferrous sulfate). Though many dealers offer rouge for optical work or plate glass polishing, the product is often of inferior quality. A poor rouge can often be improved by boiling in water, then skimming off and discarding the greasy, surface scum. Good rouge, like good emery, settles freely in water, leaving only a clear supernatant liquid. Excellent rouges are obtainable in the United States and Great Britain from the sources mentioned earlier as suppliers of high-quality emery.[20]

Amateurs who wish to make their own high-quality rouge may purchase ferrous oxalate ("Pure" grade) from some of the large chemical supply houses.[21] The procedure is the following:

Spread the ferrous oxalate in a layer about 1 inch thick in a carefully cleaned sheet-iron skillet, and place over a strong gas flame. The room should be well ventilated since considerable quantities of carbon monoxide are evolved. In about 15 minutes, the powder (initially yellow) turns brown at the point of contact with the pan. Stir the powder with a large metal spatula, but only slowly at first in order to prevent bumping. With continued heating and stirring the entire mass turns brown, finally igniting and becoming incandescent like burning tinder or punk. Continue heating and mixing until the glow spontaneously subsides, indicating that calcination is complete.

After cooling, wash the rouge by mixing with water in a large, carefully cleaned vessel; then let the rouge settle and decant the water. The rouge may also then be strained through several thicknesses of silk or nylon stocking, or better, through a flour sieve of the finest mesh obtainable. It may then be stored in the wet state in small screw-capped jars.

* The author now prefers zirconium oxide prepared for polishing precision optics. It is much cleaner than rouge and gives an excellent polish and smooth surfaces.

[20] See Appendix A.

[21] Obtainable from Amend Drug and Chemical Co., Box 797, Hillside, NJ 07205.

II-6. Summary of Grinding and Polishing Needs

In Table IV we summarize the kinds and amounts of the various abrasives and polishing materials needed. Where there is a choice among types of abrasives or manufacturers, the indicated equivalence is based on *result* given by the material. Grain size is an unreliable criterion because it may be defined differently by various manufacturers; also it cannot be applied to materials, such as carborundum and emery, which differ considerably in hardness. The quantities listed are generous, making allowance for the beginner's inevitable errors and for the reluctance of certain dealers to furnish small quantities of such low-cost materials as emery and rouge.

The recommended series of abrasives which is given in Table IV is not inviolable. Other series, approximating that shown, can give equally good results. Also, any given grade of abrasive can be omitted if we increase sufficiently the work done with the grades preceding and following.

The widely marketed kits that offer glass disks, abrasives, pitch, rouge, and accessories in a single package are a tempting simplification to the amateur. The author feels, however, that their advantage is largely one for the vendor, namely, that of sales appeal. Unfortunately, the quality and the choice of contents are not always of the best, and the quantities provided may not be sufficient to insure the best results. Most dealers will, however, supply separately the various items required. Pyrex disks can be purchased, if desired, directly from the manufacturer. Also if two or more amateurs will cooperate to purchase a minimum lot (usually 5 pounds), then abrasives and rouge likewise may be purchased directly from the manufacturer. We believe the extra effort taken to choose one's various mirror-making needs personally is altogether worth while.

II-7. Work Support and Accessories

The needs here are few and rudimentary; they may be drawn largely from materials and equipment available in the average household.

Work Support. Hand-working of mirrors is done by the "fixed support" method. The simplest kind of support is the corner of a work bench or possibly the corner of a sturdy kitchen table (Fig. 16*A*). In an arrangement suggested by R. W. Porter three fixed cleats are provided to position the lower disk, yet provide enough play to allow the operator to turn the disk freely and to interchange easily the upper and lower disks. Figure 16*B* represents an improved version in which the support is made rotatable. This permits the operator to remain seated next to the work. Neither arrangement is quite as satisfactory, however, as a separate work post that permits the operator to circle the work freely. Many celebrated optical workers (Draper, Metcalf, Ellison, and others) have worked on an upright barrel (Fig. 16*C*) filled with sufficient ballast to prevent movement during use. Figure 16*D* shows a work post often adopted in telescope-making clubs in the United States. The supports shown in Figs. 16*E* and 16*F* are the ones we have used at the workshop of the Astronomical Society of France since 1946. That illustrated in Fig. 16*E* was made by the author's colleague Luc Ott from three logs fastened together with boards. Its work surface was made only large enough to support an 8-inch mirror, in order to reduce overall dimensions. The construction shown in Fig. 16*F* was inspired by certain well-designed telescope tripods. Note the wide separation of the boards forming each leg, allowing each member to work almost entirely in compression or tension. Regardless of the direction in which a force is applied, the rigidity is high, and total weight is kept to a minimum.

Whatever the type of work support, attention must be given to the following details:

1. Stability. We must anticipate applying strong forces during polishing. The support must be rigid; and if movable, must be provided with sufficient ballast.

2. Height of work surface. Depending on the height of the operator, this may vary from 35 to 40 inches. Some prefer to have the work as high as 4, even 5 feet; but for sustained effort without fatigue, it should not be above elbow height.

3. Flatness of disk-supporting surface. Even if flannel or a similar material is interposed between the support surface and the disk, the support should be well planed.

4. Interchangeability of disks. Ease of interchanging the tool and mirror, to permit working with the mirror above or below, is indispensable. The provision of at least one adjustable cleat will allow for this; also it will permit accommodating the inevitable small differences in diameters of the disks and irregularities in their contour.

Accessories. Additional items needed for grinding and polishing are the following:

1. One or two basins, slightly larger in diameter than the mirror.

2. Four or five sponges, medium size (Du Pont cellulose sponges are economical and quite satisfactory).

3. Several small glass (screw-cap) jars for storing abrasives (labeled for grit size, remarks, etc.) and rouge.

Other conveniences and minor necessities are: a gas stove (with an iron plate at least slightly larger than the mirror and $^1/_8$ inch thick or more) or electric hot-plate; a Bunsen burner or candle; a sharp wood chisel (1-inch blade or wider); a steel rule for checking curvature during rough grinding (a spherometer is useful here but not necessary); and miscellaneous items such as clean white cloths, and a small brush for applying rouge.

The remaining important necessity, the Foucault test apparatus (which the amateur easily constructs himself), will be described in detail later.

II-8. Preparing the Mirror Disk

Except when molded, the blanks as delivered by the supplier are often

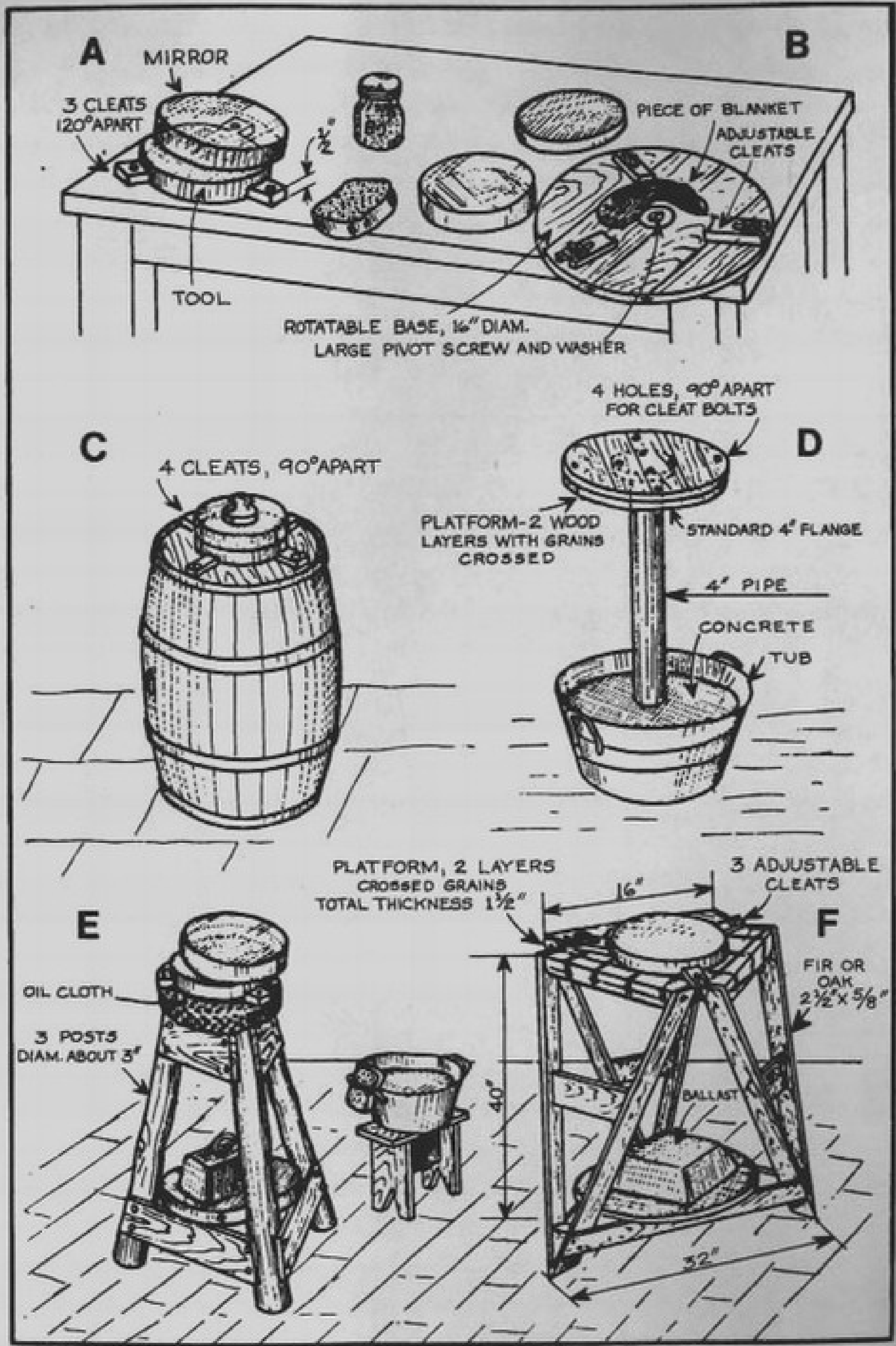


Fig. 16. Various types of fixed work posts.

quite rough at the edges. The amateur often does nothing to correct this, since the mirror, properly mounted, need rest only at three points 120° apart near the circumference, and therefore does not have to be perfectly round and centered like a refractor objective. Undoubtedly, a smooth fine-ground edge is better, not only for esthetic reasons, but because it is more easily cleaned when the disk is prepared for aluminizing. Rough edges harbor contamination—polishing rouge and the like—which may be difficult to remove completely. A reasonable amount of smoothing is therefore recommended.

A convenient method is to improvise a turntable, for example, by using a spindle bearing (Fig. 17*A*). The disk is approximately centered and fixed on the rotatable member with pitch (see Section II-9 for pitch cement-

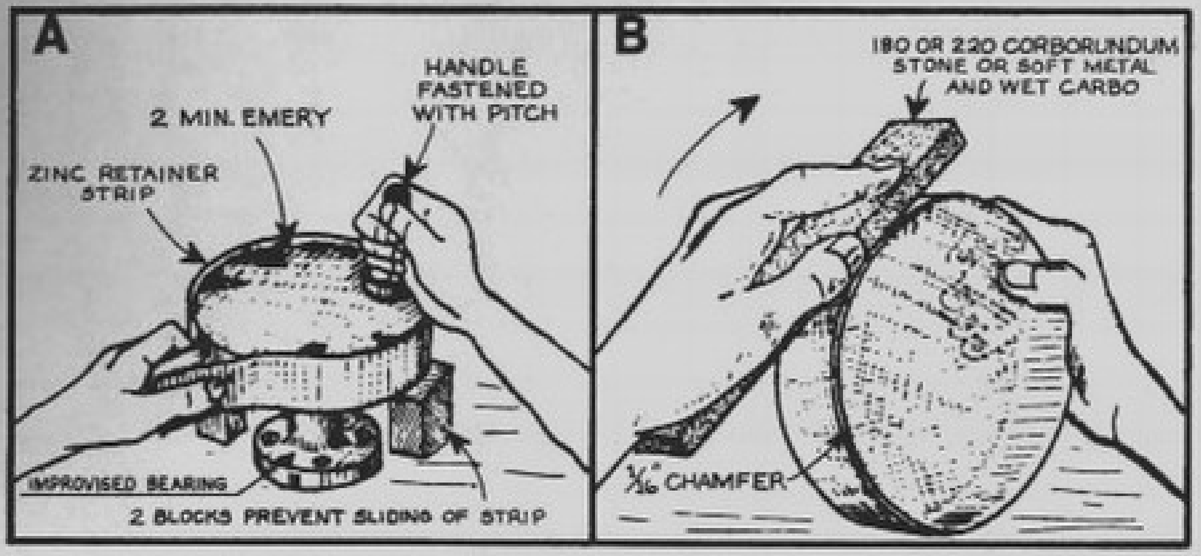


Fig. 17. Smoothing irregularities at the edge of the disk.

ing technique). A handle fastened with pitch near the edge serves as a crank. By rotating the disk and applying a soft metal collar (copper or zinc, about 0.020 inch thick and a little wider than mirror thickness) as a support for the abrasive, projections and rough spots are rapidly removed. The method easily produces a regular edge but obviously will not correct errors of general contour, for example, a slightly oval shape. This shortcoming is unimportant, however.

A simpler, alternative method is to remove the rough spots and produce a fine-ground edge merely by smoothing with a flat carborundum stone (No. 220 for example) or by grinding with wetted abrasive applied to the disk with a flat iron or brass plate (Fig. 17*B*).

We shall use a carborundum stone or metal plate for another operation also: applying a uniform chamfer to both edges of the disk, or if need be, increasing the width of an existing chamfer. An 8-inch mirror should have a 45° chamfer about $^3/_{32}$ inch wide or a rounded edge of about $^3/_{32}$ inch radius. During rough grinding it is possible for the chamfer to disappear;

this must be avoided at all costs. If either the tool or mirror face presents a sharp edge, serious chips can occur on even the slightest blow against a hard object. The chamfer of the *tool* obviously takes the most wear. It is advisable at the start to form a chamfer on the tool of $^1/_8$ or $^3/_{16}$ inch. Before rough grinding is completed, this operation may have to be repeated.

A final precaution is to check that the faces of the mirror blank are reasonably parallel. A variation of thickness around the edge of 0.005 inch or 0.010 inch is inconsequential; in any case this could easily be corrected. But if the nonparallelism or "prism" is as large, say, as 0.040 inch, the disk should be returned to the factory either for redressing or for replacement by another. Otherwise much extra time will be spent needlessly in rough grinding. Disks cut from high-quality plate glass usually do not present this problem. St. Gobain plate-glass disks, for example, are generally parallel within a half-thousandth of an inch.

II-9. Rough Grinding

Selecting the Mirror Face; Attaching a Handle. We decide first which surface shall be the mirror face. If the glass is relatively crude, it should at least have a surface free of irregularities or wrinkles deeper than about $^1/_{16}$ inch. In any case it should not contain fissures which might persist after rough grinding or bubbles which during grinding might be opened to the surface. If the raw mirror blank has been sandblasted on both sides, it is easier to spot internal defects if the disk is wetted, or better, oiled on both sides, and viewed against a light.

The working of small mirrors is made easier by attaching a small handle at the back with some pitch. This is not indispensable; in fact, when polishing begins the handle may be objectionable. To attach the handle, remember that pitch adheres poorly to a cold surface, particularly if that surface is a fairly good conductor of heat. The mirror disk must therefore be warmed. This requires care; a degree of danger is always present when one heats a thick glass. Even thin Pyrex articles are occasionally known to crack in the laboratory. A safe, quick method is to place the disk several minutes in water that is comfortably warm to the touch (90°–105° F.). Preferably the disk is warmed more gradually, by immersing it in water at room temperature at the start (the disk being raised from the bottom of the vessel with insulating spacers), then heating the vessel and raising the temperature very slowly (1 or 2 degrees per minute). On withdrawing the disk, one must avoid sudden chilling—cold drafts, for example—especially if the glass is not Pyrex. The disk is dried thoroughly, a small amount of melted pitch poured in the middle, and the handle applied and centered before the disk cools.

Cold pitch is brittle. It breaks with very little force, provided the force is applied abruptly. To remove the handle (the mirror being fairly cold) we need only strike it sharply with a small mallet that has a somewhat flexible handle.

Starting Rough Grinding. Set the tool within the positioning cleats. Play of $^1/_{32}$ inch is permissible to allow turning the disk and removing it easily. From the jar in which the 180 or 120 carbo is stored as a thin mud, take about 1 or 2 cubic centimeters of abrasive and distribute it over the face of the tool. Sprinkle on a few extra drops of water from the fingertips. Now set down the mirror and proceed to rough-grind.

To grind efficiently and to hollow out the mirror as rapidly as possible, one is guided by the following principles:

1. Let the mirror overhang the tool as much as possible. The center of the mirror may safely travel within an inch to a half-inch of the edge, the strokes being such that the center moves back and forth along imaginary chords on the tool (Fig. 18*A*). For an 8-inch mirror, stroke length along a chord may be as much as 4 inches. With a little experience one learns quickly how long the stroke may be before the mirror tips over the edge.

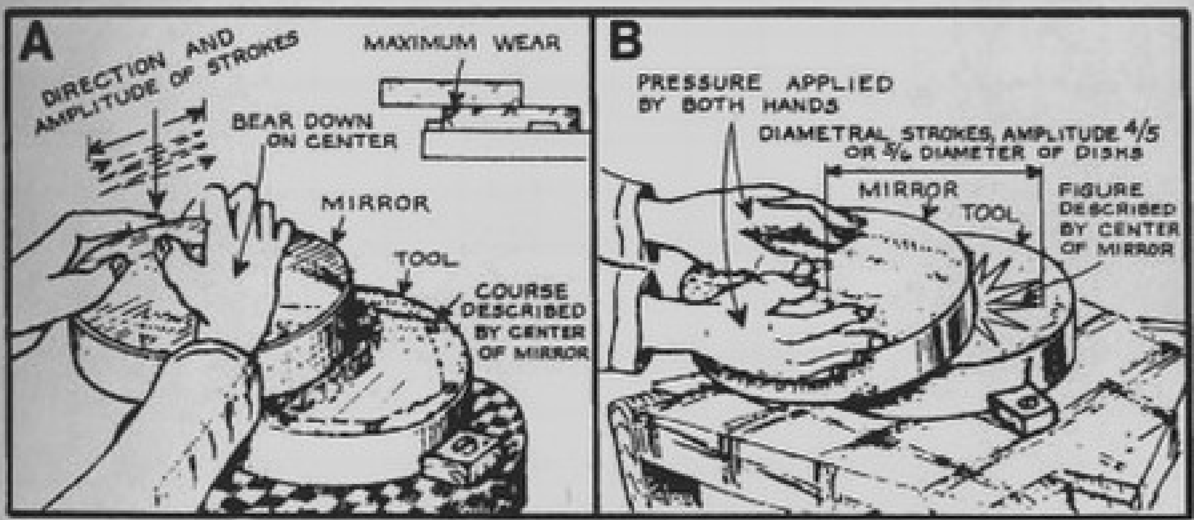


Fig. 18. Strokes used in rough grinding.

Make five or ten strokes in one position (that is, along one chord), then rotate the mirror in the hands a fractional turn, and continue grinding in a slightly different direction (along a different chord) by shifting position somewhat around the work. If the operator can circle the support freely, the tool may be fixed; otherwise the tool is turned from time to time to wear it down uniformly on all sides. Figure 18*A* shows the pattern traced on the tool by the center of the mirror during several changes of position around the work.

There is little point in circling the post rapidly, particularly in rough grinding. It is the to-and-fro motion that does the work. We suggest 60 or 80 double strokes (each a back-and-forth movement) in the course of once or twice circling the support. During this time the mirror is made to turn, say,

three or four times around in the operator's hands. Needless to say, it would be foolish to adhere strictly to these figures.

If the disk surfaces are wavy or uneven at the start, the outer portion of the mirror should first be worn down uniformly to some extent. A procedure given by Ellison is useful here: the use of a centered stroke of very large amplitude (Fig. 18*B*). This may be as much as five-sixths the mirror diameter (for example, $6^1/_2$ inches on an 8-inch mirror) or larger.

2. *Apply ample pressure.* No. 80 carbo works at maximum efficiency only under heavy pressure. Do not fear to apply even the entire weight of the body on the center of the mirror (Fig. 18*A*). If the mirror is thin and therefore exerts little weight of its own, it is helpful to fasten to the back of the mirror, as a kind of handle (during rough grinding only), a weight of perhaps 10 pounds.

3. *Wet the abrasive properly.* If too much water is used, the carbo is thrown out at the edges before it has a chance to do its work. If the work is too dry, the carbo distributes itself poorly and forms a kind of mortar between the disks that paralyzes movement and reduces efficiency. The operator knows when the carbo is properly wetted and working effectively by the loud grating sound that is characteristic of this abrasive during rough grinding.

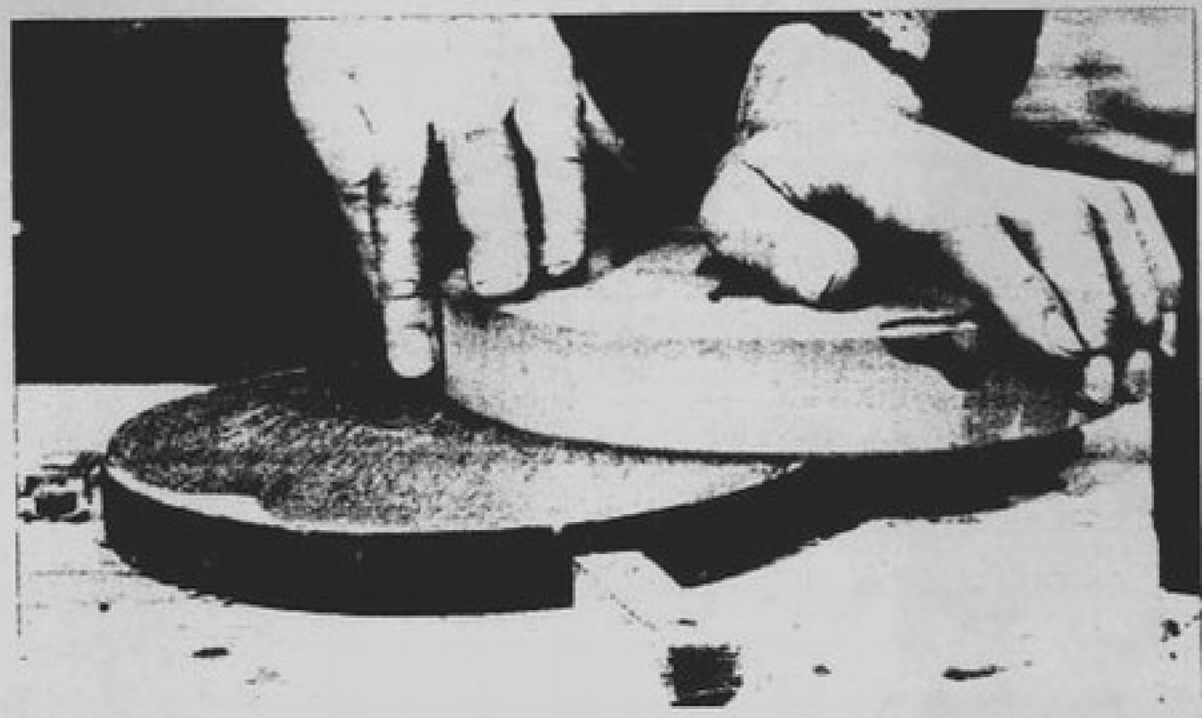


Figure 18C. Rough grinding an 8-inch mirror.

Despite its extreme hardness, the silicon carbide does not stand up long under this treatment. After a few minutes (2 to 4, depending on the initial amount of abrasive and energy expended), the sound becomes weaker and the water is taken up into a paste of abrasive debris. Usefulness of the abrasive charge is prolonged a little if one adds just enough water to wash out the debris, leaving the larger, useful carbo grains. It is more efficient, however, to interrupt the work, sponge the disks completely clean, mop them more or less dry, and start with new carbo.

This completes what is usually termed a *wet* (or what the French prefer to call *une séchée,* literally a drying–a matter of temperament, no doubt).

Rough grinding an 8-inch mirror of $f/D = 6$, using the methods described, takes about 3 hours. For the beginner, however, it should not be surprising if the job takes twice as long.

II-10. Testing Radius of Curvature

The useful mirror diameter and the desired focal ratio, f/D, determine what the focal length shall be and therefore determine also the required radius of curvature (equal to twice the focal length). The standard mirror,

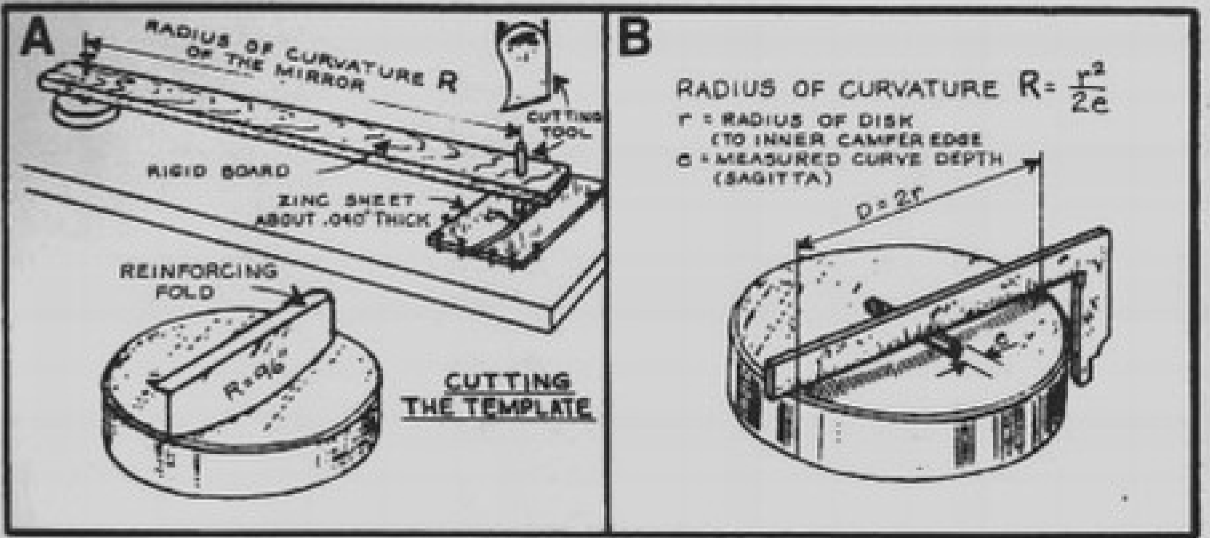


Fig. 19. Checking approximate radius of curvature of the rough-ground mirror.

for example, $f/D = 6$, has a focal length of $6 \times 8 = 48$ inches, therefore a radius of curvature of 96 inches. It is not important in forming a mirror surface to arrive exactly at the calculated focal length, since the telescope tube will not be made until the mirror is finished and can be adapted to the length required. We can, however, during rough grinding check the radius of curvature approximately, and so guide ourselves within a few per cent of the desired value.

The most convenient test for curvature is the use of a template. This is cut from a sheet of any soft metal, for example, zinc or soft aluminum, which may be sheared accurately along a scribed line. A scriber fixed in a board may serve as a compass. Better, the scribing point may actually be a cutting bit, and thereby cut the template directly (Fig. 19*A*). The appearance of light between template and glass is a sensitive test of curvature pro-

vided the light is bright, but the template should be shifted along the surface to make sure the defect does not reside in the template itself.

If a good steel rule is available (the rule in a combination square will do), the radius of curvature may be determined from the "sagitta" of the mirror; i.e., depth at the center of the disk (Fig. 19*B*). This may be measured by inserting successive objects of known thickness (wires, drills, feeler gauges) under the rule. If the object is too thick, it makes the rule teeter; if too thin, it passes under the rule without hindrance. The radius of curvature R may then be calculated from the following approximate formula, which will be amply accurate for the present purposes:

$$R = \frac{r^2}{2e}, \tag{12}$$

where r is the useful disk radius, that is, half the diameter across which the rule rests, and e the depth of the curve.

If, for example, the mirror diameter measured to the chamfer is 7.75 inches ($r = 3.88$) and the measured curve depth is 0.073 inch, the radius of curvature is

$$R = \frac{3.88^2}{2 \times 0.073} = 103.1 \text{ inches.} \tag{13}$$

If the desired radius of curvature is 96 inches, we continue grinding until the depth is about 0.079 inch. But there is no point in fussing over this; the rough-ground surface will in any case need improving in form and smoothness, and in this process we shall be able easily to adjust the radius more exactly.

II-11. Finishing Rough Grinding

Figure 20 (which greatly exaggerates surface curvatures) shows how the extreme off-center mirror position in rough grinding causes uneven surface wear. At the edge of the mirror a relatively flat "ledge" persists, and at the center of the tool, a flat spot. On an 8-inch mirror the deviation from a true sphere may be as much as several thousandths of an inch. We must therefore finish the rough grinding by a gentler method that eliminates this error. This requires only a slightly changed technique. We resume work with approximately *centered* strokes (Fig. 18*B*), and the stroke is shorter–no more than half the disk diameter. In this process the "ledge" and "flat" disappear. In the last stage of rough grinding we also reduce the pressure, in order to minimize the depth of the pits and ease the job of ultimately removing them from the surface. In this last stage, the weight of the mirror, plus the weight of the operator's hands naturally resting upon the mirror, are sufficient. The template indicates when the surface has attained approximately the right radius, and therefore when the rough grinding has been completed.

It may happen during rough grinding that the desired mirror depth is exceeded. We need then only to interchange the tool and mirror, and apply to the tool exactly the same stroke previously applied to the mirror, until the condition is corrected.

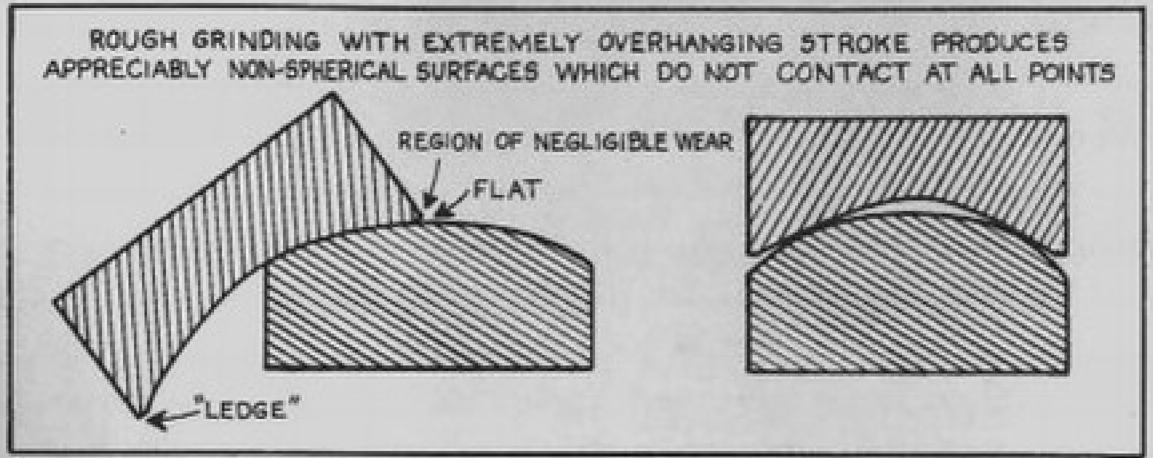


Fig. 20. Distortions incurred during rough grinding.

The fine grinding that follows rapidly and automatically improves the form further, to the point that any mechanical method of surface checking ceases to be of value.

II-12. Fine Grinding and Smoothing

The important first step is to clean scrupulously every object which has come into contact with the carborundum: the mirror, tool, work support, table, etc. Rinse these all generously with water, with particular attention to every crevice that may have retained the coarse carbo. Remove the cleats from the support and brush them in water; or better, change them for a new set. The mirror handle, if any, is now discarded and the back of the mirror cleaned. If the work support has been covered with oilcloth, wash this carefully; otherwise cover the support with white paper before reattaching the cleats, and subsequently change the paper with each change of abrasive. Similar measures at the table used for the accessories are a good precaution also. The wash basin and carbo sponge are then taken out of the workroom. If the same basin is later used for cleanup of the finer abrasives, it must first be rinsed carefully several times and checked inside and out for glittering points of carbo. These are no childish precautions—a single coarse silicon carbide grain getting into the work toward the end of smoothing may ruin an entire day's labor. Those who would scorn these precautions must do so at their peril.

The work now continues with 180 carbo; or with 1-min. emery, which will leave pits of somewhat smaller size.

At this point, and in general *for all work to follow*, we adopt the so-called

normal stroke. Let us consider this stroke carefully. It is a to-and-fro movement approximately centered over the lower disk (Fig. 21*A* and *B*), and has a total amplitude of about $^1/_3$ the disk diameter. The overhang at either end of the stroke is therefore about $^1/_6$ the diameter or $1^1/_3$ inches for an

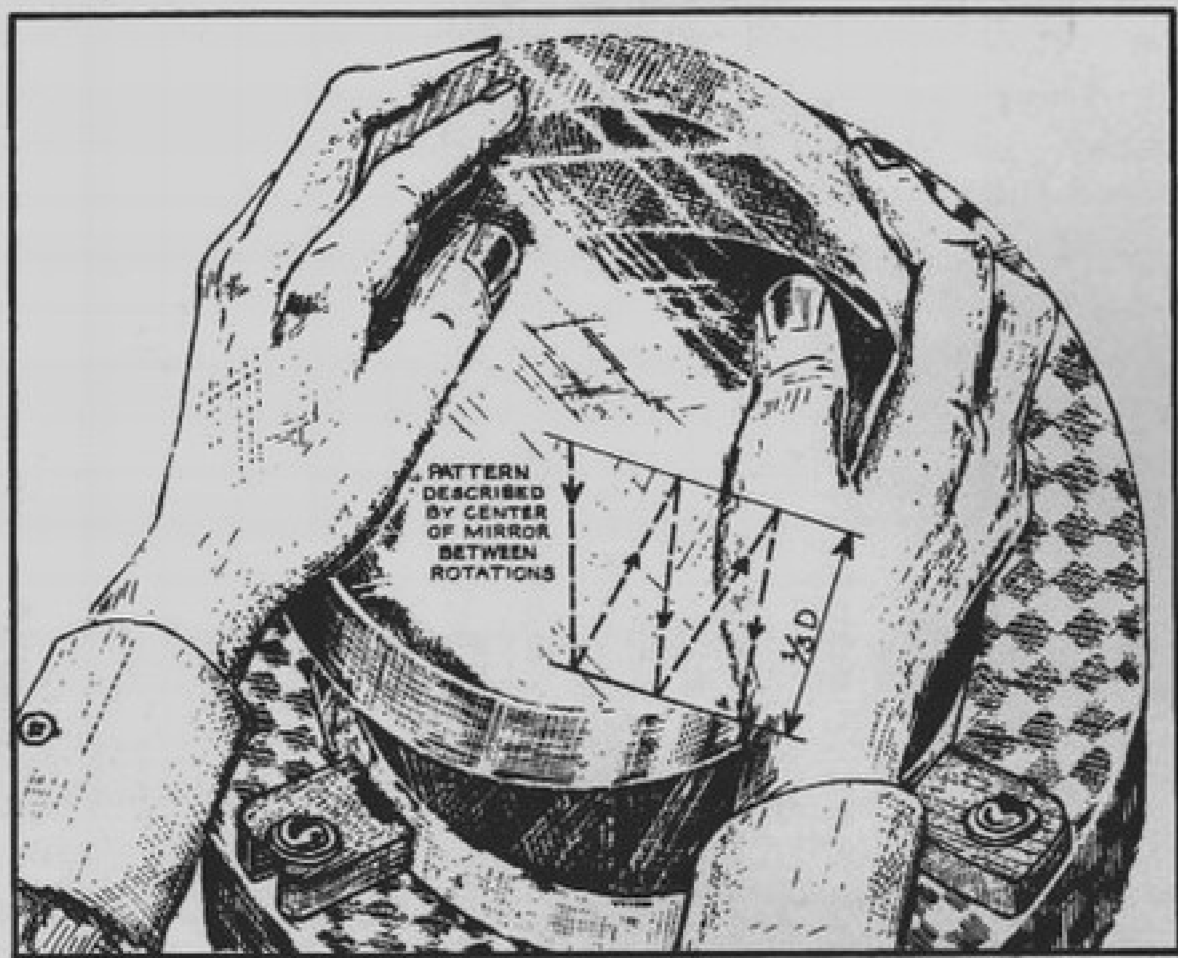


Fig. 21A. The normal stroke.

8-inch mirror. At the same time, a constant sidewise variation in stroke position is introduced, limited at most to $^1/_8$ the disk diameter in either direction. Successive strokes therefore describe a V- or W-pattern or, as proposed by G. W. Ritchey, a more complex pattern such as a figure-8. Every five or six strokes the upper disk is rotated slightly between the hands; also the operator shifts position slightly around the post, as in rough grinding. The essential factor in all this is that we observe the $^1/_3$ amplitude only *on the average*, that is, that we randomly *vary* the stroke as much as possible instead of falling into a fixed pattern of motion. The law of averages does the rest. Barring only an exceptional systematic error, such as applying pressure always at the same part of the stroke, the maximum departure of the mean surface from a sphere is then much less than the abrasive grain diameter.

The procedure in other respects is that described in Section II-9, except that now the sole pressure applied to the work is the weight of the upper disk plus that of the hands resting naturally on the work and acting only to control the motion. Fine grinding takes place uniformly and without appreciably changing the curvature *provided that in alternate wets we work with the mirror above and the mirror below.* In the first stage of fine grinding, however, if the template so indicates, we may complete several wets with the mirror position unchanged, if necessary to adjust the mirror more closely to a desired curvature. When the mirror is on top, its curvature becomes more pronounced; when below its curvature is reduced.

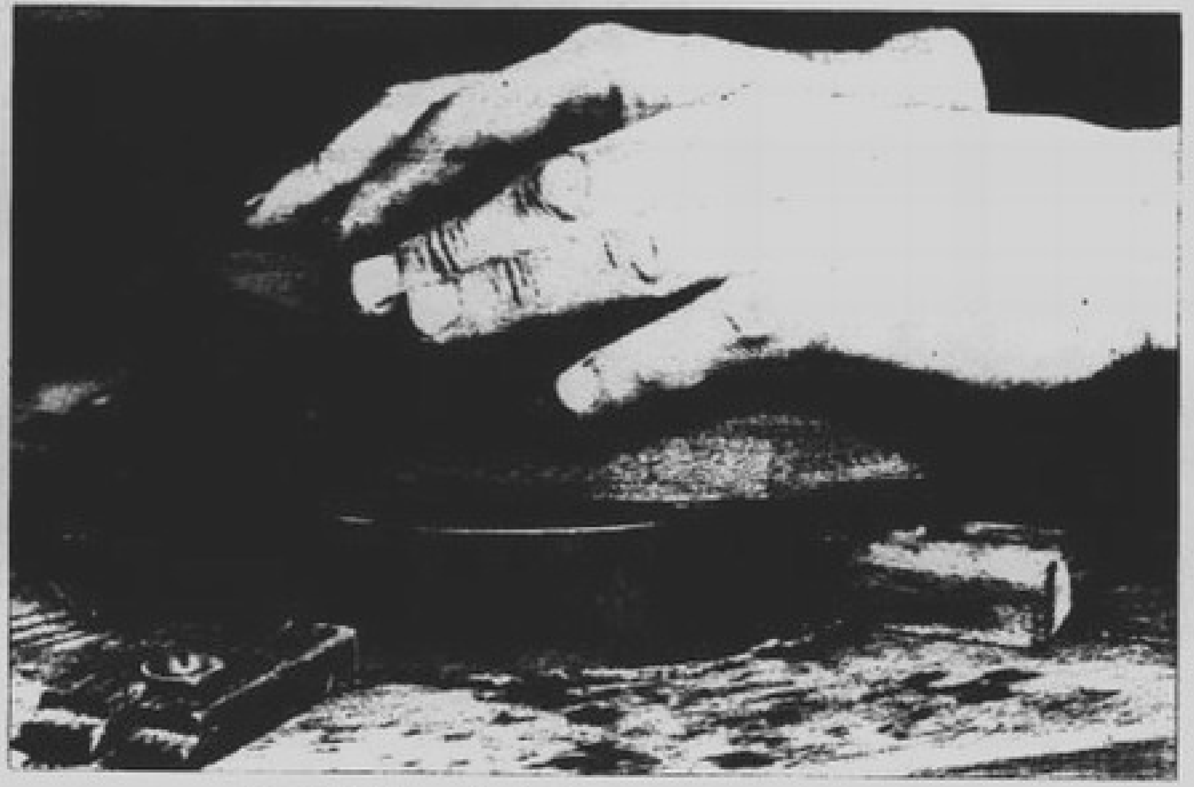


Fig. 21B. Normal grinding stroke on an 8-inch mirror.

After two or three wets with 180 carbo or 1-min. emery, a superficial inspection by reflected light seems to indicate that coarse pits left by the preceding carbo are gone. If we look more closely, however, holding the disk against a strong light, we see them still: a scattering of sparkling points against the more uniform background produced by the finer abrasive. Also present are minute fractures left by the coarser abrasive which for the moment remain invisible; with further grinding, however, these cracks release tiny chips and in the process bring further pits to light. We therefore continue grinding until we are sure that every coarse pit and fracture are eliminated. This may require 15 to 20 wets for 180 carbo, and even more for 1-min. emery. Even then, pits larger than the average remain visible, but this may be caused by the finer abrasive itself, which is never perfectly uniform. To decide when to discontinue this abrasive, mark the position of some abnormally large pits with a china-marking pencil on the dried rear

mirror surface (or with ordinary pencil if the rear surface is abraded). If such larger-than-average pits no longer appear at the same place after a further wet, proceed to the next abrasive.

During work with the 180 carbo or 1-min. emery, adjust the radius as closely as possible to the template. If the back of the mirror was originally coarsely sandblasted, use the present abrasive also to make that surface smoother. For this purpose use the rear surface of the tool as the mating face. Preferably, the rear mirror surface is made slightly concave rather than convex; therefore this work is done with the mirror on top.

Continue fine grinding in the same way with the 5-min. and 10-min. emeries (or their equivalents, as indicated in Table IV). Each abrasive is used until pits caused by the preceding abrasive are eliminated. Remember the very important cleanup operation on all equipment after each abrasive change. For those who may have difficulty knowing when to change abrasives, we indicate in Table V, for each grade, the number of wets (each comprising 5 to 10 minutes actual work) that normally suffice for an 8-inch mirror, *assuming that the proper abrasives and technique are used.* In case of doubt, it is always better to work somewhat longer than to proceed prematurely to the next abrasive.

A separate sponge is reserved for mopping the 180 carbo, another for the 5- and 10-min. emeries, and still another for the 20- and 40-min. emeries. If natural sponges are used, they should be pounded thoroughly with a mallet before wetting, in order to remove any calcareous or siliceous particles they may contain.

TABLE V
APPROXIMATE NUMBER OF WETS REQUIRED FOR EACH ABRASIVE

Abrasive	No. of wets required to remove preceding grain
180 carbo or 1-min. emery	15 to 20
5-min. emery (or equivalent)	20
10-min. emery (or equivalent)	10
20-min. emery (or equivalent)	6
40-min. emery (or equivalent)	4

"Smoothing" as such begins with the 20-min. emery. The quality of a smoothed surface depends much upon the quality of the emery (see Section II-4), but it depends even more on the way the emery is used. To minimize the risk of scratching during smoothing, and in order to use the abrasive efficiently, try always to apply just the proper amount of abrasive and water needed for each wet. Experience in the last analysis is the best guide, but it will be helpful to recite a specific procedure:

Start out always with the disks sponged clean and dried. Pass a hand over both surfaces to be sure no particle remains. Now distribute some wet emery over the lower disk, using a finger to spread the abrasive uniformly over the surface. The volume of abrasive for an 8-inch disk is about equal to that of a large pea. The amount of water added at the start is very important. This is sprinkled from the fingertips onto the work in sufficient amount to produce a bright film of emery; but not enough that if the disk is tilted any excess will run off. Now place the upper disk on the lower, and with only a fraction of the weight of the upper disk bearing on the disk below, make a few preliminary strokes to distribute the abrasive. Immediately one should hear and *feel* the abrasive biting into the entire surface.

If there is too much water, the emery is at once thrown out at the sides; if insufficient water, there forms prematurely a thick purée of worn-out abrasive and ground glass that paralyzes further movement. In either case, the thickness of the abrasive film is not uniform, and abnormally localized pressures may occur that are the cause of most scratches. If the room temperature is about 20° C. (68° F.), the experienced operator can make a wet of fine emery last 8 or 10 minutes without adding more water.

Remember to interchange the mirror disk and tool with each new wet. When the mirror is below, make sure that it rests on a surface that is quite flat and that it is cushioned with a disk of flannel or similar material. Be sure also that the cleats allow the disk a small amount of play. Unless these precautions are taken, the mirror may be strained past the tolerance of surface accuracy that we expect to obtain automatically during smoothing.

II-13. Characteristics of the Smoothed Optical Surface

Above all, we must obtain a uniform surface grain. Pits of abnormal size must not remain. If we examine the surface against a light under a strong eye loupe, we should see only a background of very small abrasive pits, free of scattered bright or dark points. To obtain maximum surface uniformity with each grade of emery, use a generous number of wets, and in case of doubt increase the number recommended in Table V.

Individual pit size is not reduced very much by emeries finer than about 40 min. In general, working with glass on glass, this only multiplies the risk of scratching without in fact making the subsequent polishing easier. Even with an exceptionally fine and uniform emery such as American-Optical M305 (grain size about 2 to 5 microns), there remain always a few widely scattered pits that take as long to polish out as the entire polishing operation on a surface smoothed only with M303 1/2 (grain size 10 microns). In the latter case the pits are merely more uniformly distributed.

The last wet with 40-min. emery receives special care. The mirror at this time is in the *lower* position. The experienced operator at this point can reduce the size of the emery grains gradually by prolonging the life of the single abrasive charge to perhaps 12 to 15 minutes. The addition of more water in the process is indispensable. The procedure is touchy, however, since the disks must not become too dry. Droplets of water merely

sprinkled from the fingers may be too large; a light, uniform spray from a small atomizer or a spray spattered off a small stiff brush is better. The disks are not separated, but only offset from each other as the water is applied. The wet is terminated with the emery as dry as possible, with the hands applying only normal pressure in order to avoid binding as the emery layer becomes very thin. At no time is the stroke forced, lest the surfaces be distorted.

The beginner will do best to avoid this "refining" process. He should be content instead merely with a longer-than-normal wet (mirror in lower position) without the addition of extra water.

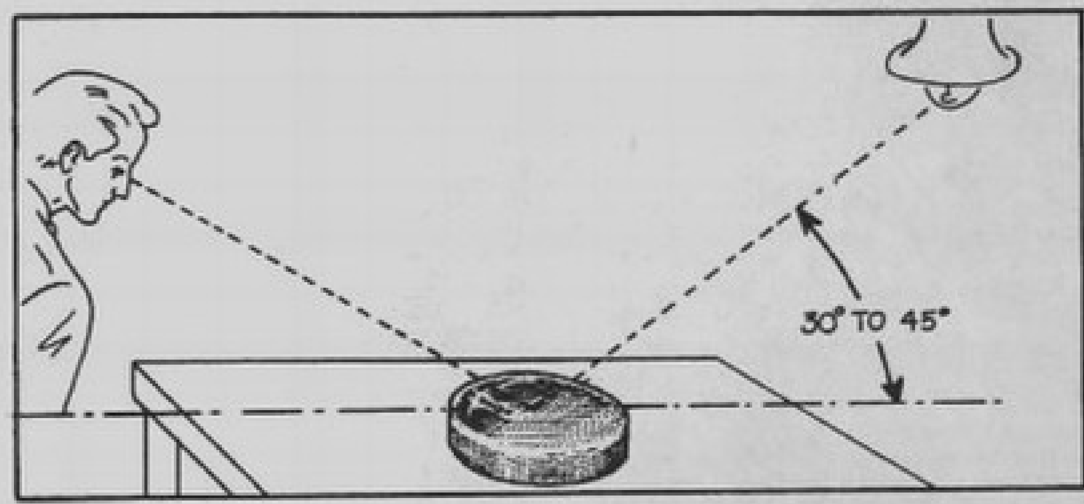


Fig. 22. Reflectivity test for a smoothed surface.

Lord Rayleigh showed that any smoothed optical surface will reflect an image if viewed at a suitable glancing angle. The smoother the surface, the farther this angle may be from the horizontal. A properly smoothed surface will reflect a pale red image of an incandescent filament (placed against a dark background) at an angle of 30° to 45° (Fig. 22). The test is not conclusive, however, since the surface may be made reflective, even at normal incidence, by a kind of superficial planing or buffing, for example, by grinding with a very completely worn-out emery, or by smoothing it with emery on a pitch lap (so-called prepolishing). The test does not guarantee that between portions of the surface that are level enough to reflect an image, there may not exist pits too deep to remove by polishing. A merely glossy surface must not be confused with a polished one.

II-14. Pitfalls in the Smoothing Operation

Scratches. To remove even a minor scratch requires returning to 10-min. emery; whereas a serious scratch, caused, for example, by a large carbo grain or similar misfortune, requires returning even to 5-min. or 2-min. emery. The emery is itself sometimes at fault. Unfortunately, it is not always possible to improve a commercial emery by repeated washing and decanting. If failure persists, it is best to try a new source of supply, or to profit, as many do, by joining an amateur group and gaining access to better working materials.

Seizing. On very rare occasions, working with emery, tool and mirror disks may lock together (we have never known this to happen at the Astronomical Society workshop). The possibility arises when we try to wear the emery extremely thin. Separating the locked disks may be difficult. The use of any brute-force method is obviously precluded. R. W. Porter has suggested using a woodworking clamp to press together the decentered outer edges. The introduction of kerosene between the disks is also considered helpful,[22] though opinion here is divided.

Incorrect Surface Figure. This is the most serious of possible failures in smoothing. A hyperbolic smoothed mirror, for example, is quite hopeless. If the reader continues for a sufficiently long time the normal stroke described earlier, especially during fine grinding, he will surely not arrive at such a figure. If at the start of polishing he notices that either the edge only, or the center only, of the mirror becomes brighter, he should discontinue polishing and return to fine grinding, starting with 20-min. emery and using only strokes that do not appreciably exceed one-third the mirror diameter.

II-15. The Polishing Lap

The cloth lap, widely used in making spectacle lenses and various inexpensive optics, produces a "lemon-peel" surface that cannot be tolerated in precision optics. Early optical workers, notably Foucault, the Henry brothers, amateurs like Vincart, and certain makers of field glasses, obtained good optical surfaces with the *paper* lap, but this has fallen into disuse. The paper lap does not easily produce a complete polish, and it takes long experience to turn the method to good account. Moreover, small-scale surface defects left by the paper are quite severe (Fig. 41*B*). Another polishing tool often used by beginners and worth mentioning is the H. C. F. (honeycomb foundation) lap conceived by the amateur A. W. Everest.[23] H. C. F. is a commercially marketed embossed beeswax sheet used for starting honeycomb in beehives. The wax sheet is either cemented to the tool surface previously used for smoothing, or else shaped against the mirror face and backed with plaster. A fine blade is drawn across the thin-walled cells to help distribute the rouge and improve contact. The H. C. F. lap polishes rapidly and with minimum scratching. Unfortunately, it also has serious shortcomings. First, it produces severe periodic "ripple" on the mirror, the spacing of which approximates the H. C. F. cell separation. The individual defects are quite serious and may diffuse appreciable light

[22] *Amateur Telescope Making II*, p. 507. Scientific American, Inc., 1954.

[23] *Amateur Telescope Making I*, p. 149. Scientific American, Inc., 1951.

even when the physical polish appears perfect (Fig. 41*A*). Second, in inexpert hands, the method can generate a catastrophic overall figure. The beeswax, being relatively rigid, merely wears; it does not flow and conform automatically to the mirror surface.

For the past fifty years the polishing tool used almost exclusively by professionals and amateurs alike has been the *pitch lap*. In industry, in the manufacture of medium-precision optics by machine, the lap is usually a single piece of pitch, and the pitch is modified by the addition of less deformable ingredients such as wax or other material.

For large precision surfaces, however, where the lap must conform more exactly, the polishing tool is assembled from squares of pure pitch. Many amateurs merely make the lap in one piece and then cut a rectangular grid of channels, but it is much better to prepare a quantity of pitch squares and attach these individually to the tool. This has been the technique of such pioneers as Alvan Clark, Common, and Ritchey. The method lends itself much better to the making of a perfect lap—an important factor in successful mirror making. We shall hereafter concern ourselves exclusively with this type of tool.

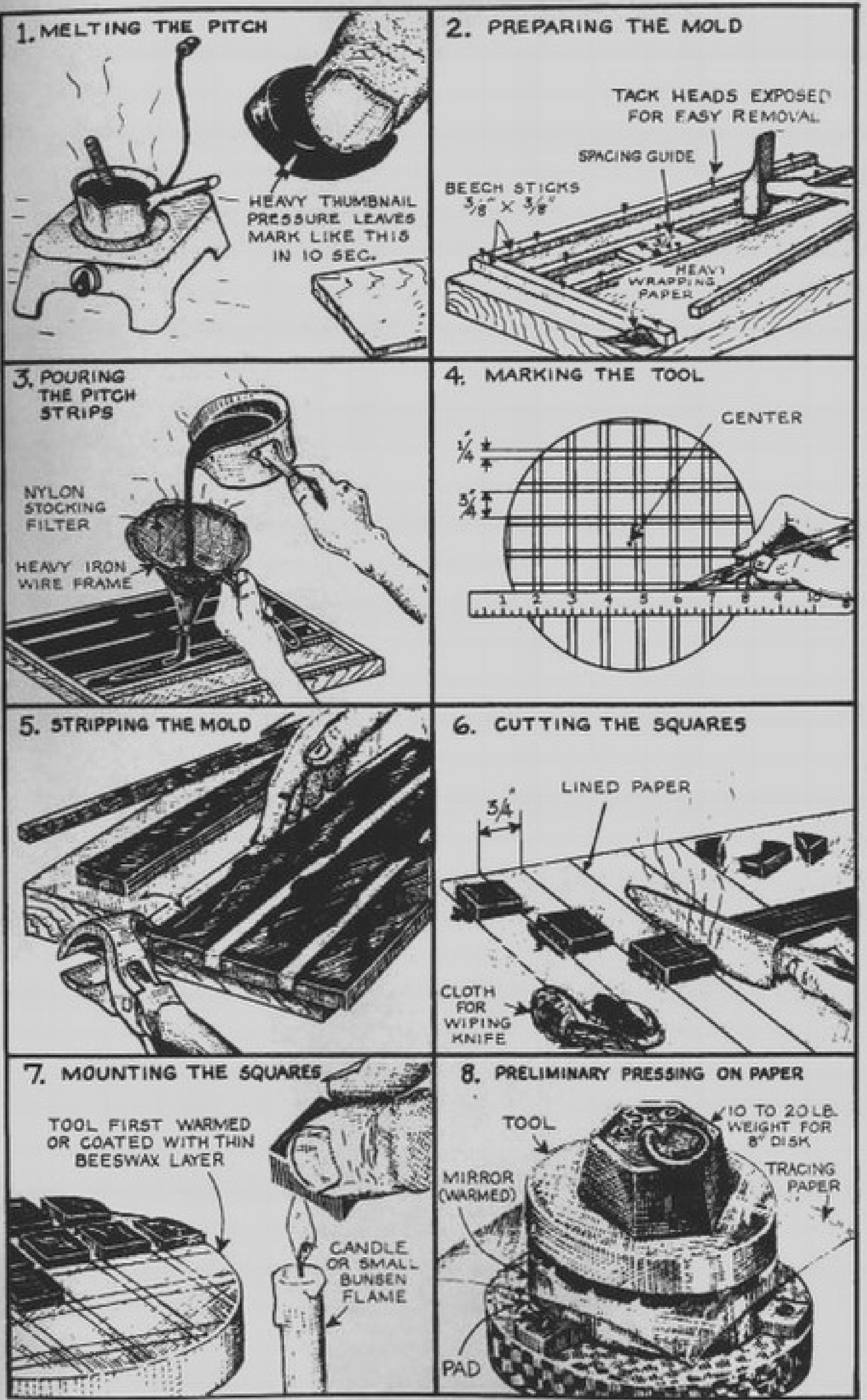
II-16. Making the Lap

(The following paragraph numbers correspond to numbering of the illustrations in Fig. 23.)

1. Melting the pitch. Break the pitch into medium-sized pieces and melt these slowly in a pan over a small flame. If a test has shown that the pitch was initially too hard (see Section II-5), add a few milliliters of turpentine when melting is complete, in sufficient amount that a cooled piece can be indented under strong pressure of the thumbnail. If the thumbnail initially penetrated easily, however, heating is now continued long enough (several hours if necessary) to eliminate a portion of the natural solvents. Spoon off a sample every 15 minutes, cool it at least 5 minutes in water at polishing room temperature (normally 65° to 70° F.), and apply the nail test after each sampling.

2. Preparing the mold. While the pitch is being heated, prepare a mold in which may be cast several pitch strips, $^3/_4$ inch wide and $^1/_4$ or $^5/_{16}$ inch thick. Any available board will serve as a base. Over the board spread a sheet of heavy paper smooth enough (on one side at least) to prevent the cooled pitch from sticking strongly, then tack down the maple, beech, or birch separator strips. It is helpful to make the mold large enough to furnish two laps.

3. Casting the pitch strips. If the pitch contains particles of any appreciable size, they are best filtered out. Make a pouch of a fine-mesh fabric, for example, a silk or nylon stocking, and stretch this over a heavy wire frame. The pitch should be hot enough to flow almost as freely as water. If the pitch is a batch recovered from previously used rouge-coated



tools, any small bubbles contained in the melt should be eliminated. Level the mold accurately end to end, and pour the pitch in flush with the top of the separators. Avoid overflow as much as possible. If a Bunsen burner is available, eliminate surface bubbles by playing the flame on the surface before the pitch cools.

4. *Laying out the lap.* While waiting for the pitch to cool, mark out on the convex tool surface (used earlier to smooth the mirror) the positions of the pitch squares.[24] Avoid centering the pattern on the tool, since this may introduce systematic zonal errors.

5. *Stripping the mold.* When the pitch has cooled thoroughly—3 or 4 hours at least—the mold may be stripped (if very cold, the pitch separates with particular ease). With care to avoid breaking the pitch, remove all the nails, then sharply strip away the paper backing. Next, separate the wood strips from the pitch by gripping them each in turn at one end with pliers, and applying a slight but sharp twisting motion.

6. *Cutting the squares.* This is simple, if the knife is hot enough to avoid sticking in the middle of a cut. It must not be hot enough, however, to melt the pitch appreciably at either side. With good technique, four or five squares are cut without reheating or wiping the blade.

7. *Assembling the lap.* Pitch adheres firmly to glass only if the surface is quite dry and moderately warm. The tool is heated by immersing it in hot water, then wiping thoroughly. At the Astronomical Society workshop, however, we have preferred the following method: A thin layer of rather hot beeswax is spread rapidly over the cold tool. The applicator is a blade of wood wrapped with three or four turns of cloth. The wax adheres well to the cold glass, and the pitch likewise to the cold wax. The wax acts also as a kind of shock absorber, protecting the glass from the fine-edged chisel that we shall use to trim the pitch squares.

To attach the squares to the tool, hold them 3 or 4 seconds against a candle flame (or better, next to a small Bunsen burner flame) until a drop of pitch almost, but not quite, runs off. Apply the square immediately to the tool, position it accurately, and apply gentle pressure for several seconds.

8. *Pressing.* The thickness of the squares now forming the lap may vary by $^1/_{16}$ inch or more. It may be helpful to equalize these somewhat by trimming with a sharp chisel; also to shave off any pitch that has domed upward from squares cut with too hot a knife. The partial squares that lie at the edge of the tool are cut approximately to shape as required.

For preliminary pressing, the tool is warmed very slowly by prolonged exposure some distance from a uniform, gentle source of heat. The pitch

[24] For a large mirror, say a 12-inch, where the tool becomes too heavy to handle conveniently in polishing, a substitute support for the lap may be made as follows: wrap a heavy paper retaining strip around the mirror (concave face upward) and cast a plaster disk which for a 12-inch mirror will be about 2 inches thick. Allow the disk to dry at least 3 weeks, and then apply two coats of shellac to seal the plaster against further moisture absorption.

must not become warm enough either to deform or run, but only warm enough to permit easy penetration of the thumbnail. It is best to preheat the mirror also by immersing in water not above 35° C. (95° F.), remembering always to dry it thoroughly afterward. On the mirror, mounted face upward in the cleats, is first placed a sheet of tracing paper or a smooth piece of silk, then the heated tool. With a weight of 7 or 10 pounds placed on the tool, warm pressing may take about 15 minutes. Two or three consecutive pressings are sometimes useful, but care must be taken never to compress the squares so that their edges touch. This would make the tool *quite useless*. If this happens, then the pitch is softer than anticipated, or the room temperature is too high (for example, 85° F.), or the mirror and tool have been overheated. Sometimes the edges only of one or two squares come dangerously close. Before pressing is continued, these edges are eliminated by cutting vertically with a sharp wood chisel. We shall refer again to the trimming operation later; when the tool has been used for a while, all of the squares will be trimmed in a like manner.

The tracing paper leaves a matte surface on the pitch indicating the areas of contact. When nearly the full surface of all the squares is found to be making contact, we proceed with *cold pressing*. The tool is applied *directly* on the mirror, the latter being uniformly coated with a little polishing rouge and water in quantity sufficient merely to cover the surface. Cold pressing is continued at least a half hour before we may proceed with polishing.

II-17. Polishing Conditions and Requirements

In order of relative importance, the attributes of an ideal polishing environment are the following:

1. Suitable room temperature. This should be near 20° C. (68° F.). It is difficult to adapt pitch to a truly satisfactory working condition at temperatures either below 15° C. (59° F.) or above 30° C. (86° F.).

2. Steady temperature. Preference should be given to a northern exposure and to a work area enclosed by heavy walls. Drafts and nearby sources of heat are avoided.

3. Suitable humidity. Excessive humidity inhibits evaporation and therefore interferes with the normal course of a "wet."

4. Cleanliness. Avoid dusty, hard-to-clean areas.

5. Suitable lighting. Use natural lighting if possible—the brightest available.

In practice, of course, no actual work area may satisfy all these conditions. The requirements listed are not mandatory, however, but merely desirable. The worker therefore makes the best possible compromise. A cellar may be desirable for its uniform temperature, but this is outweighed by the disadvantages of the cold, dust, and damp. At the risk of precipitating strife in the amateur's home, the author suggests the kitchen as a better place. There one finds a maximum of conveniences: water, gas, easily cleaned tile surfaces. It will be reassuring to the reader, however, to know that excellent mirrors have been made under working conditions undesirable from every point of view. For example, the first work of the Astronomical Society was carried out directly under a sheet-zinc roof. The polishing room now used by this group is shown in Fig. 24A

Before beginning polishing, note the following again carefully:

1. The importance of high-quality rouge (Section II-5).

2. The importance of pressing the tool sufficiently (at least a half hour if room temperature is about 65° F.).

3. The importance of cleanliness at the work post and accessory table (suitable covering, washing, replacement of paper).

Fig. 24A. Four-post polishing room at the workshop of the Instrument Group.

During polishing, it is best to restrict to a minimum the objects that are handled: the mirror, tool, rouge jar, and applicator brush. Provide a basin, large enough to permit complete immersion, in which the mirror may be warmed or cleaned. Reserve a fine sponge for mopping rouge. A supply of white cloths, softened by repeated laundering, is useful for drying and cleaning the mirror. A light cotton fabric is best. The tool may be washed after each work period with the slightly damp rouge-sponge. It is then left to dry without wiping of any kind.

If the workroom temperature is somewhat low, for example, 55° or 60° F., it is *essential* to warm the mirror and lap slightly. This must be done *in depth,* not superficially. For the mirror, a good method is a 10- or 15-minute immersion in warm water (85° F.), followed by drying. The tool would be difficult to dry if warmed this way; instead we set it up in front of a gentle source of heat and warm it very slowly and uniformly. Then comes a preliminary pressing, but this is short—10 or 15 minutes only—so that polishing may begin before the disk has quite cooled. Thereafter the heat generated by the work itself should suffice to maintain proper temperature conditions.

Some of these precautions may seem arbitrary, even contrary to "common sense." The reader must be warned in this connection that psychology plays a large and important role in mirror making. If the amateur is to master the situation, he must be aware of this, as of every other relevant factor. The author and his colleagues know from direct experience precisely how the amateur blunders ninety-nine times in a hundred. It is not the confident operator, working by "feel" and accepting facts as he finds them, who falls prey to error. Far more often it is the timid worker, the theorizer. The operator who fears scratches almost instinctively adopts a technique that *favors* scratches. If he strives consciously to avoid heating effects (but reasons incorrectly on the factors that truly affect the mirror), he is almost bound to produce a catastrophic surface. We repeat: making a good mirror is simple, provided one follows recommended procedures; but theorizing about what is taking place, unless it comes "after the fact," is more than likely to be completely amiss.

This much said, we shall try to describe objectively one of the best techniques we know, a technique that has matured out of the experience of several generations of astronomical optical workers. We trust that the reader will respect these recommendations, and that if he has his own (perhaps more enticing) theories, he will refrain from testing them before the mirror is finished.

II-18. The Polishing Operation

For mirrors under 12 inches in diameter, it is optional whether polishing shall be done with the mirror on top or below. The results depend to a large extent on factors difficult to predict: position and size of the hands with respect to the mirror, unconsciously applied pressures, etc. The author personally favors working with the mirror below. Contrary to usual belief, experience shows that the average operator working this way more easily avoids defects at the mirror edge.

If the mirror is below, make sure that it rests on a flat surface. Between the mirror and the support place two flannel disks and an intermediate layer of heavy paper. The positioning cleats provide some clearance, and permit the mirror to be turned every 15 minutes of polishing with respect to this elastic cushion. Shift the mirror always a quarter-turn, but let this vary, systematically making it a little more or less. This procedure,

suggested by A. Couder,[25] is a reliable countermeasure to astigmatism, even when the mirror disk is quite flexible.

Adopt a polishing stroke of normal amplitude, $^1/_3$ the mirror diameter, the same as that described in Section II-12. The straight-line stroke is more easily executed correctly than a curved one such as the figure-eight. But always carefully avoid too regular a stroke pattern, by varying the overhang at either end of the stroke (i.e., varying the $^1/_3$ value, plus and minus), and the number of strokes made for each shift in angular position of the lower disk. In this way, the recommended stroke length and number of strokes are observed only *on the average.* A single operator cannot imitate perfectly a truly random process, as certain studies have shown. We have achieved a much more perfect result at our workshop by engaging four or five different persons, working in rotation, to apply the "same" stroke to the work. Nevertheless, the single operator does quickly and automatically attain a sufficiently irregular stroke, unless at the start he falls into some particularly bad habit or mannerism.

Fig. 24B. Normal polishing stroke for an 8-inch mirror.

Avoid especially any tendency to "waltz" the tool at the end of each stroke, or worse, to stop at the end of each stroke before returning. In general, avoid *jerkiness.* It is best to round off the straight-line motion slightly before reversing direction. The stroke frequency should not be too high—perhaps sixty double strokes a minute. Toward the end of

[25] A. Couder, Thesis (ref. 10), p. 39.

polishing this is reduced even further, in order to minimize the possibility of "ripple."

Polishing is most effective when only a little rouge and water are applied at a time. Fill about one-third the volume of a small jar with rouge, and cover with $^1/_2$ or $^3/_4$ inch of water. The rouge brush may then pick up as needed either mainly rouge, by dipping to the bottom and stirring, or mainly water, by touching the surface only, depending on the needs of the moment. At the beginning, when the lap conforms poorly, relatively concentrated rouge is best. Later, when the tool is more perfectly adapted, a thinner, easier working mix is better. Renewing the charge of rouge takes but a moment. The disks need not even be separated, but only decentered, while a stripe of rouge is painted across the pitch squares or the mirror. Each wet ordinarily lasts only about 5 minutes. If it should last 10 or 15 minutes, then either the rouge and water are excessive, or the work space is too cold or humid.

Toward the end of the wet polishing efficiency picks up considerably. The water has thinned out, the rouge has become incrusted in the pitch, and the tool has begun partly to "wipe" the glass. If one persists with the wet, resistance to movement becomes extreme, and an anguished squeaking arises from the work. In some industrial workshops, a deaf ear is turned to these sounds. The instinctive fear of scratching under these circumstances is misleading; in fact it is precisely this way that fine, gossamer-like "sleeks" can be suppressed and a most beautiful surface polish obtained. For astronomical optics, however, we must use gentler techniques. For an appreciable portion of the polishing process, it is useful to make the wets short in duration; and if necessary a more forceful stroke is used to prevent loss of contact (due to chilly surroundings). At the beginning of polishing the lap may conform poorly despite pressing; it may catch and slip. But if the frequency of the stroke is reduced, the movement being kept as regular as possible, and if a larger charge of rouge is used as required, the active area of the lap will gradually become more uniform.

After an hour of polishing, we should feel a noticeable (though smooth) resistance to the motion of the tool (if not, a supplementary pressing is in order, with slight prewarming of the disks if necessary). The squares should appear uniformly imbedded with rouge and present a matte surface. If they are still black and streaked, it is a sign that polishing is not proceeding well and that (*1*) too little rouge is being used (or too much water); or (*2*) the workroom is too cold; or (*3*) the pitch is too hard.

If the pitch is of a poor quality, so that it does not take the rouge well, a good procedure is that suggested by G. W. Ritchey: cover the pitch squares with a thin layer of beeswax, using a cloth applicator as shown in Fig. 25. Follow with a brief pressing on the slightly warmed mirror, the latter being covered with tracing paper. Never heat a waxed tool in depth, or the wax may yield and slip like a skin over the pitch. Nor should the disks ever be

worked completely dry; the water and rouge both are used more abundantly. The waxed tool polishes more rapidly than bare pitch, but the general surface figure that results is usually less regular, and ripple more pronounced (see Fig. 41*C*).

Even after the first few minutes of polishing, the mirror brightens. If the mirror is in the lower position, the polished area normally advances inward from the edge; if the mirror is above, it is the center that is polished first. A simple way therefore to polish the mirror uniformly over its entire surface is to interchange the mirror and tool occasionally, say every 2 hours.

The efficiency of polishing is improved and, most important, the *surface form is better,* if the work continues long enough to produce steady thermal conditions throughout the mass of the mirror and tool. For an 8-inch mirror disk, $1^3/_8$ inches thick, continue working *at least an hour,* pausing only to renew the polishing. If one can endure 2 to 3 hours of steady polishing, so much the better.

The endurance of the pitch, however, is limited. The squares flatten steadily, growing convex at the side and finally threatening to close together.

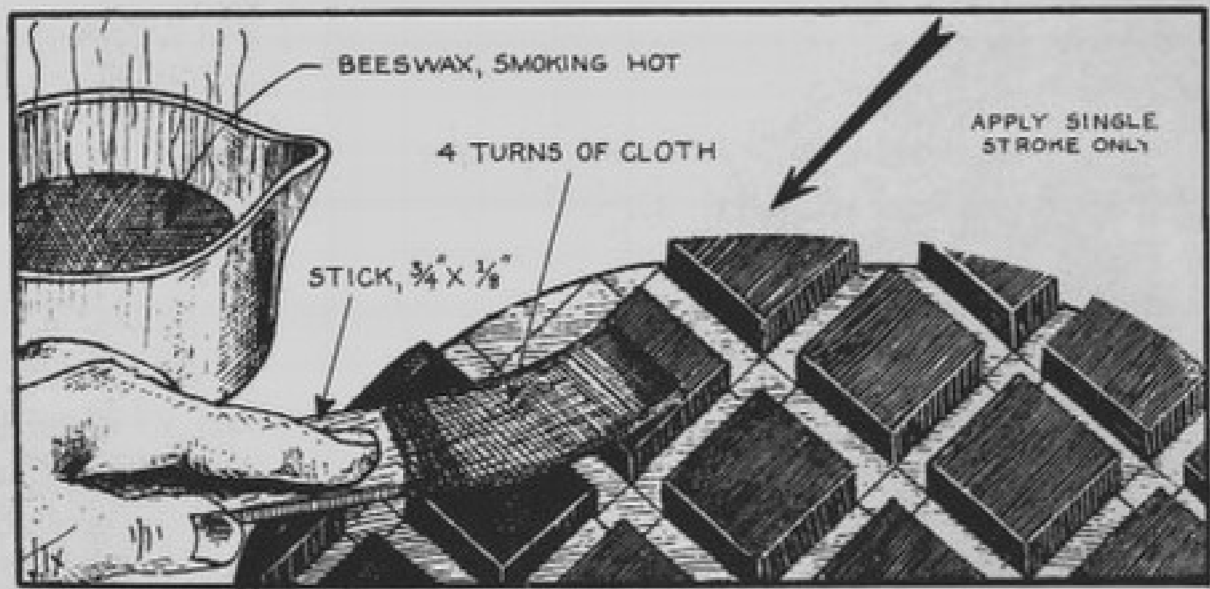


Fig. 25. Waxing the squares.

This must be avoided *at all costs;* otherwise the tool is lost, or one must resort to the inferior method of channeling the solid pitch. At a suitable time, therefore, proceed to trim the squares. The edge of the tool must be acutely tapered and perfectly sharp. The tool may be a chisel with a blade $^3/_4$ inch wide or more, or the blade of a plane or router. Hold the blade vertical and drive with a light stroke. A thick board, aligned with the marks originally drawn on the tool, serves as a guide (Fig. 26). Trim the four sides of each square neatly in this manner without seriously chipping any of the edges. Carefully brush the fragments and powdered pitch onto a sheet of white paper, to reuse them if desired but mainly to keep them from sticking everywhere, especially on the hands and arms. If necessary, use turpentine as a removing fluid. After trimming, and with the lap and mirror at a uniform temperature of about 75° F. (by warming if necessary), cold-press the lap once again. We could use, if need be, a somewhat softer pitch to make the lap conform more quickly, though this might require trimming every hour. On the other hand, if the lap is not much deformed after 3 hours work, it is too hard, and should be waxed, or better, rebuilt with softer pitch.

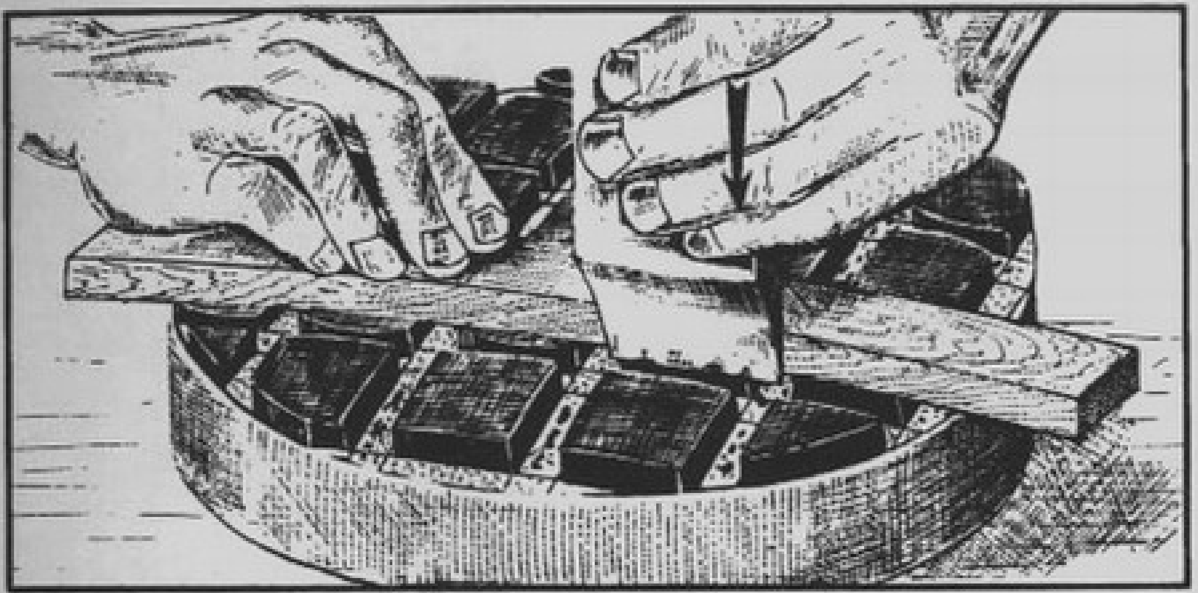


Fig. 26. Trimming the squares.

After 3 or 4 hours the polishing is about half done and the lap has been trimmed two or three times. The squares are thinner and quite uniformly imbedded with rouge. We sense a very uniform adhesion, a kind of heavy lubrication, between the disks. This provides us with extremely valuable information about the regularity and progress of the work. The operator's entire consciousness, as it were, is in "rapport" with the work.

If we represent the degree of polish of a glass surface by the number of pits remaining per square millimeter of surface, we can draw a curve of polishing progress versus time expended (Fig. 27). The curve in the region of interest is nearly exponential. It predicts that we must pay dearly to remove the last of the pits. A very small mirror, worked by any reasonable technique, attains a satisfactory polish in perhaps 4 hours or less. For an 8-inch mirror even twice as long is ordinarily not enough. If at the end of such a time we focus carefully on the surface (with a good eye loupe, unless one is quite myopic), and look at a point near the reflected image of a lamp filament against a dark background, we see a uniform gray veil comprising a multitude of tiny abrasive pits. Depending on whether the grayness is more pronounced at the center or the edge, polishing is continued with the mirror above or below. It is *normal* to work for 15 hours

on an 8-inch astronomical surface before, according to this test, it is completely polished. Allowing time for pressing, trimming, etc., this represents at least three full days work.[26] Preferably, uninterrupted periods

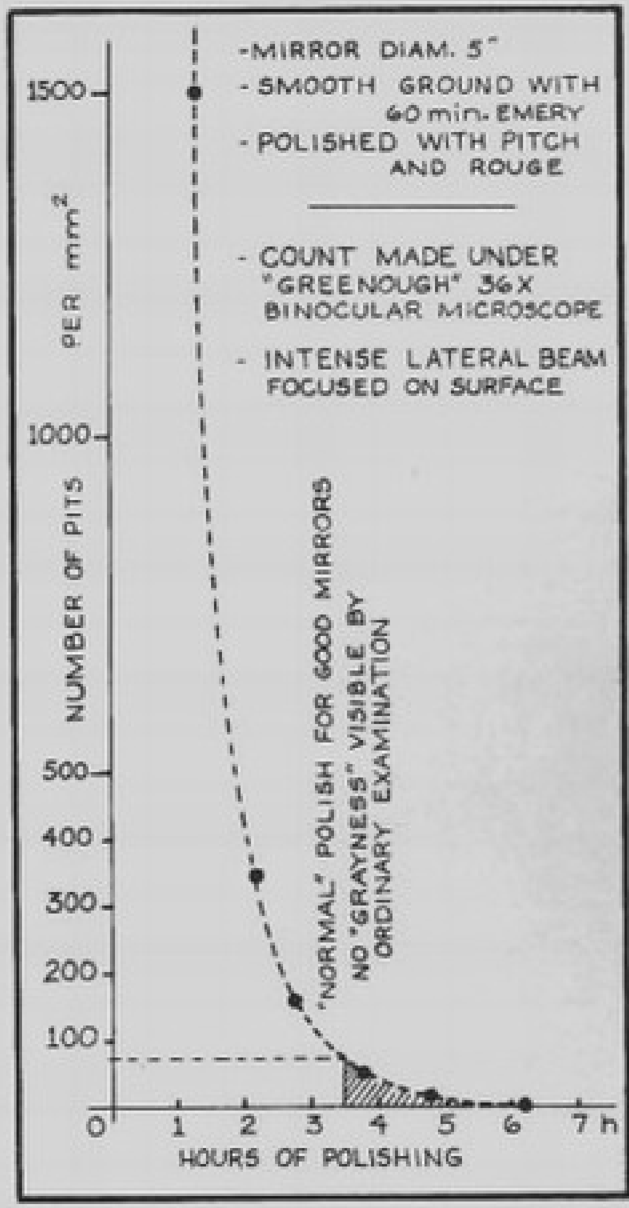


Fig. 27. Improvement of surface polish as function of polishing time.

of a whole or half a day should be available for polishing. In any case, it is certainly useless to attempt less than an hour's polishing at any one time.

If for any reason the prior smoothing operation has not been quite successful, a total of 30 hours, or more, of polishing will not suffice to eliminate completely a certain scattered grayness. This will consist of rather large pits, very thinly distributed, that should be considered irremovable by

[26] Many amateurs, apparently inspired by the feats of certain operators who report polishing a mirror which is 6 inches in diameter in 6 hours time, make it a point of honor to polish like mad. We must point out to this "lunatic fringe" that certain polishing machines (using cerium oxide) will polish a disk of this size in 1 to 3 *minutes*. The polishing of astronomical optics, however, is quite a different affair.

polishing. The novice especially is susceptible to this misfortune. But it is not a reason for despair. Scattered pits, grayness, sleeks, or even actual scratches, if not too large or numerous, have practically no effect on the quality of the diffraction image. The question, of course, is how much light such defects will scatter, and here we find that the amount is negligible compared with the total light received by the mirror (except in special observations, for example, the solar corona, or occultation of a very faint star by the bright lunar limb, or viewing the companion star of Sirius). We also remind the skeptics and perfectionists that the four blades supporting the secondary mirror behave exactly like four enormous scratches on the mirror—yet everyone reconciles himself easily enough to this. Moreover, those who frown on "grayness" should begin by removing carefully all the dust on their own mirrors.

II-19. Completion of Polishing

As we complete the polishing operation we may consider two alternative situations:

1. The amateur has modest ambitions. He wishes merely to complete his mirror in the simplest way possible. Assuming he is satisfied with a 6-inch disk and a focal length long enough to make parabolization unnecessary (Section II-1), he may, *if he must,* dispense with all testing. By applying carefully and intelligently the principles given earlier, he would have a fair chance of obtaining automatically a useful spherical mirror.

2. The amateur wants a truly perfect mirror. In any case he wants an 8-inch, *f*/6 mirror of parabolic figure, and this cannot reasonably be obtained by chance alone. Optical testing and retouching are indispensable.

The second alternative is much the more interesting. We have avoided discussing testing and retouching earlier because it is unwise for the novice to test a mirror before it is nearly completely polished. If he should observe prematurely that the surface form is good, he will not dare continue polishing and may remain content with a very "gray" mirror. Or if he sees a defect, he may attempt retouching, usually with unfortunate results, and follow this with attempts even more disastrous. From that moment he is lost. His mirror will never be either well polished or quite satisfactory in form. If instead he had continued polishing steadily, adapting and acclimating the tool perfectly in the process, he would have reduced major surface irregularities *automatically.* The surface would have been easy to parabolize, and the promise of success excellent. The author remembers painfully his first mirror, a 10-inch, *f*/7, which he completed only at the cost of eighty retouching steps and a total of 20 days work. Many amateurs have written the author telling of 200 hours of figuring on a 6-inch mirror! We wish to spare our amateur friends such trials of endurance. Actually, if the principles we teach here are properly applied, *a polished mirror is a nearly finished mirror.* It is difficult to overemphasize the importance of a regular surface form at the start of figuring.

II-20. Surface, Wavefront, and Image Errors

An error in the mirror surface and the corresponding errors in the wavefront and the image are merely different aspects of a single phenomenon. Given the magnitude of one, we can easily calculate the magnitude of the others. This is not meant to imply that all these errors are comparable in magnitude. Defects in the surface and in the wavefront are expressed in *hundredths of a micron,* but corresponding image errors, when measured as transverse beam deviations, are *whole microns,* and when measured as longitudinal deviations, are *millimeters* in magnitude (Fig. 28).

Obviously, we can measure an error most precisely where it exercises the largest effect. This is the basis of our preferred test method. For the amateur, certainly, who has no precision optical reference surfaces, it is the method of choice.

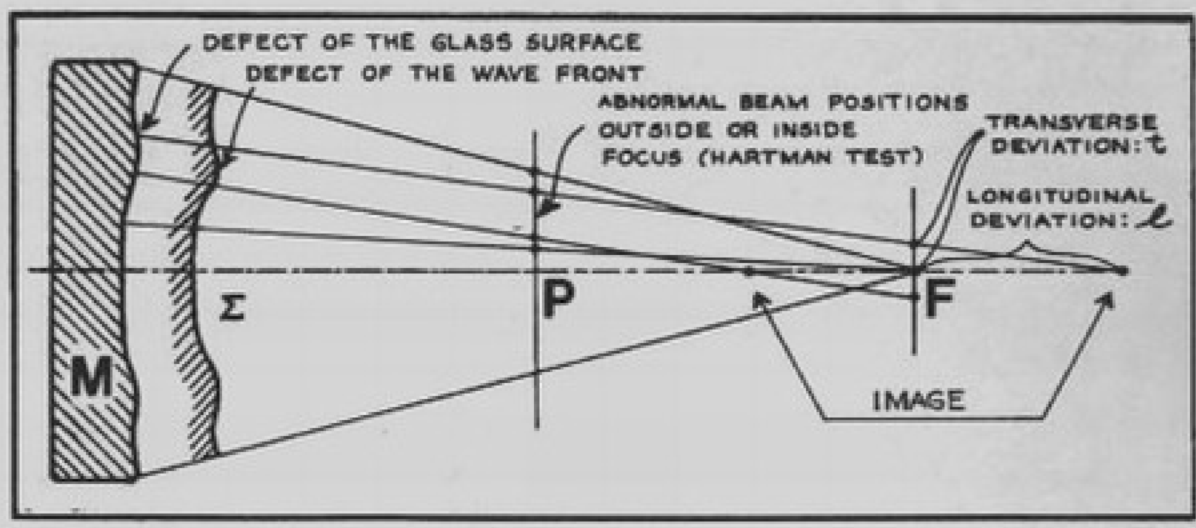


Fig. 28. Principal means of access to surface defect measurement.

II-21. Review of Possible Test Methods

We may eliminate at the outset any method of direct measurement on the glass. Mechanical gauging and optical comparator methods are not even remotely sensitive enough. Nor can we consider, for 8-inch or larger astronomical elements, use of the interference method (widely applied in industry) that positions the surface to be tested in near contact with an optical reference disk.[27] This test, moreover, involves a vicious circle: the reference element must itself first be checked against another reference, etc.

[27] We discuss this method later in some detail, relative to testing the flat diagonal mirror (*see* Section III-4).

Optical methods that measure defects of the *wavefront* are somewhat more feasible. A Michelson-Twyman interferometer[28] of sufficient size, for example, would serve, but this is out of the question here; its cost is several thousand times that of our mirror. The Michelson interferometer method,[29] on the other hand, does not demand an expensive reference piece. The sphericity of the wavefront is examined directly, using a screen pierced with two apertures, one fixed (at the center of curvature, theoretically), and the other movable to explore the surface of the mirror. The two relatively small apertures produce a large diffraction spot that is traversed by interference fringes (Young's two-hole diffraction effect). If the optical path remains unchanged as the moving spot explores the mirror, the central fringe remains fixed; if the path changes, fringe-shift is a direct measure of the wavefront error. But the magnitude of error which interests us (of the order of a micron) is much too small to measure accurately this way. One is limited by imperfect stability of the interferometer supports, and the fact that readings under a microscope can be made only with limited precision.

The method of Leon and François Lenouvel[30] offers the advantage of direct interferometric measurement without some of its inconveniences. Interference is produced by an arrangement comprising a Michelson beam-splitter, or Wollaston prism, and two Nichol prisms. The beam splitter is in the immediate vicinity of the image, and therefore may be of small dimensions. Nevertheless the apparatus is expensive, and amateurs will make little use of it.

In practice, then, it is the *image*-testing methods that are the most important. Direct inspection of the diffraction image, in and out of focus, has no doubt been practiced almost as long as telescopes have existed. H. Dennis Taylor has elaborated the method and described it in detail in a brochure published by the Cooke lens makers.[31] The method is very useful for the astronomical observer, but for the optical worker its value is limited, because it does not indicate directly either the magnitude or position of the defects.

In the Hartmann method[32] a perforated screen is placed in front of the mirror, and two direct photographs are taken, one on a plate positioned inside the focal plane, the other on a plate positioned outside. From these may be determined with great precision the points of intersection of isolated pairs of rays coming from mirror positions symmetrical with the axis. The data are extremely reliable, but the method is feasible only for final testing of large optical pieces. Advanced amateurs undertaking to test a 20-inch

[28] F. Twyman, *Phil. Mag.*, [6th Ser.] 35, 49 (Jan., 1918).
[29] A. A. Michelson, *Astrophys. J.*, 47, 283–288 (1918).
[30] Léon Lenouvel and François Lenouvel, *Rev. opt.*, 17, 350–361 (1938).
[31] *The Adjustment and Testing of Telescopic Objectives.* T. Cooke and Sons Ltd., Buckingham Works, York, 1921. Re-printed 1983.
[32] J. Hartmann, *Z. Instrumentenkunde*, 24, 1–21, 32–57, 97–117 (1904).

mirror can study with profit a beautiful example of the method applied to the 32-inch at the Observatory of Haute Provence.[33]

It is to Leon Foucault,[34] however, that we owe the most useful of all test methods—the method from which nearly all the other image test procedures have been derived. The Foucault *knife-edge* or *shadow test* is the most remarkable of all for its sensitivity and simplicity. We shall discuss it in detail later, but summarize it here briefly. A sharp, opaque vertical edge is inserted in the beam close to the image plane. The operator's eye, positioned behind this edge, views the mirror. Any lateral displacement of the rays from their normal position is translated into a shadow appearing on the defective area. The impression is striking: one appears to see the defects in true relief, as though the surface were illuminated by grazing light and the defects amplified about a million times! Figure 29*A* is an example of a Foucault shadowgram. The density of shadow is determined by the *slope* of the actual reflected wavefront at any point with respect to the ideal wave whose center lies at the knife edge. To calculate the height of the defects, we could, if necessary, determine the various slopes and graphically join a series of lines of corresponding slope end to end to give a quantitative picture of the mirror profile. Mathematically speaking, we "integrate" the slope curve by this process. Actually, this operation is useful only at the end of figuring, when we must be sure that residual defects lie within tolerable limits. With a little practice the operator need in fact only glance briefly at the shadow pattern to obtain, during figuring, *exactly* the information he needs to apply a correction. To have merely the numerical data on the other hand—so many millimicrons of glass to be removed at such and such a point—is of little practical value. It cannot suggest how the tool shall be modified, nor the duration of the corrective step, nor the kind of stroke to use. The point deserves emphasis because so often the judgments passed on test methods are made by theoreticians who have not themselves made a single mirror.

The method of inserting a ruled screen near the focus, also originated by Foucault,[35] was subsequently further developed by V. Ronchi[36] and L. Lenouvel.[37] The screen is marked with alternately opaque and transparent spaces of equal width. If the wavefront is accurately spherical, the shadows formed by the multiple "knife edges" of the screen appear as straight lines; if there are errors, the shadows show corresponding distortions (Fig. 29*B*). Unfortunately, if the screen has more than merely a few lines per millimeter, interference effects occur that are inseparable from the effects to be observed, and interpretation becomes difficult and unreliable. It is not surprising

[33] A. Danjon and A. Couder, *Lunettes et Télescopes*, Section 115.
[34] L. Foucault, *Compt. rend.*, 47, 958 (1858); reprinted also in *Classiques de la Science II*, Armand Colin.
[35] References cited.
[36] V. Ronchi, Ann. *école normale sup. de Pise*, 15; *Rev. opt.*, 5, 441 (1926); *ibid.*, 7, 49 (1928).
[37] L. Lenouvel, *Rev. opt.*, 3, 211–243. 315–333 (1924); *ibid.*, 7, 395 (1928).

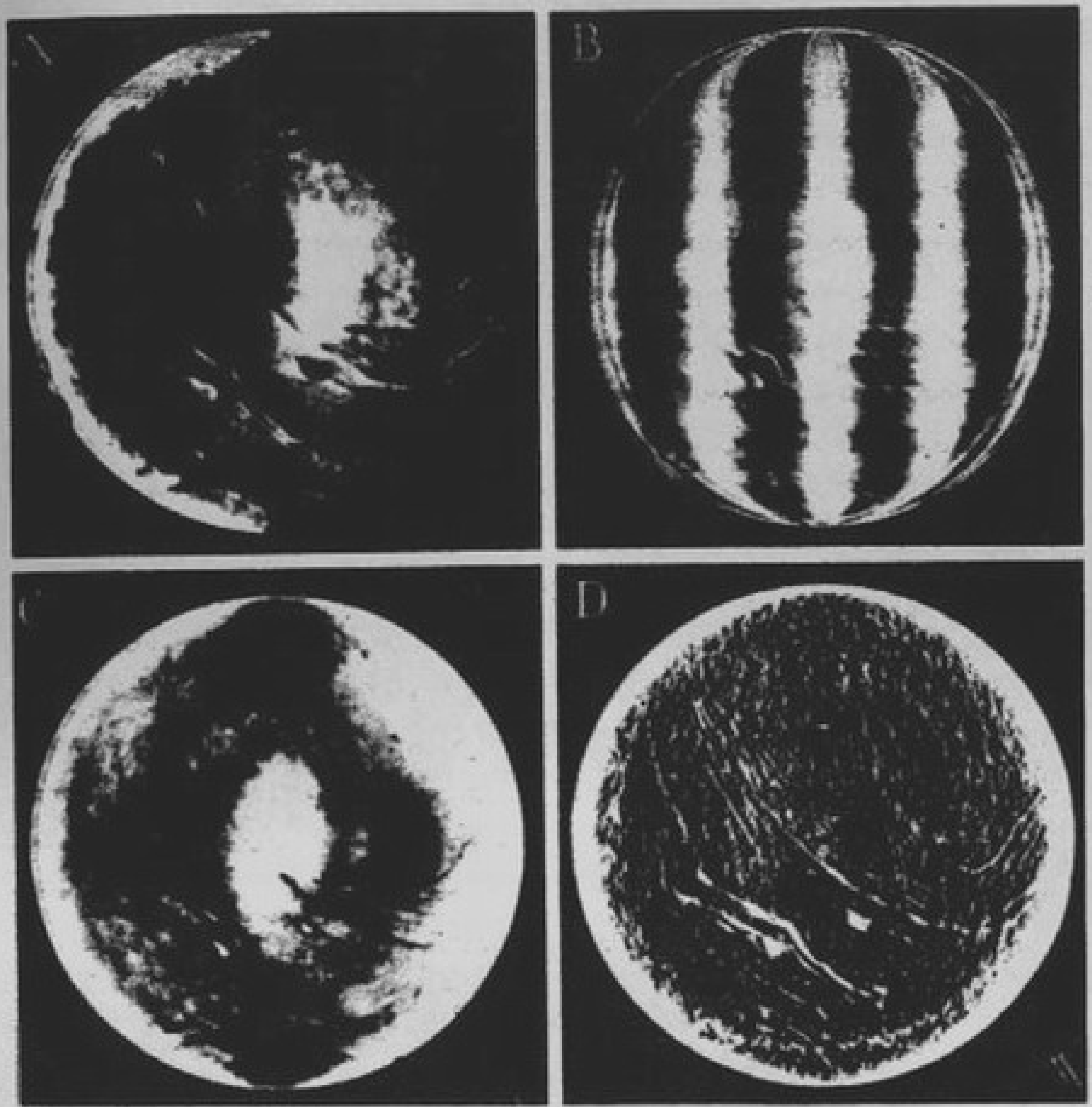


Fig. 29. Four methods applied to testing of the same small mirror, showing a variety of defects (diameter 125 mm.; radius of curvature 2 m.; polished with HCF). *Large-amplitude defects*: Turned-down edge; astigmatism; central depression of ⅛ wave (depth on glass surface 0.035 μ). *Defects of medium amplitude*: Micro-ripple caused by HCF (average depth on glass: 100 Å. or 0.01 μ); veins of varying hardness in the glass. *Small-scale defects*: Micro-ripple (average depth 40 μ). (A) Foucault test: Slit width 10 μ; knife edge at the right. (B) Ronchi test: Slit width 40 μ Line spacing on test grating: 5 lines per mm. (grating 14 mm. inside focus). (C) Zernike test: Slit width 10 μ. Phase plate:166 mμ (0.4 mm. inside focus). (D) Lyot method: Slit width 450 μ. Phase plate: partial aluminum film, optical density 1.7. The combined defects do not seriously alter the normal diffraction image and would pass quite unnoticed when observing a star at the focus.

therefore that the method commands little enthusiasm among optical workers, notwithstanding the reams of theory that have been devoted to it. It remains useful, however, as a rapid test for the stigmatism of camera objectives and such other small lenses as can be tested with coarsely ruled screens and relatively wide light sources.

F. Zernike[38] has derived an astonishingly beautiful test by modifying the Foucault method to take into account the vibrational nature of light. Instead of an opaque edge, it uses effectively a circular *wave plate* small enough only to cover the central diffraction spot, and of such thickness as to cause a phase displacement of 90°. If mirror imperfections exist which deflect light rays outside this spot, then by diffraction these rays will form spectra laterally displaced from the image center. These spectra and the central phase-displaced image partially interfere; as a result, phase variations in the wavefront are translated into the appearance of brilliant variations of color and intensity at the mirror surface. The photograph we show here (Fig. 29*C*) does poor justice to the method. We have photographed such images in full color, and regret we cannot reproduce them here. The method has found its widest application in the now-famous technique of phase-microscopy. Its usefulness in testing astronomical optics is more limited. Interpretation of the results is difficult, and to apply them reliably requires a precise understanding of how the rays are altered in undergoing 90° phase displacement at the focus.

We must mention finally the phase contrast technique developed by B. Lyot,[39] though it is of only indirect interest to the amateur. It is applicable to surface defects that are small in area and of extremely small amplitude, but which, because of their large number, may diffract appreciable light throughout the field of view. The test source is a relatively wide slit (100 to 200 microns, for example) intensely illuminated (e.g., with a high-pressure mercury-vapor arc). The normal image of the slit traverses a phase plate that simultaneously produces quarter-wave retardation and reduces the intensity by a large factor, say 1000. A wide-aperture camera lens behind the phase-plate is focused on the mirror and receives both the light of the phase-retarded, attenuated image and the light which, diffracted by mirror defects, passes unaltered to the side of the phase-plate. It is possible to photograph with a 15 per cent contrast defects that deviate from the mean surface by as little as 1 Angstrom. The method is selective; it makes visible merely the relatively narrow defects (under $^1/_8$ inch wide) which alone can diffract light outside the phase-plate area (compare Figs. 29*A* and 29*D*). We shall later show some other applications of the method (Sections II-34 and VII-3).

All the tests that involve introducing an element, opaque or other-

[38] F. Zernike, *Monthly Notices Roy. Astron. Soc.*, 94, 377–384 (1934); *Physica*, 1 (No. 8), 689 (1934).

[39] B. Lyot, *Compt. rend.*, 222, 765–768 (April, 1946).

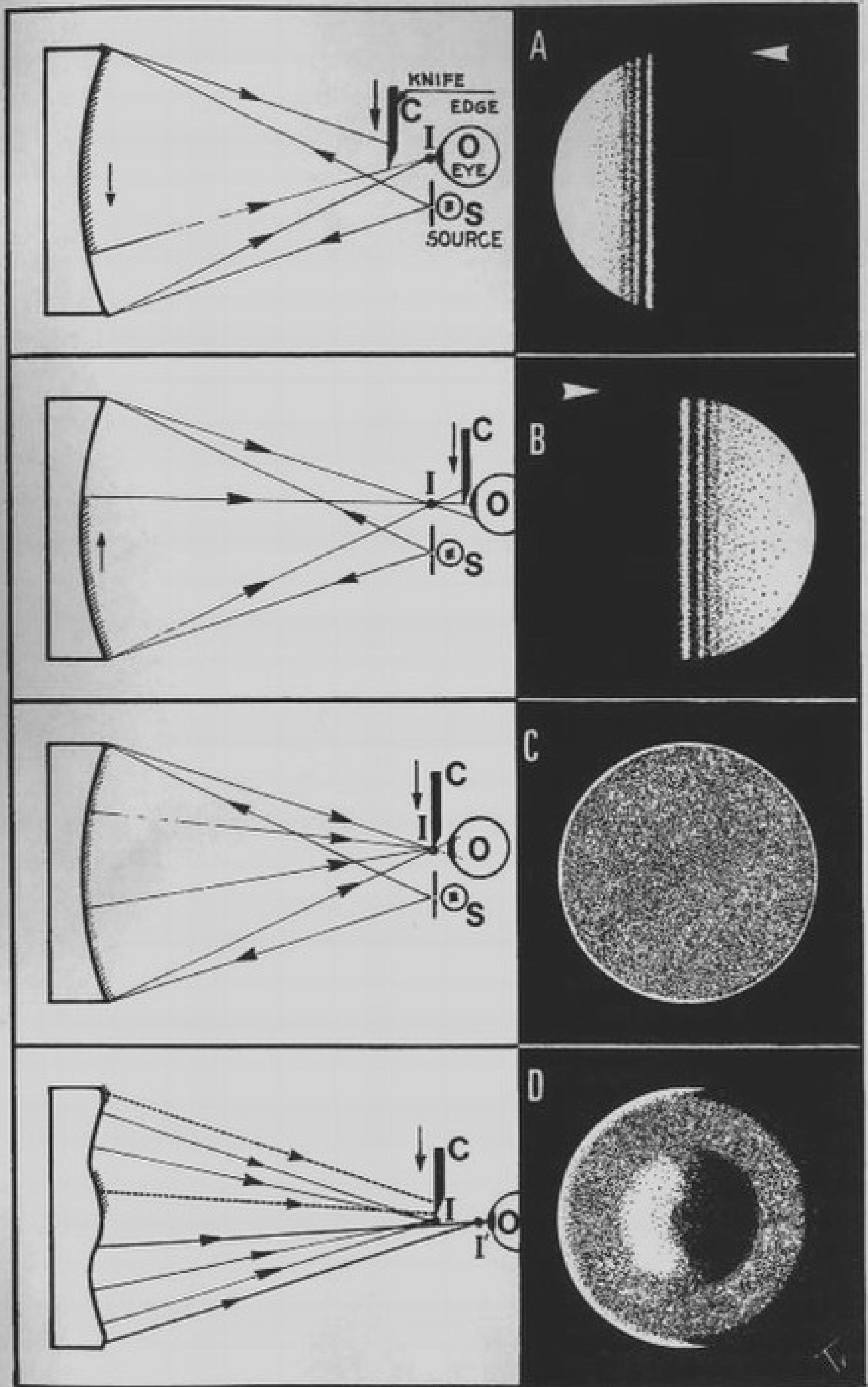


Fig. 30. Geometrical explanation of the Foucault test.

wise, near the focus may be made by slightly modifying a single apparatus. For example, it is possible to employ the photographically ruled screen used to make Fig. 29*B* (5 lines per millimeter) for four different tests (though not all under optimum conditions, of course):

1. The normal Foucault test—by using a single line at the focus.

2. The Ronchi test (Fig. 29*B*).

3. The Zernike test—by utilizing the phase displacement produced in a single line (probably the effect of different gelatin thickness, and perhaps also refractivity, in the photographically exposed area).[40]

4. The Lyot test, by enlarging the slit.

II-22. Nature of the Foucault Test

The mirror is positioned on its support with the optic axis horizontal. At the center of curvature is provided an "artificial star" *S*, i.e., a source of which the horizontal dimension at least is very small (Fig. 30). The mirror is polished but still lacks a reflective coating; however, the reflection is sufficient to give an image *I* of the source *S* bright enough to permit testing. If we position the source exactly at the center of curvature, the image formed by the reflected rays coincides with the source, and therefore is inaccessible. Accordingly, we displace the source slightly to one side of the axis. By the basic laws of reflection, this causes the image to shift an equal amount in the opposite direction. The eye is positioned immediately behind the image *I*. Assuming (as in our standard mirror, for example) that the angle of the cone of rays is not too large, the surface of the mirror appears fully and uniformly lighted. We now insert into the reflected beam, immediately in front of the eye, an opaque straight edge or "knife edge." We shall assume in the following discussions, as a general rule, that the source has been displaced to the *left* of the axis as we face the mirror, and that the knife edge is inserted from the *right*.

Consider first a perfectly spherical mirror. The source *S* is close to the center of curvature; therefore aberration is negligible and all the reflected rays converge to the same point *I*. If the knife enters the beam in *front* of point *I* (Fig. 30*A*), we see a shadow moving across the mirror in the *same* direction as the knife. If the knife enters *behind* this point (Fig. 30*B*), the shadow appears at the left and moves in the *opposite* direction. Assume now that the knife enters exactly at point *I* (Fig. 30*C*): since every part of the mirror surface contributes equally to the image, the entire mirror darkens uniformly. This does not occur abruptly, but gradually, because the source does in fact have a measurable width and because our explanation according to "geometric optics" is only approximately true. We can determine very sensitively when the knife edge enters exactly in the image plane: as we insert the knife, we need merely to compare the brightness at the right- and

[40] The incompletely opaque shadows seen in Fig. 29*B* are also evidence of phase displacement occurring at the lines of the ruled screen.

left-hand edges of the mirror. If the right is somewhat darker, we draw the knife back to a position slightly farther from the mirror; if the left, the knife is moved forward. We arrive quickly at a point of uniform darkening, the "flat field" position. The knife now intersects the point *I* at which all the rays converge.

In most cases, however, the mirror is not perfectly spherical. Truly enough, it is a *figure of revolution* to very close approximation, provided we use the recommended procedures, except possibly for small-scale ripple and certain rare surface anomalies. The defects, in other words, appear always as raised or depressed circular zones concentric with the rim of the mirror. Figure 30*D* shows the knife entering the beam at the convergence point *I* of rays arriving from a wide circular band or zone in a defective mirror. This zone accordingly appears flatly lighted. At the mirror edge, however, and at the center, are zones of somewhat larger radius of curvature. Rays reflected from these zones converge at a slightly different focus (*I'*), and therefore cannot be entirely intercepted by the knife at the same time as rays from the intermediate zone. Rays originating from the "slopes" turned toward the knife edge are, of course, intercepted first; these are, therefore, the first regions to darken. By the same token, slopes inclined the other way remain lighted longest. In short, the appearance at the moment of halfway penetration of the blade is that of Fig. 30*D*. The shadows suggest in relief the differences of height between the defective zones and a "flat" or uniformly tinted area which is the "sphere of reference." The appearance is that of a modeled surface seen under grazing illumination. We need only to decide whether we shall consider the light as coming from the left or from the right to know whether any given defect is raised or depressed. The rule is: assume the light to come always from the side opposite the knife edge (in testing an objective *lens*, the rule is reversed). If then, as agreed, the knife enters always from the right, it is the slopes that are inclined toward the left that appear lighted, while those inclined to the right are in shadow. In Fig. 30*D*, then, we see a central bulge and a turned-down edge; and in Fig. 29*A* a central cavity, a small intermediate ridge partly masked by other (more serious) defects, and a turned-down edge.

Clearly, if we change the distance between the knife and the mirror we change completely the appearance of the shadows. If, for instance, the shadows are those shown in Fig. 30*D*, and the knife edge is drawn back slightly to enter the convergence point of rays from the *central* zone, it is the *center* of the mirror that appears flat, while the adjacent band appears concave, like the inner slope of a crater or funnel. Either appearance gives a valid picture of the *relative* slopes of the various zones. In correcting the mirror, we will obviously choose the picture for which the apparent defects, in size and position, are the easiest to remove. It matters little that the mirror differs slightly in radius of curvature. Note, however, that the picture in which the defects appear in least relief is not necessarily the best one from

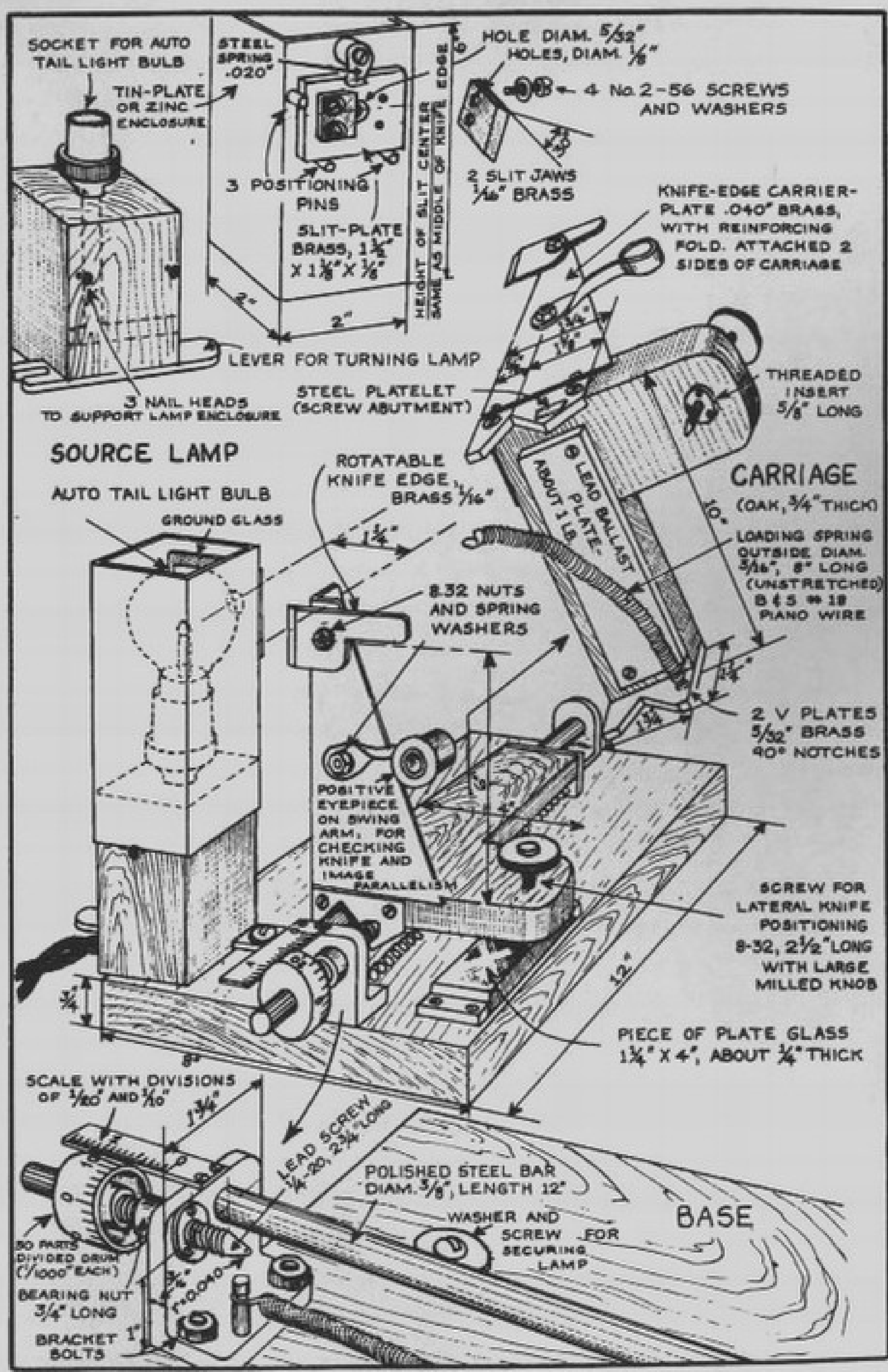


Fig. 31. Details of the Foucault test apparatus.

which to work in making corrections. Examples of this will be given later.

II-23. Foucault Test Apparatus

A rudimentary setup assembled from odds and ends can give valuable service,[41] but it is much more convenient, for serious testing of paraboloidal surfaces, to have an apparatus that provides fine adjustment both for longitudinal and transverse knife positions.

The arrangement shown in Fig. 31 is based on an apparatus made in 1946 for the Astronomical Society's Instrument Group workshop. Attention is directed especially to the following:

Degrees of Freedom of the Knife Edge. For the required smooth motion and two degrees of freedom of the knife edge, the design is based on kinematic principles. As shown by Maxwell, six contact points are needed to define completely the position of one body with respect to another. Omission of any of these contact points leaves a corresponding number of degrees of freedom in the relative motion. In the present case, therefore, we require four nonadjustable points of support. In Fig. 31 these are represented by the contact points in the two V-notched plates which bear against the round steel support bar under the weight of the carriage. The carriage bears down also on a fifth contact: the end of a screw which abuts a flat glass plate mounted parallel to the support bar. By adjusting this screw, we gently rotate the whole carriage, and even with a screw of quite ordinary quality can make the knife edge penetrate the beam very smoothly. The knife does not move strictly along a straight line but rotates slightly. If the source is a vertical slit, therefore, the knife does not intersect all portions of the image simultaneously. However, the radius of motion is relatively large, and with the width of slit ordinarily used the effect is negligible.

The carriage is biased by means of a spring to bear longitudinally against the sixth and final point of contact: the rounded end of an improvised "micrometer" screw. This is merely a ¼–20 screw, fitted with a drum or disk marked with 25 or 50 divisions (for example, on an attached paper strip), that permits measurements of longitudinal carriage displacement to about a thousandth of an inch.

Lateral Spacing between Knife Edge and Source. This is kept as small as possible to prevent introducing astigmatism (and if the apparatus is later used for testing by autocollimation, to minimize parallax). The diameter of ordinary electric bulbs prevents reducing the separation to less than about $1^1/_2$ inches, unless one uses an accessory small total-reflection prism; but this is not required except for mirrors of very short radius (under 3 feet) or very low *f* number (less than 4).

[41] An example of a simplified arrangement is given in the publication of the Astronomical Society of France: *L'Astronomie*, 53, 315 (July, 1939).

Source or Artificial Star. The Foucault test is most sensitive when the width of the source is approximately equal to the diffraction spot diameter (cf. Section I-3), i.e., not more than 8 or 10 microns wide (about 0.0004 inch). Interestingly enough, a source ten times as wide is still quite satisfactory for ordinary testing. The source is often a simple pinhole made by piercing a sheet of tin or aluminum foil with a fine needle. Penetration is controlled by backing the foil with a moderately hard surface. The hole is usually about 100 microns in diameter. Truly round holes, less than 50 microns in diameter, are very difficult to make this way; moreover, small pinholes may admit insufficient light and give so-called stenopaic (narrow-cone) vision in which refractive defects in the eye will produce disturbing, moving shadows.

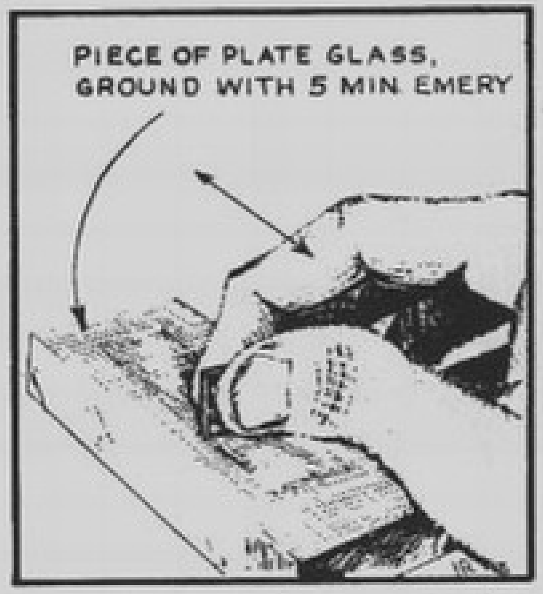


Fig. 32. Finishing the slit jaws and knife edge.

A. Couder[42] has shown that the use of a *slit* source offers important advantages. The width of the slit may be reduced to the theoretical optimum value; and the height may be as much as $^1/_8$ inch. This acts both to provide more light and to eliminate stenopaic effects. Figure 31 shows the construction of a slit of fixed width. If desired, the jaws may be set as close as 5 or 10 microns and parallel to within better than 1 micron merely by inspection against a bright diffusely lighted background. This is too fine, however, for routine testing; the diffraction effects (which we shall discuss later) are disturbing to the beginner. Instead, we adjust the jaws to about 30 or 50 microns, either by direct measurement under a microscope or, roughly, by inspection against a moderately lighted background.

The slit edges must, of course, be straight to a very good approximation. Many persons have highly distorted notions about how to make an edge straight to within a fraction of a micron. We shall therefore describe the extraordinarily simple process that we use to shape the slit jaws and knife edge. A common mistake is to attempt making a very acute chamfer—

[42] A. Couder, *Bull. astron.*, 7, 423–433 (1931); also *Lunettes et Télescopes*, p. 528.

literally a razor's edge. Actually, a small blunt facet at the edge is quite satisfactory. This may be 0.005 inch wide without causing difficulty and can easily be made straight. Brass is better than steel because of its superior corrosion resistance. We first make the working edge approximately square. Then, holding the piece in a small vise, we file a taper at 30° or 45°, trying to produce a clean, continuous edge the whole length of the piece. The metal is soft, of course, and irregularities are inevitable. To plane the edge precisely, we now apply it perpendicularly to a flat, *clean and dry* ground-glass surface,[43] and with a pressure of about a pound or so make a dozen double strokes (back and forth) in a direction perpendicular to the jaw or knife edge (Fig. 32). In a few seconds we have formed a tiny, brightly reflective continuous facet. If breaks appear along the edge, indicating that irregularities have not yet been ironed out, these are removed by a few extra strokes.

To illuminate the slit uniformly and to provide a wedge of emitted rays of sufficient included angle to cover the mirror, a quiet luminous flame, perhaps $^1/_4$ inch wide and set fairly close to the slit, would be quite suitable. Early optical workers often used a small kerosene lamp; and the acetylene flame, with its temperature of over 2,200° C., can give excellent results. Far better, however, from a practical point of view, is a small, intense electric light fitted with some form of diffuser. An opal glass would diffuse the light perfectly, but the loss of intensity would be excessive. It is better merely to frost the side of the bulb facing the slit by grinding it with a little M302 emery. A piece of lead, hammered or bent into a concave shape of roughly the same radius as the lamp bulb, can serve as a tool. Auto tail light or movie projector lamps are best because their overall size is small and because the shape of the filament permits them to be used efficiently. It is best not to attempt (by means of a lens or mirror, for example) to project an image of the filament on the slit. Experience shows it is then very difficult to make the emitted beam uniform enough throughout the required included angle. The method works well enough, however, with sources that lack "structure," such as the high-pressure mercury vapor arc; indeed this brilliant source is very valuable in making more exacting mirror tests and detecting defects of very small amplitude. For the amateur, however, this is only of minor interest.

Finally, we must make provision for turning the lamp and slit assembly, in order to make the intensity of the useful beam as uniform as possible.

Stability of the Supports. Fortunately this is much less important here than in the Michelson or Zernike tests. Nevertheless, testing is made more convenient and the data are more reliable if the apparatus is stable. Amateurs often mount the mirror in a way that subjects it to excessive strain. Here again we can use kinematic principles to good advantage. André

[43] This is a piece of plate glass abraded against another plate with 180 or 220 Carborundum

Couder has devised a number of such supports. We have borrowed some of their features to make a particularly effective and inexpensive mount. As seen in Fig. 33, the mirror edge is supported at two points, 60° to 90° apart, on a pair of wood rails. The rails diverge slightly to the rear, thereby tending to tilt the mirror backward and into contact with the heads of three nails projecting from an upright board and defining a vertical, mirror support plane. The base itself is fitted with three contact points and rests on a firm support which either stands directly on the ground (if one works in a cellar) or is braced in a corner between two walls (if the room has a wood floor). The Foucault test apparatus is placed on a broad, steady tripod-mounted surface, preferably adjustable in height so that the apparatus can be positioned quickly without losing sight of the image and without manipulation of the mirror support.

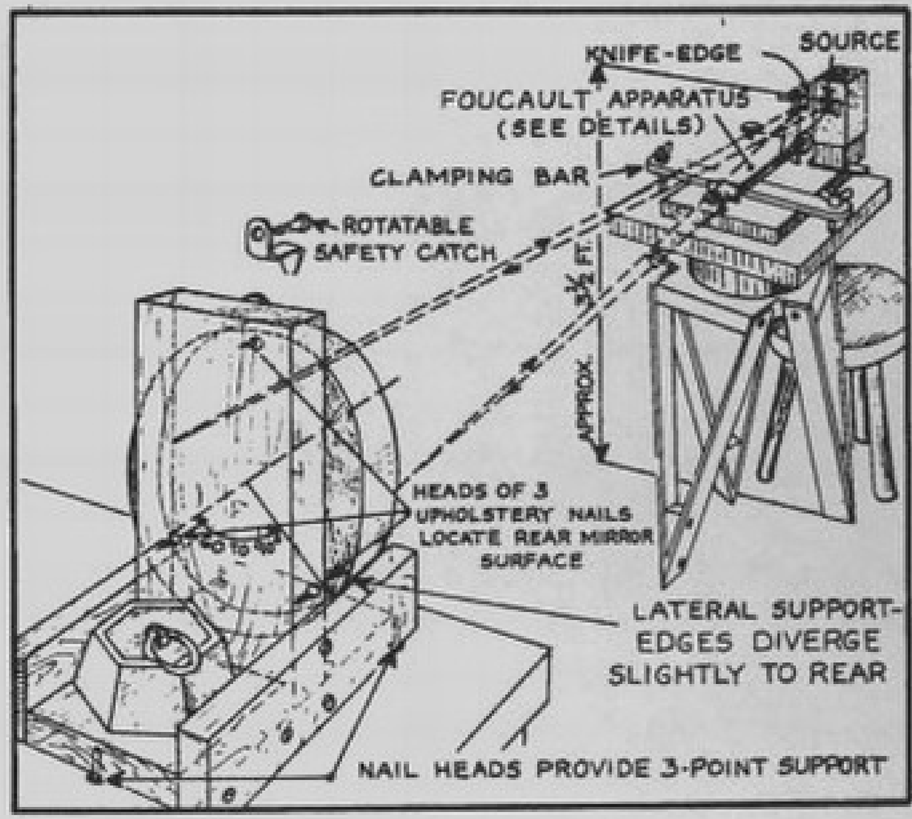


Fig. 33. General mirror-test setup.

II-24. Making the Foucault Test

The area used for testing should be enclosed and sufficiently constant in temperature so that there are no disturbing optical nonuniformities in the air. Cellars are often best, except in winter, when warm air rising from the operator and the test source, subsequently cooling by contact with the walls, may set up objectionable air currents. Cellars may be troublesome also because often they are much cooler than the location used for polishing. This may make necessary a wait of as much as several hours before each test, to let the mirror settle uniformly to room temperature. In locations other than a cellar, however, the walls should not be exposed directly to the sun. A relatively dark test room is helpful, but sufficient light may remain in which to walk about conveniently and to see the mirror, its support, etc.

No useful test can be made unless the mirror is in perfect thermal equilibrium with the surrounding air. The mere act of lifting the mirror and returning it to its support makes it necessary to wait a half hour before testing can be done. If the mirror has just undergone polishing or figuring, it is a half hour before even a sufficient outer layer has cooled to permit recognizing the general surface figure. For several hours thereafter the radius of curvature and the precise surface form continue to change slowly.

To position the Foucault apparatus rapidly, we set it first at a distance from the mirror that is deliberately a little greater than the radius of curvature. The lamp is turned on and the slit plate removed. Then, looking at the mirror (the eye being approximately alongside the source), we try locating the image of the lamp house window by shifting the head from side to side or up and down. The image formed by the reflected rays is actually located in space, somewhat in front of the observer's eye. The aperture being rather large ($^3/_8$ inch, for example), the image is easy to find. The image at this point is somewhat smaller than the aperture. We now shift the entire Foucault apparatus (lamp and knife edge), and if necessary the supporting platform also, closer to the mirror, so as to shift the image (which we keep continuously in sight) into the immediate vicinity of the knife edge. The image increases in size, presently equaling that of the aperture itself when the source and knife edge both are near the center of curvature. We now put the slit plate back on the lamp housing, and make a trial insertion of the knife edge into the beam. The knife edge must be exactly parallel to the image of the slit. If the apparatus is provided with a Ramsden eyepiece that will swing into the beam as shown in Fig. 31, we obtain simultaneously a sharp view of knife edge and of the image, and can make the adjustment for parallelism precisely. Lacking this refinement, we may simply withdraw our eye to a position about a foot behind the knife, and check whether on penetration of the knife the image is extinguished simultaneously along its entire height. The distinctness of the diffraction fringes seen along the knife edge (see next section) is an even more sensitive test. After determining more accurately at which point the rays converge (cf. Section II-22), we shall probably note that the knife is somewhat closer or farther from the mirror than the slit. This difference may remain an inch or two without adversely affecting the test. When making a measurement of the radius of curvature of the mirror, however, the operator should take this difference into account as follows: a long, light-weight rule is positioned with one end at the middle of the mirror and the other end extending past the Foucault apparatus. Two marks are drawn on the rule, one at the position of the slit, the other at the knife edge. The radius of curvature is the average

distance of the mirror from the two marks.

As soon as possible, the beginner should learn how to position the knife edge to make any desired zone of a defective mirror appear "flat." Always, in determining whether a given zone is raised or depressed, he will remember from which direction the lighting must be assumed to come (Section II-22).

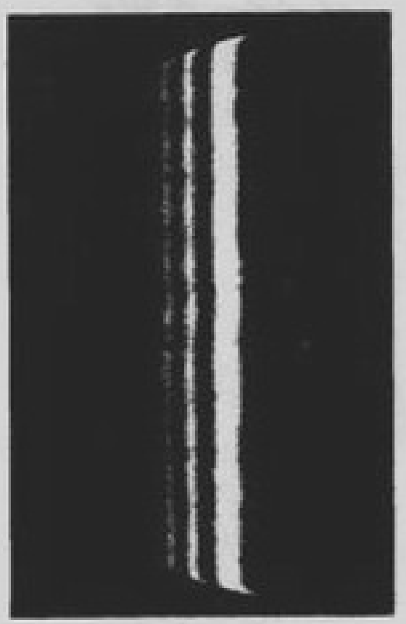


Fig. 34. Shadow fringes seen with knife inside the focus. Spherical mirror with turned-down edge of 1/3 wave (5 μ slit).

II-25. Diffraction Effects in the Foucault Test

Because of the great interest the Foucault test holds for the astronomical optical worker, he has naturally been prompted to inquire what its limitations are, and especially whether the vibrational (physical-optical) nature of light seriously affects the "geometrical" explanation given in Section II-22. Remarkably enough, diffraction plays a rather secondary role (although this is not true, generally speaking, of the "improved" Foucault tests). Indeed the diffraction effects are so small, we would have passed over them in silence in a book intended primarily for the amateur, except first, that they may lead to certain misinterpretations, and second, that they can serve certain useful purposes.

Rayleigh was the first to note the bright diffraction ring that appears at the edge of the mirror just as the knife completely covers the image. This ring makes it difficult to evaluate precisely any defect at the extreme edge. Banerji[44] has proposed a test that is based upon this effect. More recently, Gascoigne[45] and Linfoot[46] have worked out a complete theory of the Fou-

[44] Banerji, Sudhansukumar, *Astrophys. J.*, 48, 50–58 (1918).
[45] S. C. B. Gascoigne, *Monthly Notices Roy. Astron. Soc.*, 104, 326 (1944).
[46] E. H. Linfoot, *Proc. Roy. Soc. (London)*, 186, 72 (1946); *ibid.*, A193, 248 (1948).

cault test, taking diffraction effects into account. Their conclusions do not cast any serious doubt on the validity of the geometrical interpretation except where severe defects exist of the order of a whole wavelength or more. But such defects can be studied easily with a relatively wide pinhole or slit as the source, in which case the diffraction effects become negligible.

We have already noted how F. Zernike, proceeding from "physical-optical" theory, derived a method that is especially useful for the small, more or less periodic, defects caused by the tool structure.

In 1931, A. Couder directed attention to the Fresnel-type fringes bordering the knife-edge shadow when the knife is displaced somewhat from the focal position, and, in some cases (where the wavefront is defective), even at the focus itself. This phenomenon, which becomes visible only with a rather fine slit, is of considerable practical interest. It allows us very quickly to adjust the slit width to the proper value, and to position the knife edge exactly parallel to the image. At the focal ratios which exist in our Foucault tests, effectively $f/12$ to $f/16$, two or three fringes are visible at the edge of the "geometrical" shadow for a knife position about $^3/_4$ inch inside the focus and a slit of the recommended 30 to 50 microns width (Fig. 34). If the source is monochromatic, and we narrow the slit to 3 microns, we may actually see and photograph a series of fringes covering the entire bright half of the mirror!

Couder has shown that these fringes reveal quickly and without calculation the extent of wavefront error. Briefly, if the wavefront is accurately spherical (the knife being inside the focus and covering more than half the beam), the fringes are straight lines. If the wavefront is distorted, the fringes are distorted also, and indicate the nature and extent of the error. The first fringe adjoining the shadow is the sharpest, and is separated from the shadow by a space of about three-fourths of a wave. This spacing may serve as a unit of measurement in estimating fringe deviation. Figure 34 shows the appearance of the fringes on a mirror with a turned-down edge. In the normal Foucault test, with the knife edge positioned at the center of curvature, the defect would not be nearly as apparent because of the presence of the Rayleigh diffraction ring mentioned earlier.

When we examine a mirror surface that gives a strongly nonspherical wavefront under the conditions of the test, for example, a paraboloid of small f number tested at the center of curvature, the diffraction fringes are evident even with the knife centered at the image position. If the slit is at least 30 to 50 microns wide, however, the fringes are not disturbing to the normal Foucault test. In any case, as the knife enters the beam, the fringes move along with it, and therefore are not confused with the normal Foucault shadows that are characteristic of the "slopes" of the mirror surface.

II-26. Sensitivity of the Foucault Test

When the wavefront produced by the mirror under the conditions of the test differs but little from a sphere, the diffraction phenomena are not troublesome except possibly at the extreme edge. The detection of small surface errors is then limited only by the least contrast of shadow that is perceptible to the observer. Assuming a slit only 10 microns wide (0.0004 inch), a lateral knife movement of 0.5 micron produces an easily detectable change in brightness. If the radius of curvature is 100 inches, this corresponds to a slope error (measured on the wavefront) of 2×10^{-7}. The minimum detectable *height* of defect then depends on how wide the defect is. If it is relatively broad, say an inclined zone $2^1/_2$ inches wide, the corresponding detectable height is 4 ten-millionths of an inch, or about $^1/_{60}$ wave. But if the defect is narrow, the minimum detectable height is extraordinarily small indeed. We have photographed surface defects less than a millimeter wide, the slopes of which (from geometrical considerations) were known to be 1×10^{-6}; and the height of which therefore was 10 Angstroms, or $^1/_{600}$ of a wave! These values were confirmed in tests made by the Lyot phase-contrast method.

II-27. Principle of Parabolic Mirror Testing

To test the paraboloidal mirror under conditions similar to those of actual use, i.e., using a *parallel* incident light beam, would involve great difficulty. We should require a source far removed from the mirror (see Section II-1) or else a special optical arrangement such as an autocollimator that employs a reference flat, or a perfect collimator of an aperture at least equaling that of the mirror. Even the professional rarely resorts to such means. It is better to test the mirror instead at the center of curvature, using the methods already described. Under such conditions only a perfectly *spherical* mirror gives a perfect image. The paraboloid, on the other hand, appears quite defective; it exhibits a kind of aberration that is the inverse of that produced when a sphere is illuminated by parallel rays. The defects in either case are forms of *spherical aberration*.

We can predict how large this image aberration should be for the case of a perfect parabolic mirror, for example, in terms of error in the longitudinal position at which the rays intersect the axis (see Section II-20, Fig. 28). We may then merely compare these ideal or theoretical errors with those actually observed in the mirror under test. The differences are a measure of mirror imperfection. By a simple calculation we can convert these errors, measured at the center of curvature, to the *lateral* errors that would appear, in actual use, at the *focal plane*. These may then be compared directly with the magnitude of the ideal diffraction spot (see Section I-3) as a criterion of figure perfection.

II-28. Definitions Relating to Spherical Aberration

Consider a parabolic mirror (Fig. 35) which produces an image of a

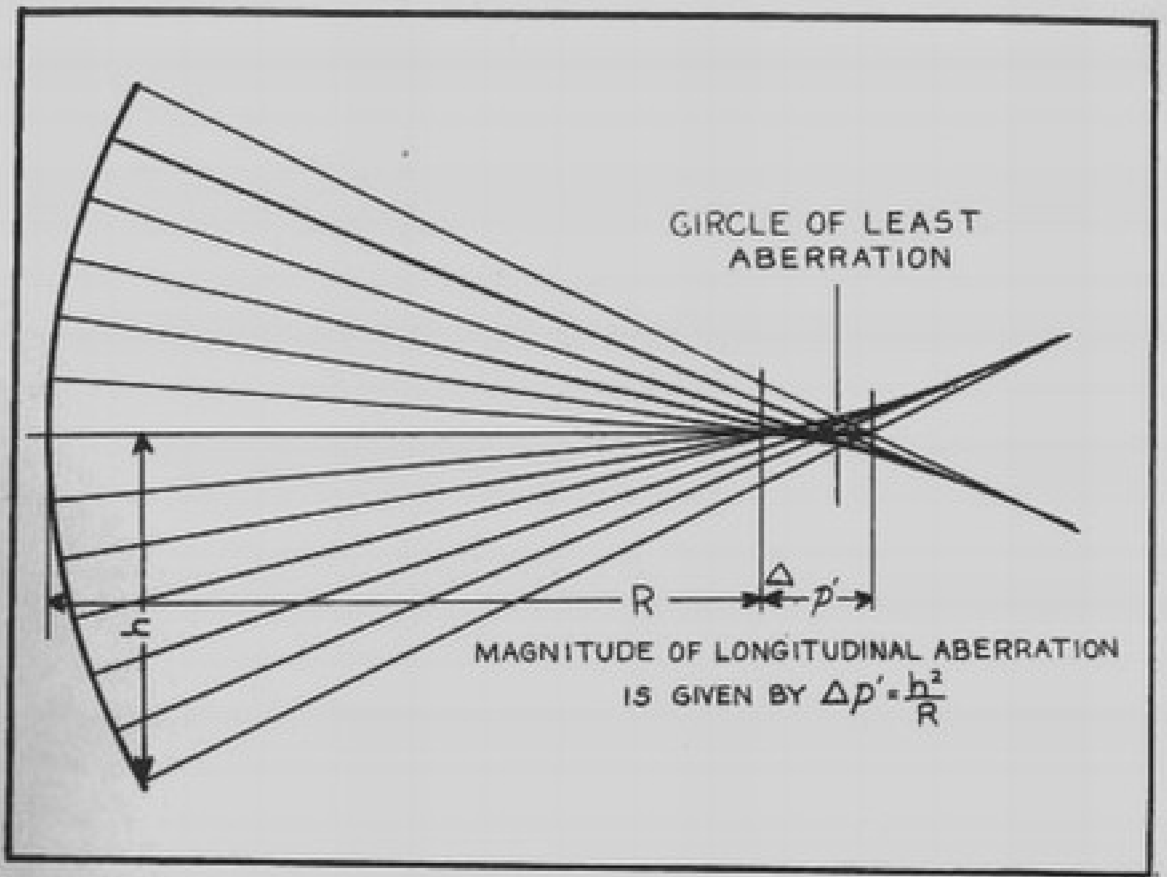


Fig. 35. Aberration of a parabolic mirror at the center of curvature.

point source of light located at the center of curvature. The image cannot be a point because the rays reflected from zones progressively farther from the center of the mirror intersect at positions progressively farther along the axis. The radiant energy in the image is concentrated largely in the curved "envelope" formed by the intersections of neighboring rays that arrive from adjoining mirror zones. The envelope defines a so-called *caustic* surface. This is a "figure of revolution" about the optic axis that resembles a trumpet horn. Its appearance in cross section is indicated in Fig. 35, in which, however, we have greatly exaggerated the mirror curvature to emphasize the character of the caustic curve.

Another feature of the caustic figure is the short line of concentrated radiation that lies on the axis inside the caustic envelope and is produced by "stacking" of the image points formed by zones successively farther from the mirror center. This linear segment is particularly interesting. Its length is a measure of the total "longitudinal aberration" of the mirror. In a more general sense, we speak of longitudinal aberration of a mirror *zone* as the distance between the axial intersection of rays from that zone and the axial intersection of the central mirror rays. This distance we designate

$\Delta p'$.[47] For any zone at a radius of incidence (distance from the mirror center) equal to h, it is given (with sufficient accuracy, in mirrors of moderate diameter and focal ratio) by the simple expression

$$\Delta p' = \frac{h^2}{R}. \tag{14}$$

The longitudinal aberration of any zone of radius of incidence h equals the square of this radius divided by the radius of curvature R of the mirror.

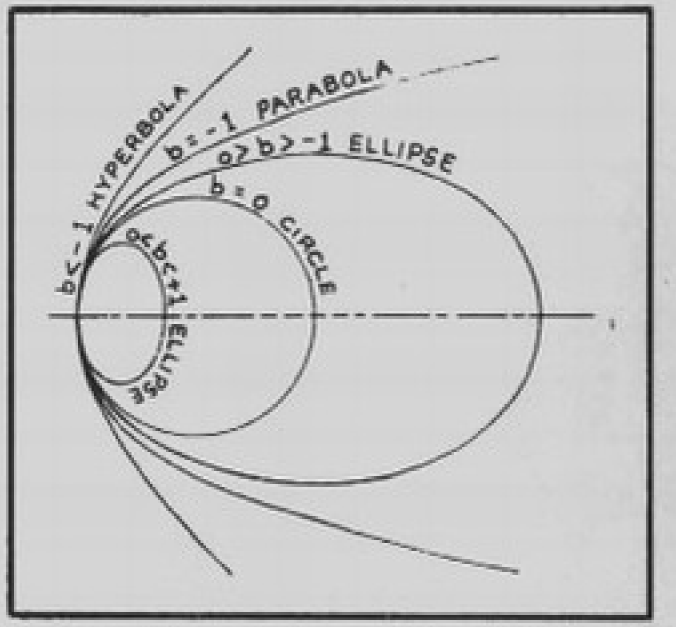


Fig. 36. Significance of the coefficient of deformation *b*.

The paraboloid, however, is only one of a family of deformed surfaces that we are likely to encounter when we figure our mirror. The relationship between these various curves may be shown by introducing a *coefficient of deformation b* in the formula, which in a general form may be written

$$\Delta p' = b\left(\frac{h^2}{R} + \frac{h^4}{2R^3}\right) \tag{15}$$

For the parabola, b assumes the value -1 (the sign indicating that in this case the marginal rays intersect farther from the mirror than axial rays). If b is a number more negative than -1, the surface is hyperbolic. If it is between -1 and 0, the figure is an ellipsoid of revolution about a major ellipse axis; if between 0 and 1, it is an ellipsoid of revolution about a minor ellipse axis. At $b = 0$ the figure is, of course, a sphere. The series is depicted graphically in Fig. 36. In the second-mentioned kind of ellipsoid ($0<b<1$) the marginal rays converge at a point closer to the mirror than the central rays; we characterize this as *undercorrection*. Here the caustic "horn" opens *toward* the mirror. Figures with a *negative* coefficient (cf.

[47] This notation, as well as all others relating to mirror measurement, is borrowed from *Lunettes et Télescopes*, in which the subject is treated at greater length.

Fig. 36) give forms of *overcorrection* and result in caustic curves that open *away* from the mirror.

At a certain point on the caustic curve, the cross-sectional diameter of the image is a minimum. This is the position of the *circle of least aberration* (see Fig. 35). Its distance from the intersection of the axial rays is three-fourths the length of the longitudinal aberration segment.

II-29. Effects of Spherical Aberration

The optical physicist thinks of spherical aberration primarily as a formula or, more exactly, as a mathematical series of powers of h. But the astronomical worker and mirror maker are more concerned with the concrete aspects of this phenomenon encountered often in their work. These are the composite effect of geometric optics and diffraction. If one examines a bright star with a sufficiently strong eyepiece, and overcorrection is present, the image is affected in several ways: at the focus for the central rays (Fig. 37*A*), he sees a diffraction figure that is nearly normal at the center but is surrounded by rings of unusual number and brightness. If the image is agitated, or the source is not a precise point, the rings usually fuse into a wide, pale halo. As the eyepiece is slowly drawn farther from the mirror, the halo decreases in diameter and the energy is concentrated more nearly in the outer ring (Fig. 37*B*), the latter continuing to contract until the eyepiece is focused on the circle of least aberration. Here the image is very poor: nearly all the light is in the caustic ring. As the eyepiece is withdrawn farther still, to focus on the plane of intersection of the marginal rays (Fig. 37*C*), a small amount of light may still be seen on the axis where the marginal rays impinge, but now it is the outer rings—the fringes of the caustic boundary—that are sharp and dominant. When the observer encounters *undercorrection,* the sequence of image forms is of course *reversed.*

What interests the mirror maker most, however, is the appearance of the shadow pictures given by these aberrations in the Foucault test (Fig. 37*A* to *C*, right). As agreed earlier, we shall always bring the knife into the beam from the right. We shall start by inserting the knife at the point of intersection of the axial rays, i.e., at the peak of the caustic curve. The center of the mirror appears flat (Fig. 37*A*). Rays coming from the right side of the mirror are intercepted by the knife, causing that side to appear dark, while leaving the left side bright. The composite picture is that of a pronounced dome flattened at the center (keeping in mind that we imagine the light to come from the *left*).

Drawing the knife now a little farther from the mirror, we insert it at the middle of the longitudinal aberration segment (Fig. 37*B*). This is the intersection point of rays from the 0.7 mirror zone, or more exactly the zone at $\sqrt{2}/2$ or 0.707 of the mirror radius. This zone accordingly appears flat. The central area, being of shorter radius of curvature, appears to incline

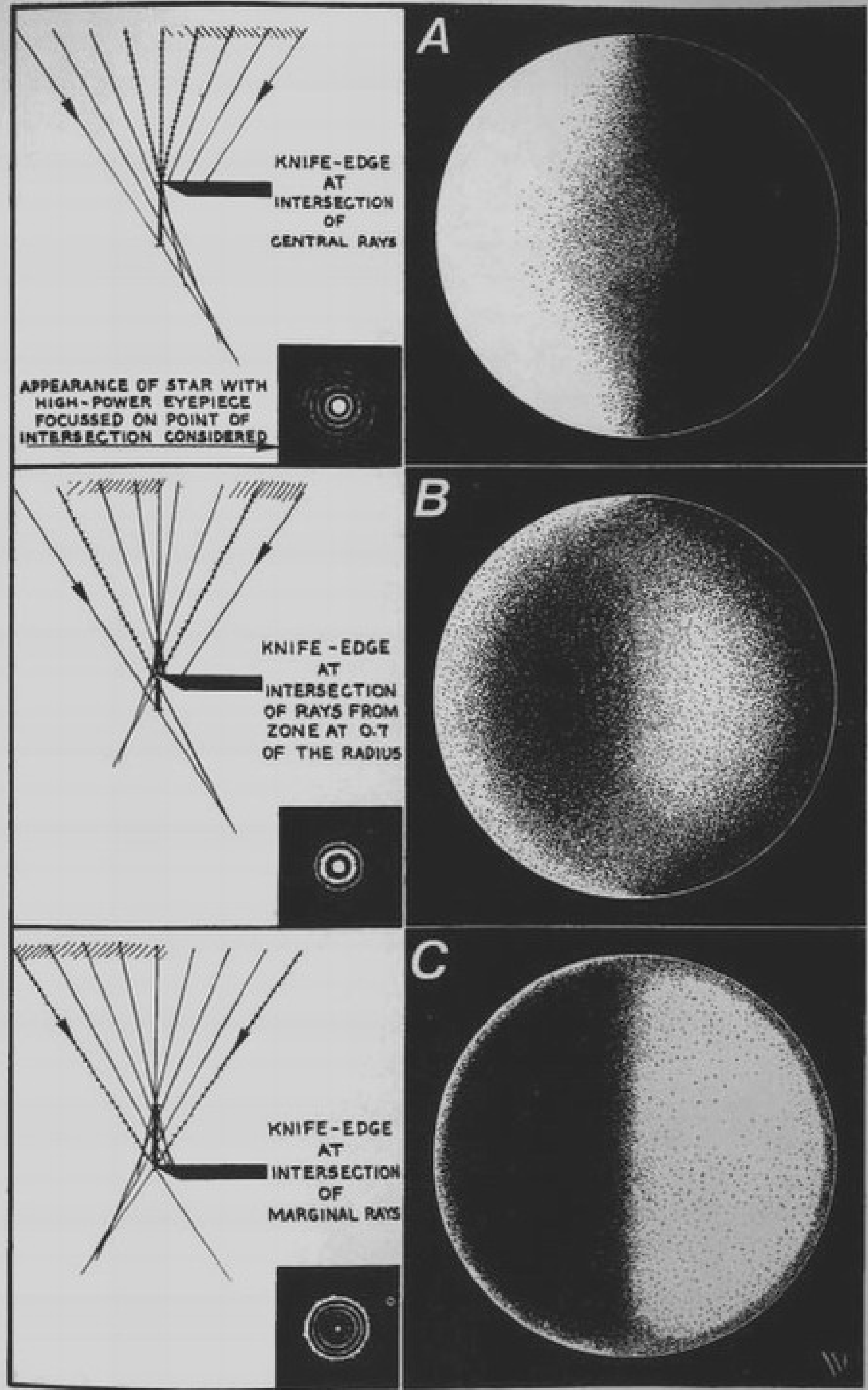


Fig. 37. Spherical overcorrection.

inward, forming a depression, while the marginal zone, of longer radius, is turned outward, i.e., appears convex. The composite picture is that of a toroid or doughnut-like figure, the surface of which slopes in gently toward the center. The figure is a familiar one to the optical worker.

We now draw the knife back farther still. The "neutral" or flat reference zone now reaches the extreme edge of the mirror (Fig. 37*C*); all other zones, being of shorter radius of curvature, appear to slope inward, like the walls of a deep basin.

All spherical aberration figures (ellipses, parabolas, hyperbolas) that have a negative coefficient of deformation present a similar picture sequence, differing from one another only in the apparent depth or contrast depending on the value of the coefficient. Surfaces with a positive coefficient give a similar sequence, except that the figures are turned "inside out" (the lighting being assumed still to come from the same direction); thus the middle picture (Fig. 37*B*) would show a central bulge and turned-up edges. But other factors than the coefficient of deformation may affect the contrast, e.g., sensitivity of the Foucault apparatus (dependent on the slit or pinhole width),

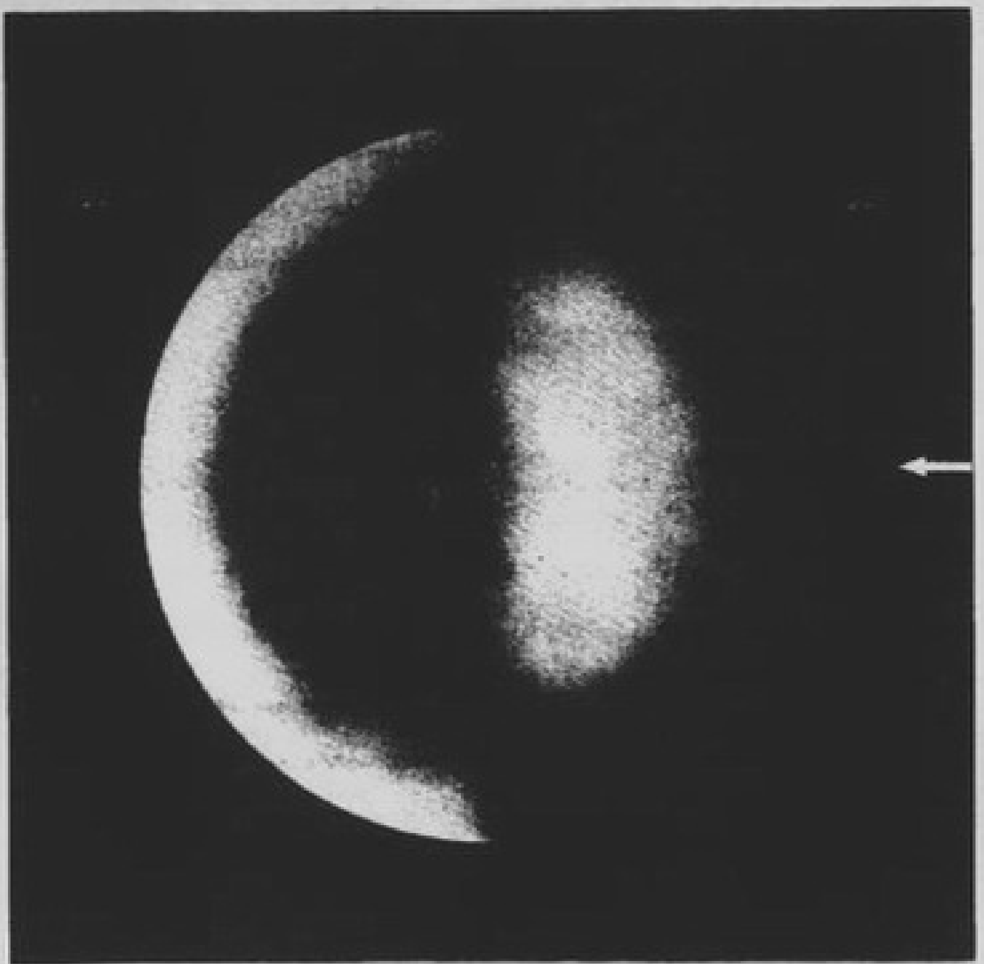


Fig. 37-D This is a Foucault shadowgram of the first 8-inch $f/6$ mirror made by the Astronomical Society's Instrument Group, with the knife edge at 0.707 zone. Microripple is approximately $\lambda/50$.

focal ratio of the mirror, and the radius of curvature. Assume, for example, that with a standard 8-inch parabolic mirror, $f/D = 6$, we use a Foucault apparatus test as per Section II-23 fitted with a 30-micron slit and observe shadows such as seen in Fig. 37*B*. If then we substitute a mirror of smaller f number or one with a hyperbolic, rather than parabolic, surface, the shadows appear darker and the transitions between light and dark areas are sharper. Or, if the focal ratio is made larger, say $f/D = 10$ (or the surface is a pure ellipse), the shadows are fainter and less sharp, suggesting a pattern in lower relief. To make any meaningful corrections, then, some form of *quantitative* measurement is indispensable. The reader must guard especially against "simplified" methods often described by writers who cannot possibly have understood the meaning of the Foucault shadows.[48]

II-30. Measurement of Spherical Aberration

Leon Foucault himself described the "differential solids" (i.e., three-dimensional figures of "differential" or "slope") shown in Fig. 37, and used them to measure longitudinal aberration.[49] The method consists, first, in finding the longitudinal knife position that gives the appearance of Fig. 37*A*. This we read against a longitudinal scale, like that shown in Fig. 31 (the location of the zero point of the scale is unimportant, only *differences* will be of interest), or we mark the position on a card fixed to the base. Next we note the knife position, slightly farther from the mirror, that gives the appearance shown in Fig. 37*C*. The difference of reading, or spacing between the two marks, is the length of the image segment $\Delta p'$. By simply comparing this with the theoretical value, we determine whether the mirror is more or less deformed than a parabola. Assume the mirror is 8-inch, $f/D = 8$. Then $h = 4$ inches and $R = 128$, and from the formula given earlier we obtain for the ideal segment length $\Delta p' = {}^{16}/_{128} = {}^{1}/_{8}$ inch.

In addition we must verify whether at the midpoint of the image segment we obtain the appearance of Fig. 37*B*, i.e., whether the neutral zone is properly positioned at 0.7 of the mirror radius, and whether the zones are regular and blend smoothly with one another. This much testing could suffice, if need be, to check a mirror differing only slightly from a sphere, for example, an 8-inch of $f/D = 8$. It does, however, require a rather skillful appraisal of the shadows. The convergence point for the central rays (which meet very obliquely at the axis) is not sharply defined; moreover, readings at the extreme edge are affected by the bright Rayleigh ring (Section II-25).

[48] One writer modestly characterizes "his" method (actually a poor copy of that by Everest) as "simple, elementary, scientific, elegant, and good to a first approximation." His criterion for a parabolic surface is merely that the longitudinal shift in knife position required to change the appearance from that of Fig. 37*A* to that of Fig. 37*B* shall equal that needed to change Fig. 37*B* to Fig. 37*C*. But this is true of all surface figures (ellipses, parabolas, or hyperbolas) of the form $\Delta p' = b\,(h^2/R)$, regardless of the value of b. The method is therefore quite useless.

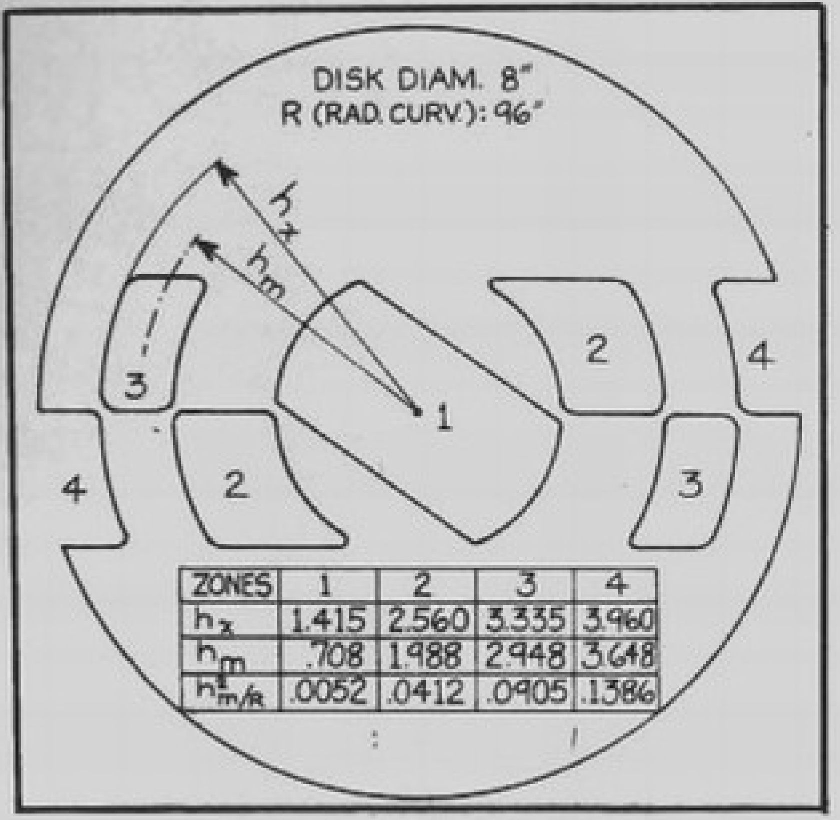
[49] L. Foucault, *Compt. rend.*, 70, 389–392 (Feb. 21, 1870).

Quite frequently also irregularities at the center or the edge pass unnoticed in the simple Foucault test, and lead to an inaccurate evaluation of the mirror.

G. W. Ritchey[50] conceived the idea of covering the mirror with a mask or screen to expose simultaneously two portions of the same zone at opposite sides of the axis. The light from the two apertures can then be compared quantitatively. The openings of the Ritchey screen are very narrow, however, and diffraction effects interfere seriously with the measurement. A. Couder[51] has described a much more practical screen which we shall consider here in detail.

II-31. The Couder Screen

This screen exposes a series of mirror zones whose radii are related in a preferred, optimum manner. The zones immediately adjoin each other, and the *squares* of the radii of successive zones differ always by approximately the same quantity. The zones therefore decrease progressively in width from the center to the edge. This assures that toward the edge, where



ZONES	1	2	3	4
h_x	1.415	2.560	3.335	3.960
h_m	.708	1.988	2.948	3.648
h_m^2/R	.0052	.0412	.0905	.1386

Fig. 38. The standard Couder screen.

the parabola deviates most rapidly from a sphere, the exposed areas are narrow enough to appear uniformly bright across their width. The screen

[50] In a memoir reproduced in Henry Draper's *On the Construction of a Silvered Glass Telescope*, Smithsonian Institution. Washington, 1904.

[51] *Lunettes et Télescopes*, p. 534.

is cut from heavy drawing paper or thin cardboard, and marked out as follows:

The outer circumference is made equal to the outside mirror disk diameter. A circle a small distance inside the edge corresponds to the mirror diameter measured at the chamfer. This is also the outer diameter of the outside test aperture. The width of the outside zone is determined by practical considerations: if it is too narrow, good measurements are difficult to make; if too wide, the zone will not appear sufficiently uniform in brightness. If the desired parabola is strongly nonspherical, many zones must be cut (one for each millimeter of longitudinal aberration, for example), but for the standard 8-inch, viewed at about 100 inches, it is not advisable (for the beginner) to make any zone less than $^5/_8$ inch wide. This condition leads to four zones—a number that is found altogether adequate. Reliable readings taken at four zones are much better than questionable readings taken at ten.

Having decided on the width of the outside zone, we may then calculate the successive outside radii of the other zones, using the simple law that the squares of the outside radii diminish always by a constant quantity.[52] Figure 38 shows a screen made in this way for an 8-inch mirror. This law sometimes leads to central apertures of an exaggerated width, but there is no harm, if one wishes, in arbitrarily modifying the theoretical dimensions to some extent.

The finished screen may not conform precisely to the values which were planned; therefore after cutting we determine the *actual* inside and outside zone dimensions to the nearest half-hundredth inch or 0.005 inch. We must average the radii for left- and right-hand apertures. This we can do conveniently by measuring the inside and outside zone *diameters*. For each zone then we derive first the average radius h_m by adding inside and outside diameter and dividing by 4, then calculate the ideal longitudinal aberration h_m^2/R with which we shall later compare the values found experimentally.[53]

[52] Call this constant quantity a. If the outside and inside radii of zone 4 are $h_{x(4)}$ and $h_{x(3)}$, respectively, a is equal to $h^2_{x(4)} - h^2_{x(3)}$. The zone 3 outside radius (same as zone 4 inner radius) is known. The zone 2 outside radius (inside of zone 3) is

$$\sqrt{h^2_{x(3)} - a}.$$

Similarly, the zone 1 radius is

$$\sqrt{h^2_{x(2)} - a}.$$

[53] A. Couder in *Lunettes et Télescopes* (p. 533) uses, instead of our arithmetic mean h_m, the quantity h_n, the "root-mean-square" of the inner and outer radii (i.e., square root of the average of the squares of the two radii). Theoretically, this leads to a more accurate surface figure. We feel, however, that the observer's eye more nearly compares the *middle* of the apertures, both as a natural tendency and because the diffraction effects occur equally at either edge. The difference in final result in any case is very small; it corresponds for the standard screen to transverse deviations in the image of less than a micron. The reader must let his conscience be his guide.

II-32. Screen Test Procedure; Errors

Before testing, allow the mirror to remain on its support (accurately positioned for testing) for several hours. Uniform mirror temperature and absence of convection currents in the room are particularly important. Mount the slit (adjusted to 10 or 20 microns) on the lamp house and make it accurately parallel with the knife edge (look for four or five shadow-fringes with the knife about $^3/_4$ inch inside the focus). Also adjust the knife edge quite perpendicular to the optic axis. Next, carefully align the knife-carriage rail parallel with the optic axis by noting that penetration of the knife into the beam is unchanged as the carriage moves toward or away from the mirror. Before masking the mirror, check that it is uniformly illuminated (rotating the lamp housing if necessary) and verify that the image sequence of Fig. 37 occurs within the measuring range of the longitudinal scale. Now secure the Foucault apparatus firmly to the support and place the Couder screen over the mirror. Adjust the center-line of the screen openings so that it is horizontal and align the circumference accurately with the mirror edge. If necessary, improvise a light wire clip to hold the screen in place (avoiding touching the mirror). Again check carefully the evenness of lighting, especially at the outer apertures (the knife being completely out of the beam). When comparing light intensities, the eye works best if the room is not quite dark. It is desirable even to allow a little diffuse light to fall uniformly over the screen and test apparatus. These many preparations must not discourage the beginner. After a few attempts he will understand the precautions better and know quickly how to set his apparatus in working order.

It remains for us now only to make the measurements. Start for instance with the central zone: if it darkens at the left as the knife enters the beam, move the knife closer to the mirror; if it darkens at the right, draw the knife away (controlling the longitudinal knife-positioning screw with the left hand, the lateral knife-positioning screw simultaneously with the right). When the knife enters at the center of curvature the entire zone darkens uniformly. Refer now to the divided longitudinal scale and take a reading of the position of the knife carriage. As mentioned earlier, the position of the zero or reference point from which we take our readings is unimportant; we shall be concerned only with measuring differences.

Look next at zone 2, the openings of which we can identify easily in the staggered arrangement of the Couder mask. The right side appears darker of course; therefore, to locate the center of curvature we draw the knife farther back from the mirror.

We proceed in this way from zone to zone, and for each pair of apertures obtain a corresponding longitudinal reading. When the last reading is taken, it is good practice immediately to take a second set of readings, working back to the central zone. In comparing widely separated apertures,

we use a technique practiced by observers when they compare intensities of stars widely separated in a field, i.e., look at the two positions alternately, instead of trying to fix attention on both at once.

To compare brightness more easily, and to minimize error due to lateral scattering of light, it is better to make the comparison at the beginning of extinction, rather than when the knife is more than halfway in the beam.

The appearance of the masked mirror seen in Fig. 39 illustrates some of the mentioned difficulties and sources of error: diffraction at the edges, nonuniform illumination, etc. But the method, despite its shortcomings, is the most useful we know.

If the mirror surface is quite regular and properly lighted, and the air is quiet, the seasoned operator, who has tens of thousands of observations behind him, can pinpoint the center of curvature of an intermediate zone

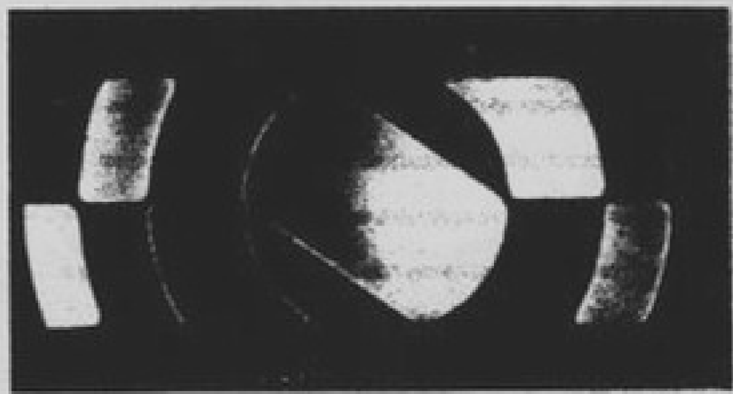


Fig. 39. Foucault shadowgram of a standard mirror.

(say a zone of focal ratio $f/D = 12$) with an average error of about plus or minus 0.001 inch. The beginner of course cannot expect such precision—his first readings may differ by as much as 0.010 inch or 0.015 inch. But with patience he can reduce this quickly to at least 0.005 inch or 0.008 inch, and by taking the average of four repeated readings on each zone, his results will no doubt be reliable to 0.004 inch or 0.005 inch. This permits him to approach the ideal mirror figure (assuming a disk of the dimensions and focal ratio of interest here) with a precision ten times better than the Rayleigh tolerance. We shall take up the question of "reducing" these data later, when we discuss the tabulation of the "Test Data Sheet."

II-33. Defects Other than Figures of Revolution

These can be serious, but we shall discuss them only briefly here. If one follows the rules and uses the "fixed post" method, these defects will practically never be encountered.

The Foucault test is not recommended for detecting these defects; the shadows are difficult to interpret unless the worker is quite familar with them, especially for certain orientations of the defect with respect to the knife edge. A simple examination of a "star" image with an eyepiece, however, focused on a plane slightly removed from the focal point, can put one's mind at ease. As mentioned earlier, it is difficult to obtain a "star" either small or round enough for this test merely by using a pinhole. It is better to substitute temporarily for the slit on the lamp housing, a small round hole, $^1/_8$ or $^3/_{16}$ inch in diameter, and to fasten a $^1/_4$ inch steel ball with rosin next to the eyepiece (Fig. 40).

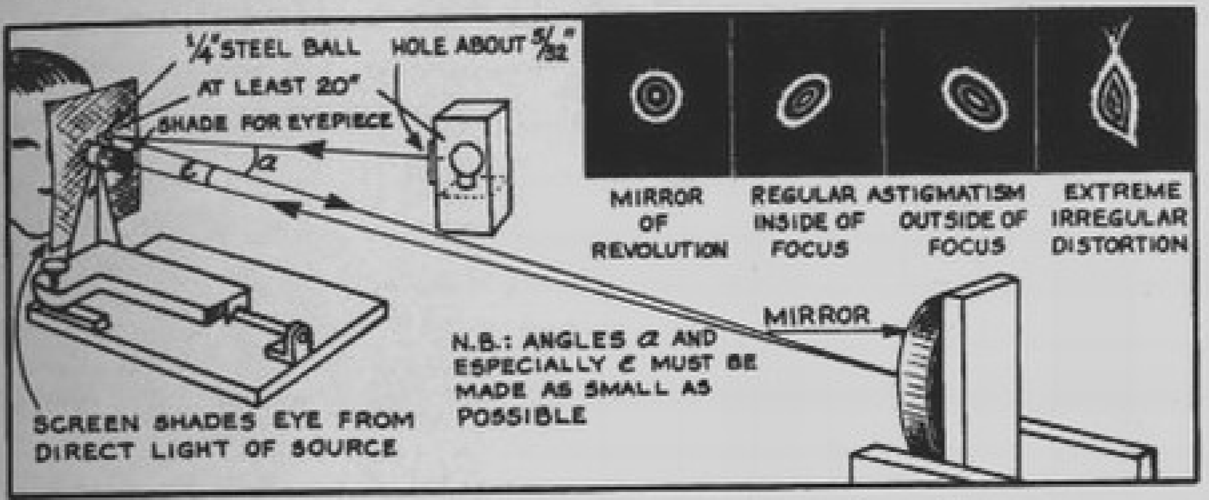


Fig. 40. Studying defects which are other than figures of revolution.

If the ball is highly polished, its surface will produce a "star" in the form of a tiny image of the lamp filament. The quality of the ball surface can be much improved by polishing it with rouge against a small pitch tool mounted in a lathe. Rays from this "star," reflected and focused by the mirror, give an image which we then examine with a rather high-powered eyepiece (for example, 10 millimeters focal length for the effective focal ratio, in this setup, of $f/12$). If the mirror is very nearly spherical, we may focus the eyepiece on a plane close to the focal point, i.e., within 2 or 3 millimeters. If the mirror is exactly a figure of revolution, the image remains quite round. If astigmatism of even $^1/_{10}$ wave is present, the image appears distinctly elliptical. If astigmatism is more pronounced, we detect two distinct eyepiece positions at which the long axis of the ellipse lies in different directions, these being at right angles to each other as shown in Fig. 40. If spherical aberration is also present, we must examine image planes somewhat farther from the focus. The appearance of the images remains quite characteristic, however. In unusual cases, when the mirror is under severe stress (for example, if a handle or glass "reinforcing" plate is cemented at the back), or if it is internally severely strained, the images are quite startling and disastrously irregular, for example, as in Fig. 40, right. Such patterns are not uncommon in commercial objectives.

Before concluding that a mirror has astigmatism, rotate the ball on its center or change the direction of illumination slightly in order to eliminate the possibility of a defective ball surface. Remember, too, that astigmatism

may result merely from improper positioning of the optical elements in the test. For example, if the ball is excessively off-axis, or is illuminated too obliquely, this astigmatism "of position" may no longer be negligible. A good test is to rotate the mirror on its axis; if the axis of the elliptical image, viewed slightly inside or outside the focus, turns simultaneously, the astigmatism must reside in the mirror.[64]

We shall say little about correcting these defects. Surfaces other than figures of revolution result only from a systematic and often inexcusable error, for example, forgetting to turn the mirror when it is in the lower position, or attaching a backing plate or an excessively large handle. In very rare instances, another cause may be a severe nonhomogeneity of the glass. The best remedy in any case, even for the experienced worker, is to try to eliminate the defect automatically, merely by continuing ordinary polishing for at least an hour, and consciously avoiding systematic error by interchanging the disks and varying the stroke, or better (if possible), by changing operators. Only if several attempts of this kind are unsuccessful should one resign oneself to making a new mirror. Such a case has never occurred at the workshop of the Société Astronomique.

II-34. Primary and Micro-Ripple

The efficiency of the polishing action increases greatly at the end of the wet, together with the effort expended in moving the tool. As the latter comes to rest momentarily at the end of the stroke, it may initiate slight "physical-chemical" attack on the glass through contact of the pitch squares loaded with abrasion products, particularly silicates. The point of attack corresponds to a weak spot that is more easily worn down for a period of time, thereby creating a pattern of elevations and depressions corresponding more or less to the structure of the polishing squares. This embossment of the surface is *primary ripple.*

The Foucault test photograph of a 16-inch mirror in Figure 41A shows the partially eliminated ripple on a wide zone finally treated with a local polisher. The amplitude of these defects is about $\lambda/20$, but the corresponding diffraction in the image is not necessarily negligible because quasi-periodicity in the pattern may reinforce some of the higher-order diffraction rings. Figure 41B shows a much more severe, although irregular ripple obtained by an athletic novice working with zirconium oxide and pushing the wets too far. We see clearly the areas of the glass where the *physical-chemical* attack has become catastrophic. Though these defects are less than a quarter-wave, the change they induce in the image is unacceptable, and elimination of such havoc requires several hours of gentle

[64] Avoid touching the mirror. This may heat the disk along a preferred diameter and in itself give the appearance of astigmatism. To avoid a long recooling period, handle the mirror only with thick gloves or through heavy flannel.

polishing. But it is unnecessary for this to happen: polishing should be completed with *varied strokes and without total drying* of the polishing compound. Further, the tool *should not be left in place* at the end of the wet.

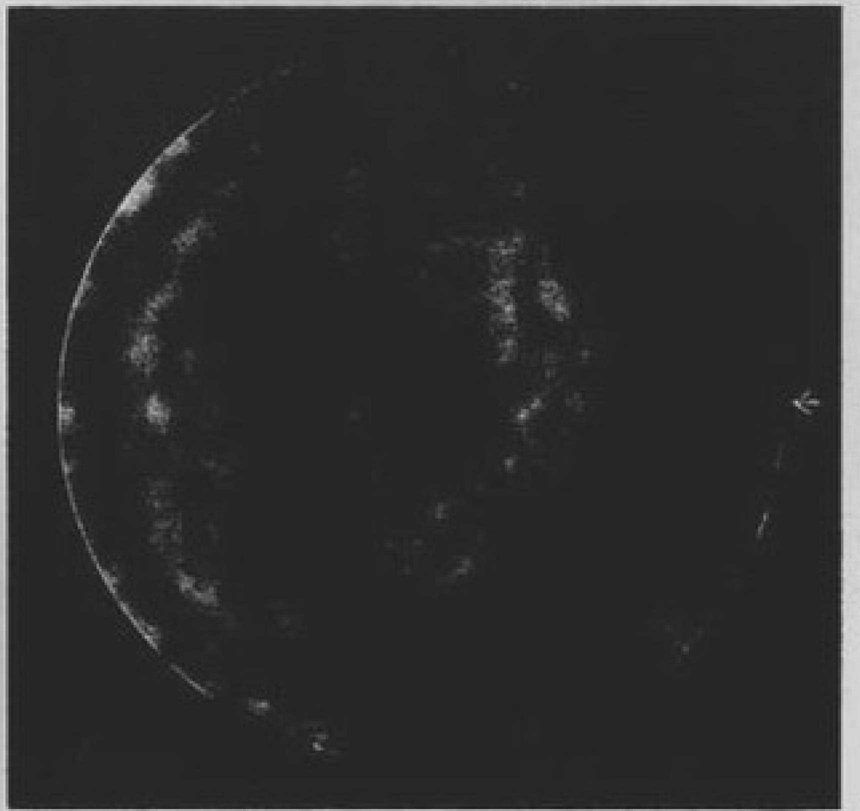


Fig. 41A. Micro-ripple on a 16-inch mirror. Average amplitude λ/20.

The Lyot phase contrast method has revealed a much finer lever of polishing defects that constitute *micro-ripple.*[55] These defects have a width of the order of a millimeter and an amplitude of only a thousandth of a wave (several Angstroms), but there are millions of them on the optical surface and in serious cases the corresponding diffracted light represents a perceptible level of stray light over the entire field. Micro-ripple is something to be particularly mindful of in the difficult case of faint objects of interest near a brilliant source (e.g. solar corona; the companion star of Sirius). Since the defects produced depend almost entirely on the selected polishing technique, i.e. the *nature and structure of the tool; pressure* and *type of polishing agent,* it is easy to produce a mirror of very smooth surface. We have assembled some typical surface patterns in Figure 41C. We see in Figure 41C-1 the large defects formed by the cells of a honeycomb foundation (H.C.F.) tool, and in 41C-2 the defects produced by a paper tool. The shape of these defects may be about 1×10^{-5} millimeters, whereas the more compliant pitch tool leaves defects only a thirtieth as high and with slopes of about 1×10^{-6}. The stray

[55] J. Texereau, *Ciel et terre*, 66 (Nos. 3 and 4) (March and April, 1950). For an account of the author's work in English, see also F. Twyman, *Prism and Lens Making*, 2nd ed., pp. 576-584. Hilger Publications, London.

light diffracted by the surface of Figure 41C-6 is about a hundred-fold weaker than that of the surface of Figure 41C-1.

Tool *materials* are of two kinds: the *compliant* variety, which flow and conform to the mirror surface during polishing (for example, pitch); and the relatively *rigid* variety (for example, beeswax or paper), which do not deform and generally leave defects having slopes ten times as great (10^{-5} instead of 10^{-6}). See Figs. 41C-1, C-2 and C-6.

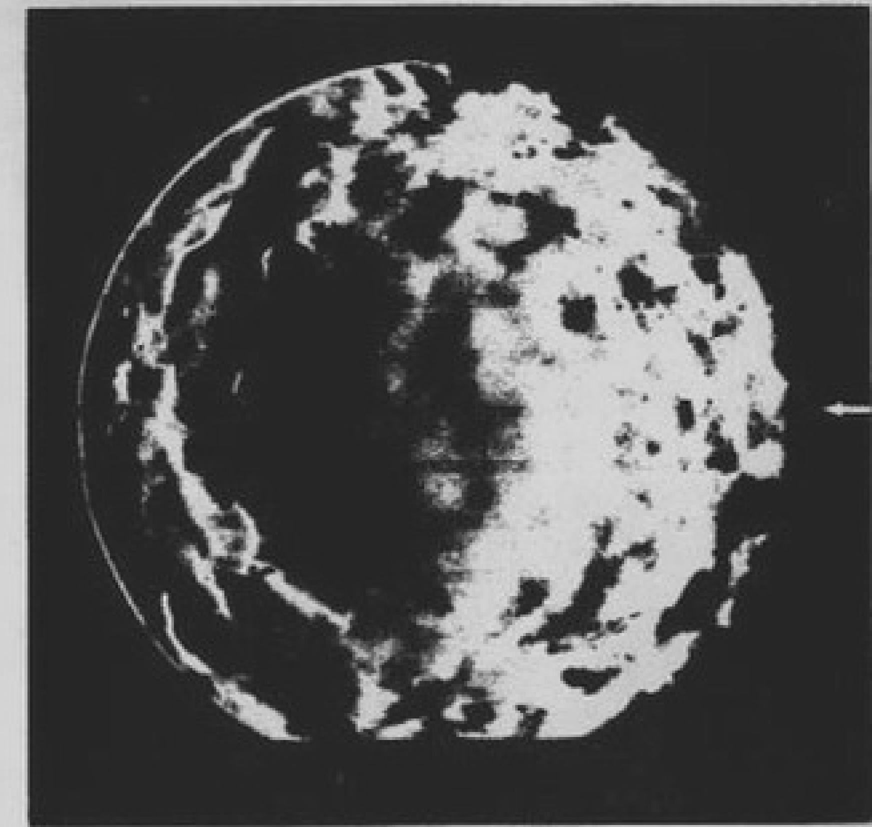
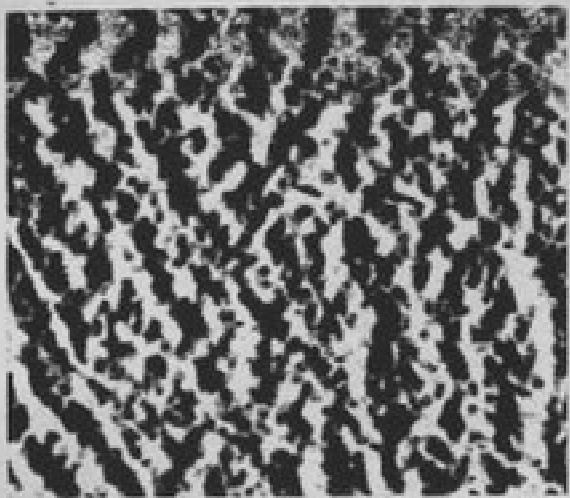


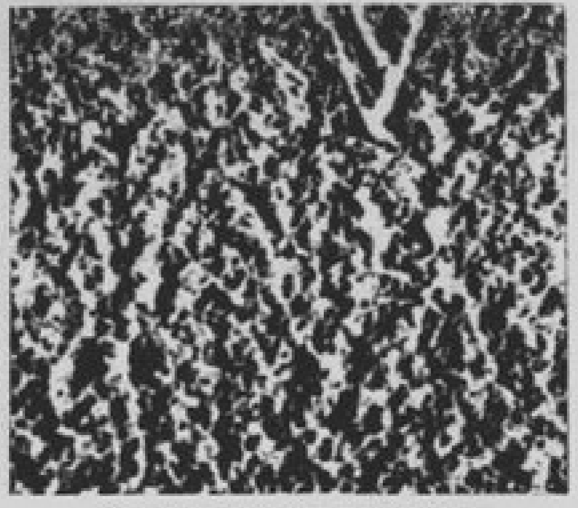
Fig. 41B. Severe micro-ripple on a 7-inch mirror.

Tool structure can imprint itself quite faithfully as ripple on the glass surface, determining both the magnitude of the ripple and its spacing. This is true whether tool features are large or small. Primary ripple, as we have noted, always matches more or less the spacing of the squares of a pitch lap. The hexagonal cells of an H.C.F. lap leave a corresponding ripple that is serious enough to detect even in the Foucault test (Fig. 29A), but can be fully appreciated and analyzed only in the Lyot test (Fig. 41C-1). Even the weave in a silk taffeta (125 lines per inch) used to cover a local polishing tool will leave its trace: a pattern of grooves of corresponding spacing about 1 Angstrom deep!

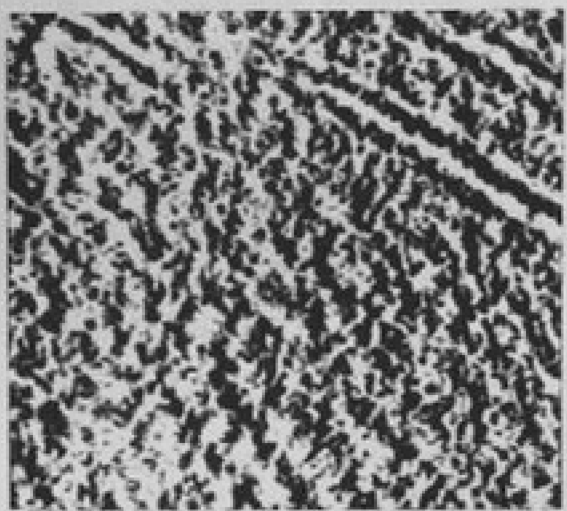
Regarding *polishing agents,* we note that the ultra high-speed materials, if at all capable of producing a "black" polish, generally leave a much more serious ripple than ordinary rouge. Figure 41C-4, illustrating the action of cerium oxide, shows the primary ripple and seizure streaks resulting from the rapid action.



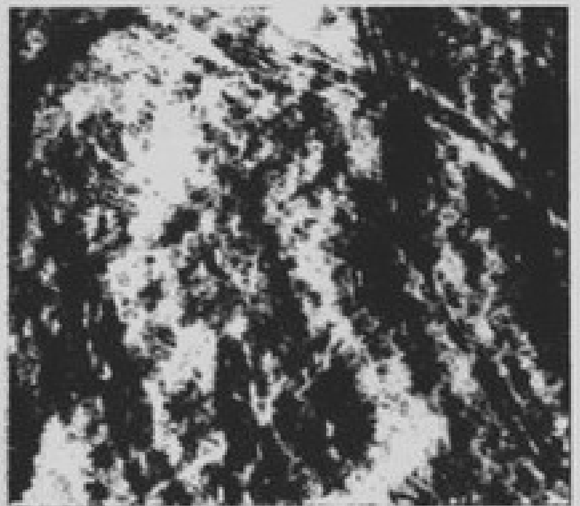
1. H.C.F. lap and rouge.



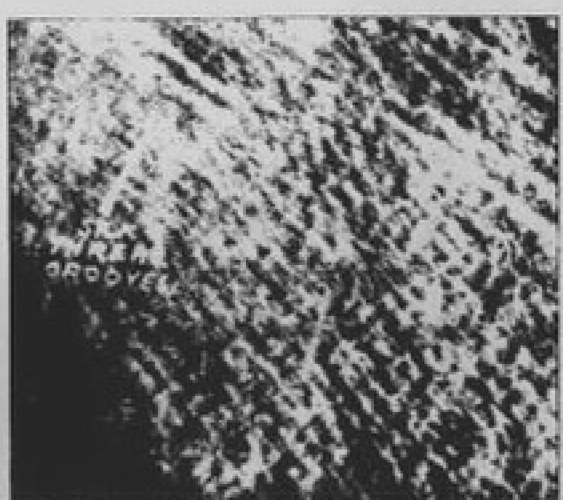
2. Paper lap and dry rouge.



3. Waxed pitch lap and rouge.



4. Pure pitch lap and cerium oxide.



5. Local polisher consisting of rubber eraser covered with silk taffeta.

6. Pure pitch lap and rouge.

Fig. 41C. Lyotgraphs of surfaces polished by various techniques, revealing micro-ripple invisible in the Foucault test. Enlarged 2× actual size. Phase plate optical density: 1.69 for 1, 2, 4, and 5; 2.81 for 3 and 6.

The photographs of Fig. 41C, taken with various phase plates and exposure times best adapted for each picture, cannot be directly intercompared. The mentioned magnitudes of micro-ripple were obtained from the original photographs by measurement with a microphotometer and represent the average error with respect to the mean surface. The amount of light diffracted by the surface of Fig. 41C-1 close to the beam direction is about 50 times that for the surface shown in Fig. 41C-6 under similar conditions.

Primary ripple can be eliminated by alternately using tools with different-sized squares. But this complication is usually unnecessary. The first simple precaution is to avoid screechy, "brute-force" polishing. This heats the work unevenly, causing local sticking. A. Couder[56] has emphasized the importance, in polishing large pieces by machine, of avoiding any tendency of the tool to pivot on abnormal squares. This action may become self-sustaining and build up a disastrous periodic defect. By working with the "fixed post" method, the hazard is reduced. Still, we must control any pivoting tendency that may occur through loss of contact, and permit only such rotation as we introduce deliberately. This is allowed only *during* the back-and-forth movement, not at the end of the stroke. At the Société Astronomique workshop we have *most effectively* combated primary ripple by having four or five persons work on the same mirror (in rotation, 10-minute spell each, using the four available work posts). But the solitary worker too can obtain good results if he will disguise his "personality" by a varied technique: for example, by alternately using the normal "W" and a figure-8 stroke. It sometimes happens that the novice uses so inefficient or poorly defined a polishing technique that primary ripple is almost absent. Unfortunately, the general figure is then also completely out of control, usually badly zoned, and turned down at the edge. In giving attention to very small defects, we must not lose sight of those that are the largest and most serious.

II-35. Zonal Defects

Zonal defects are by far the most frequent and important of surface irregularities. Let us consider again the forms that are most commonly generated (Fig. 42). The sphere (Fig. 42-1) is merely the special case in which the surface error is zero; it is the figure we might produce under perfectly unperturbed polishing conditions. But frequently we arrive at surfaces that are deformed either in the sense of undercorrection (Fig. 42-2) or overcorrection (Figs. 42-3, 4, 5). A rough measurement of longitudinal aberration with the test mask, see Section II-30) immediately suggests the correction that is required. If the deformation is less than that of a parabola, we proceed at once to parabolize, as though starting with a sphere. This is the most favorable possibility; correction can be applied here even

[56] A. Couder, *Cahiers phys.*, 26, 35 (Dec., 1944).

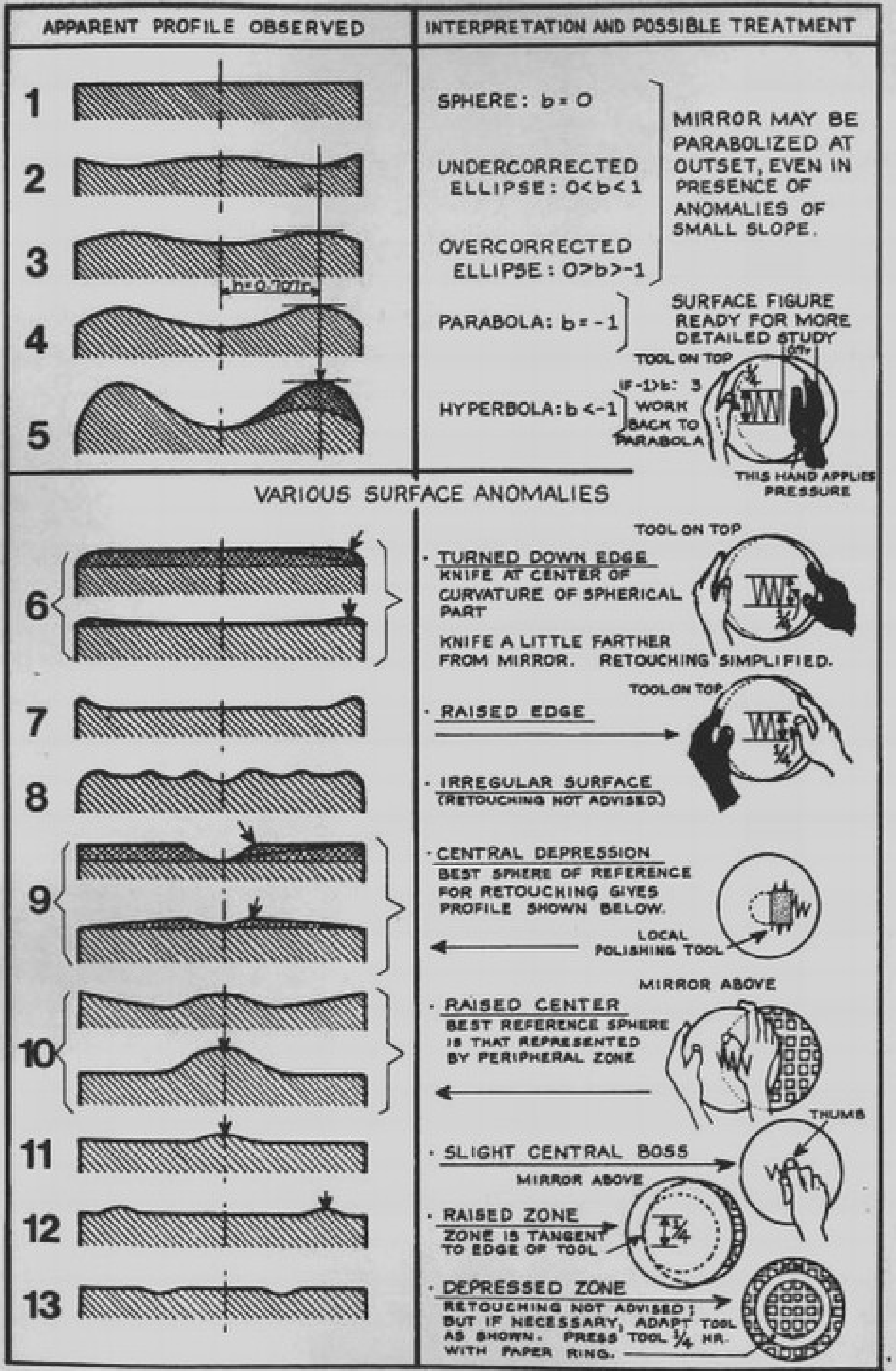


Fig. 42. Examples of retouching procedures for defective zones.

in the presence of a zonal irregularity, provided this irregularity is of rather gentle slope. If the surface is a hyperbola, and the longitudinal aberration is not more than two or three times that of the parabola, we can directly restore the surface to a parabola by applying extra pressure at the 0.7 zone. This is one of several different techniques that we shall describe in detail later.

Quite commonly, however, an abnormal zonal defect exists, owing either to a defective tool or to some persistent error of the operator, that may remain to the end of polishing. We cannot rely on the defect to disappear during the several minutes of parabolizing; therefore we must remove, or at least reduce it.

Before attempting a local retouching step as such, we try to eliminate the defect automatically, by continuing normal polishing at least an hour (checking the condition of the tool and stroke carefully). A defective edge (Fig. 42-6; 42-7) often results from unconsciously applying pressure at the edge of the tool, or from too long a stroke or too soft a lap. An irregularly zoned mirror (Fig. 42-8) is intolerable; polishing must continue, with the tool in good contact, as long as necessary to improve the figure. Other zonal irregularities (Fig. 42-9, 10, 11, 12, 13) may result from a visibly faulty tool, for example, from chipped, missing, or poorly trimmed squares. These must be repaired, and normal polishing resumed for as long as necessary. Often we see a defect difficult to retouch (for example, a concave zone or a central depression), but with continued polishing it disappears or at least is replaced by a defect that is less difficult to cure (a central bulge, for instance).

II-36. Local Retouching

A notebook should be kept for recording, after each successive figuring step, one or more of the important views seen in the Foucault test. Figure 42 gives some examples of the profiles that may be selected by suitable knife positioning. One should record also the kind of stroke, the duration, the pressure applied to tool, etc. For any given worker, this record is the best possible guide for future progress. Unfortunately we cannot in mirror figuring always rely strictly on the operation of cause and effect. This is not meant to cast doubt on any hallowed principle of causality, but to confess merely that we can never understand fully nor reproduce the combined causes that determine the action of a tool at any given time. With the full-size tool (barring a deliberate, strongly perturbed polishing action) we *cannot* predict the effect on the mirror when polishing is sustained only a few minutes. And with the smaller, local polishing tool, it is very difficult to blend the zonal wear into the general surface form. We can nevertheless formulate certain general working principles that remain valid so long as other, disturbing influences do not intervene:

1. *Wear is a function of pressure.* We have found this to be the

most important and reliable of figuring principles. The methods of parabolizing, as we shall see, are merely correlaries to this. The experienced operator, using a full tool, can use this principle to attack almost any type of zonal defect. The advantage, compared with using the smaller, local tool, is considerable. If the mirror is on top, it is possible to increase the pressure locally by decentering the mirror, the stroke being so directed that the zone which is to be reduced is kept tangent to the edge of the tool (Fig. 42-10, 12). Or better, if the mirror is below, the pressure is localized by bearing down on one edge of the tool. (In Fig. 42, the hand applying the pressure is in each case drawn darker.) The edge of the tool, in other words, is a critical area that very easily can be made to produce localized, abnormal wear. Using the same stroke, for example, we can correct at will either a turned-down edge (Fig. 42-6) or a raised edge (Fig. 42-7) merely by bearing down, respectively, on the inner or the outer edge of the suitable decentered tool.[57]

A loose weight, held with the hand on the back of the tool, can permit constant local pressure to be applied without fatigue, but this is not convenient. We must remember always to vary the position of the stroke slightly from side to side; otherwise the removal of the glass may be too sharply localized.

2. *Wear is a function of polishing time.* This is obvious perhaps, but not without its surprises in practice. The "function" is not a simple one, nor is it reproducible. Certainly the wear will not be uniformly proportional to the working time so long as the disks have not settled to a stable temperature. This cannot occur merely in the time taken for a single retouching operation. Typically, using a modified tool or special stroke, 5 or 10 minutes suffices for a figuring action, unless the defect is rather severe (for example, a deep hyperbola) or in a difficult position (e.g., a turned-down edge). If the defect is narrow and the polishing action is markedly abnormal (for example if there is a corrugated central peak, and the mirror is on top, far off center), a single minute's work can produce a cavity very difficult to correct. In case of doubt it is wiser always to work a relatively short time, even if one must return to remove the defect completely.

3. *Wear is a function of relative velocity between tool and mirror.* This principle is of some value in the high-speed, machine polishing of small optics, but for the amateur it is of little practical interest. We must remember, however, that a rapid or jerky stroke will not favor a regular, progressive figuring action and smoothly blended contours.

4. *Wear may be modified by altering the tool surface.* If we deliberately inactivate a portion of the polishing lap, whether by depressing the lap at a certain zone with a piece of paper, or by lightly scraping the lap locally, or by removing certain squares, we alter the action on the

[57] Herein lies an amusing way to mystify the unsuspecting "determinist"—the worker who thinks he can always predict the effect of any given stroke.

mirror correspondingly. The procedure is often used when working with full-sized tools on rather small objectives. On larger surfaces, however, such as our standard mirror, the results are quite unpredictable; it is difficult to control fully the effect produced or to terminate the action abruptly once the defect is sufficiently minimized. The merit of the full, unimpaired tool, in perfect working condition, is not a thing to sacrifice lightly. Nevertheless, for treating a turned-down edge, the method of trimming the corners of the outside squares (a procedure originated by G. W. Ritchey) is quite effective, as is also the procedure, in parabolizing, of reducing the squares progressively in area toward the edge (the Ellison method).

5. *Wear may be localized by using a small tool.* This method, used as early as 1857 by Foucault, is undoubtedly the most reliable; the results, that is, are the most predictable. However, the beginner must not for this reason credit it with every virtue.[58] The local polisher is usually made of wood, about $^3/_4$ inch thick, and may be square, rectangular, or circular depending on the condition to be treated. The tool width may vary from under $^1/_2$ inch to 4 inches. Like the large tool, it is covered with pitch squares, but these are waxed to avoid sleeking, or better (a method of A. Couder), covered with a taut layer of silk taffeta that is tacked down at the back. The action of the cloth is more vigorous and reliable; however, it does cause some micro-ripple and an increase of scattered light. The small-tool method should, in general, be used sparingly. For effective figuring, *never use a small tool on a pronounced defect.* Judging by the curvature of the knife-shadow fringes, the defect should not exceed a quarter-wave. In making the shadow test, we mark on the mirror the position of the high point of the defect; this helps us avoid cutting a groove next to the ridge. The rouge is used thicker than in normal polishing. If the defect is rather narrow (for example, as per Fig. 42-11), the operator's thumb, well covered with rouge, can be an effective tool or (on a narrow turned-down edge) even the index finger.

The pressure applied to the small tool may be considerable—easily as much as a pound on a tool, say, 2 square inches in area. To blend the treated zone into the adjoining surface, we must sufficiently vary the stroke, not only in direction and length, but in lateral displacement to either side of the zone peak. The neglect of these precautions is, for the beginner, the commonest error in local retouching. Working time may be reckoned by the number of complete turns made around the disk. The strokes are short and rapid. A single turn around the work, lasting about a minute, is often enough for a weak zonal defect.

Mastery of the small tool comes only with experience. A volume of instruction could be given, but at this point it would only confuse the beginner. Unless he is quite sure of himself, the amateur is advised to avoid

[58] Remember that Foucault polished with a paper lap, and that this did not lend itself to other, better retouching techniques.

the method altogether. Clumsily handled, it can easily turn a broad, gentle defect into a seriously irregular surface. When we consider how small the defects are that may properly be treated by this method, it is apparent that for the average amateur its use is not compelling. But for the worker who must trifle to obtain better than $^1/_{20}$ wave precision (and will take the risks involved) the method may hold some interest.

II-37. Parabolizing

This technique, of which so much has been said and written, is in truth only a rather simple example of a modified polishing procedure. For mirrors of moderate size and of the ordinary focal ratios it offers little difficulty.

Classical Method (Fig. 43*A*). The mirror is in the upper position, and both the stroke length and the lateral displacements are greater than normal. The stroke length may be as much as four-fifths the mirror diameter. Preferably, we trim the corners of the outside pitch squares to reduce the possibility of a turned-down edge, but this is not reliable if the pitch is too soft. If the *f* number is 6 or less, the squares may be diminished progressively toward the edge. In Ellison's method,[59] the opposite edges of each row (and column) of squares are trimmed to converge in the form of arcs from the center toward the edge of the tool. The tool is pressed carefully but should not be too cold; unfortunately we cannot count on a prolonged working spell to stabilize tool and mirror temperature. The first figuring step on an 8-inch, *f*/8 may last 8 or 10 minutes. This is a good duration for an *f*/6 also, since it is better not to attempt parabolizing all at once. Rouge and water are applied thicker than in normal polishing to prevent irregular drying and loss of contact.

If we could continue always to have an "average" operator, we would obtain almost at once, in moderate focal ratios, a parabola to a very close approximation. The author's group has parabolized a number of mirrors "automatically," in effect, by using a team of four or five operators all applying the "same" stroke. The stroke used was shorter than normal for parabolizing, i.e., not more than two-thirds the diameter. Total parabolizing time was about an hour, the operators being changed every 10 minutes.

Method of the Small Tool (Fig. 43*B*). If the mirror is a 12- to 20-inch, working with the mirror on top is laborious. Also it is hazardous, and the figuring action is difficult to control. The pressure, moreover, may be excessive. A tool of half the mirror diameter may be used here to good advantage. The method is of interest mainly in perfecting the form after the full-sized tool is used. If used too long, however, the small tool introduces the danger of sleeks and micro-ripple.

[59] Described in A. G. Ingalls, *Amateur Telescope Making I*, pp. 90–91, Scientific American, Inc., 1951.

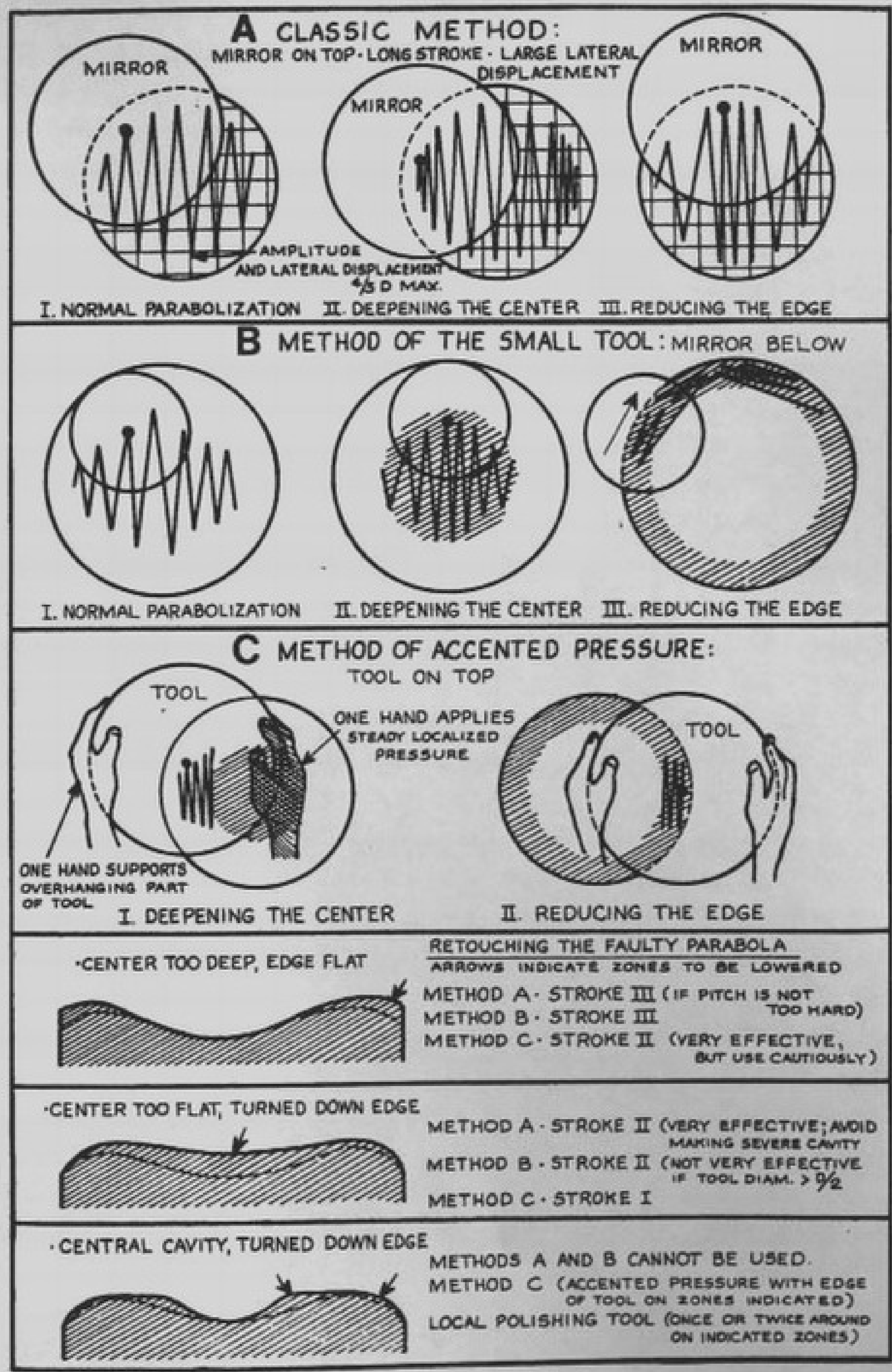


Fig. 43. Parabolizing methods.

Method of Localized Pressure (Fig. 43C). The author chanced upon this technique while figuring a 10-inch, $f/4$ mirror, in which the "classical" method could safely give only an ellipse no more than half as deep as the required parabola. In this method we deepen the center of the mirror by placing the tool on top in a decentered position, concentrating pressure on the inside tool edge (Fig. 43C-I). If we decenter the tool a relatively extreme amount (Fig. 43C-II), it is the edge of the mirror that is worn down. In a like manner, we may treat any high zone in an imperfect parabola by steadily working the inside edge of the tool, under localized pressure, over that zone. Naturally, the tool must be varied sufficiently in position, side to side, to prevent grooving and to assure smooth blending. The treatment is applied, of course, around the whole zonal circle, and should comprise moreover a whole number of turns around that circle. The method requires some experience for full success; but it does serve where often the only other available recourse is the small tool.

II-38. Retouching the Defective Parabola

We must develop, through practice, a certain "feel" for the Foucault shadows before we can interpret forms which differ somewhat from those of Fig. 37. Having then arrived at approximately the desired form, that is, one giving a shadowgram resembling Fig. 37*B*, we measure the longitudinal aberration (without screen, Section II-30) and determine whether to deepen the mirror further or to return to a form closer to the sphere. This has been discussed in Section II-35. Aside from mere depth of the figure, however, we must consider its regularity. Figure 43, lower portion, shows retouching techniques applicable to three very common types of defect.

We are now approaching more precisely the desired surface form.[60] It is advisable at this point, for the beginner especially, to make at least a couple of quick measurements on each zone with the Couder mask (Sections II-31 and II-32). To avoid making a complete calculation after each retouching step, the author recommends the following simplified procedure, which will suffice to bring the standard mirror to completion:

Assume we have found the following knife positions for zones 1 to 4 respectively:

Knife position (inches):	1.103	1.163	1.227	1.255
h_m^2/R (theoretical):	0.005	0.042	0.090	0.139

The values of h_m^2/R (rounded to three decimal places) are the precalculated (theoretical) values written on the Couder screen. To visualize how the

[60] Ellison started a vogue for the partially parabolized mirror (e.g., 90 per cent of theoretical longitudinal aberration) on the theory that it compensates for subsequent temperature effects. Actually, this could compensate only under exceptional circumstances, and cannot justify a permanent, deliberate error. Be this as it may, the theory has served for some as a convenient cover-up of imperfections which in this way are made to appear calculated.

surface departs from the theoretical, let us for the moment assume that the departure at zone 3 (where the readings are most reliable) is zero. We must therefore subtract from each knife position reading the constant

$$1.227 - 0.090 = 1.137.$$

This gives for the respective zones:

$$-0.034 \quad 0.026 \quad 0.090 \quad 0.118.$$

Comparing these with the theoretical values of h_m^2/R, we note that the readings for all zones are too small, except for zone 3, which we have taken as zero. It is therefore zone 3 which differs distinctively with respect to the ideal values (and in fact may depart the most from the desired radius of curvature). By adding another suitable constant we can distribute the errors more evenly, that is, we can make the maximum positive and negative departures more nearly equal, and so obtain a more balanced picture of relative zone error. For example, by adding 0.015 we obtain

$$-0.019 \quad 0.041 \quad 0.105 \quad 0.133.$$

To guide us in retouching the mirror, we need only to make a rough sketch of the mirror profile as it varies along the radius. We draw this freehand (only roughly to scale) in the figuring notebook as follows (see Fig. 44): The

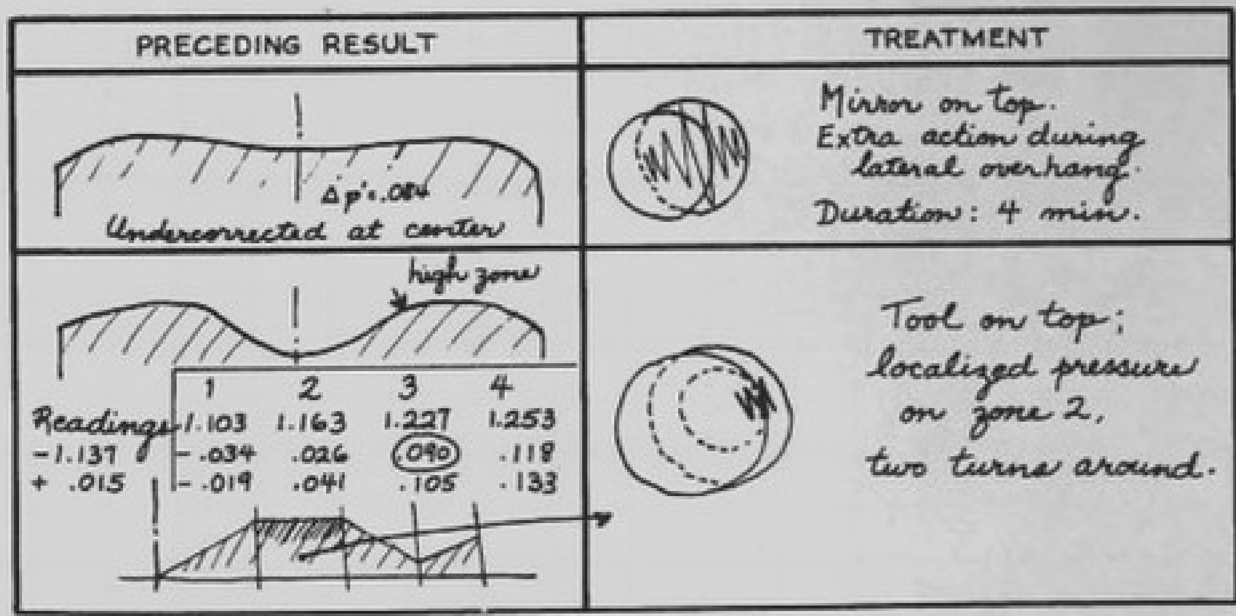


Fig. 44. Excerpt from a retouching notebook.

zone demarcations starting from the center of the mirror are laid off along the horizontal axis using four vertical lines spaced to correspond roughly to the aperture limits. We note that zone 1, with a relative knife position of −0.019, is too short in radius of curvature with respect to the selected reference surface by the amount 0.019 + 0.005 = −0.024 inch. Thus zone 1 is too concave, and must appear in our picture of the right half of the mirror profile as a rising slope. In zone 2 the error is negative merely by 0.001. The contour is therefore practically parallel to the horizontal axis. In zone 3 the departure is strongly positive: 0.015 inch; the surface here descends noticeably. Finally in zone 4 we have a deviation of —0.006; the curve turns up again slightly.

The broken line shows qualitatively how the half-profile varies with respect to a horizontal line representing the reference surface. We note immediately the presence of a high zone that may be corrected by working chiefly on zone 2, for example by localized pressure on that area with the edge of the tool (Fig. 43).

When the longitudinal errors have been reduced to less than 0.005 or 0.01 inch, it is time to perform a more careful set of measurements and to make a complete calculation of the surface figure.

II-39. Reducing Aberrations to the Focal Plane

To determine whether the mirror is satisfactory, we must know what the residual aberrations correspond to in the *focal plane*, i.e., what the quality of the reflected wavefront is when the mirror focuses the light from a very remote source, such as a star.

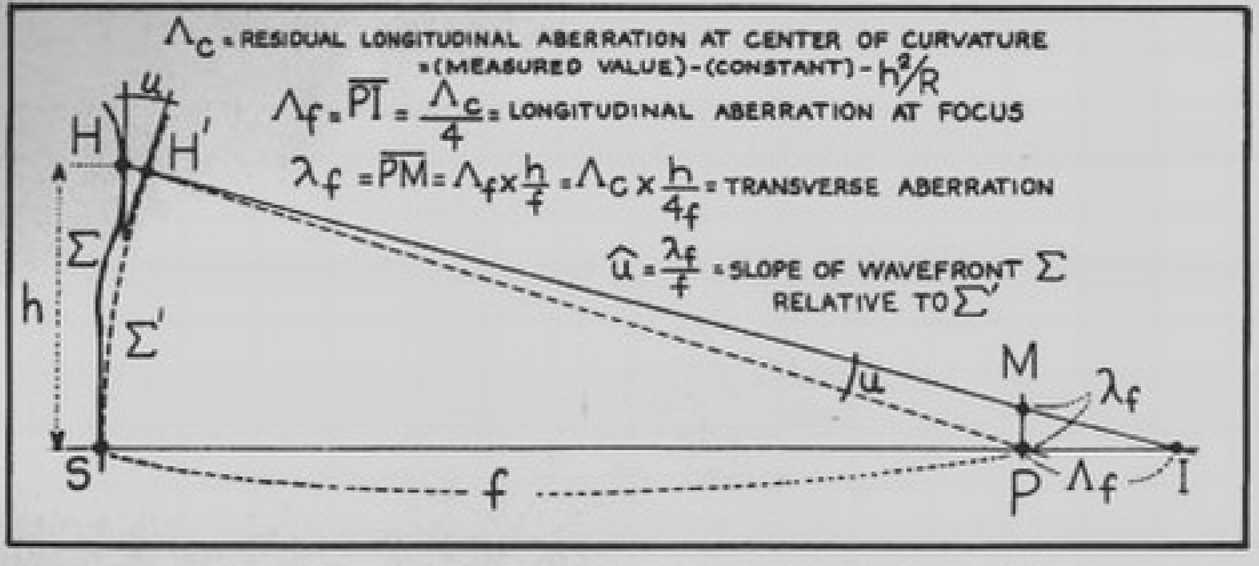


Fig. 45. Relationship between the various measures of aberration.

The residual errors we obtained by subtracting from the knife positions a suitable constant and the theoretical aberration h_m^2/R represent true mirror defects, and are designated *as residual longitudinal aberration at the center of curvature.* These are symbolized by Λ_c.

The corresponding longitudinal errors *at the focus*, Λ_f, will be one-fourth as large. Figure 45 shows the conditions at the focus. A reflected ray *HMI*, originating in a defect at *H*, intersects the axis at a distance *PI* from the *ideal* ray *H'P*. The longitudinal aberration error Λ_f is this distance *PI*.

The short line *PM* is the corresponding *transverse aberration* λ_f. It is easy to show that since *PI*, and especially *HH'*, are very short compared with the focal length *f*, the transverse aberration can be expressed with sufficient accuracy by the relationship

$$\lambda_f = \Lambda_c \frac{h}{4f}. \qquad (16)$$

The angle between the tangent at point *H* on the actual wavefront Σ, and the tangent *H'* on the ideal wavefront Σ', is equal to *u*. This angle is a measure of the *slope* of the wavefront Σ at point *H* with respect to the ideal wavefront Σ', and may be obtained of course (to a sufficient approximation) by dividing the transverse aberration λ_f by the focal length *f*. If we make a diagram, joining a series of these slopes end to end, we can schematically show the wavefront profile and determine quantitatively the magnitude of the defects. For this we require no more than simple arithmetic.

II-40. Test Data Sheet*

Figure 46 illustrates a useful form in which to tabulate the final mirror test data. Successive numbered rows in the table are filled in as follows:

1 to 4. These data are copied from the worker's Couder mask. See Section II-31.

5. The average zone radius (h_m) divided by $4f$. This is the quantity we later multiply by Λ_c to obtain λ_f in a single step—a convenience if the mirror is not immediately acceptable and the calculations must be repeated.

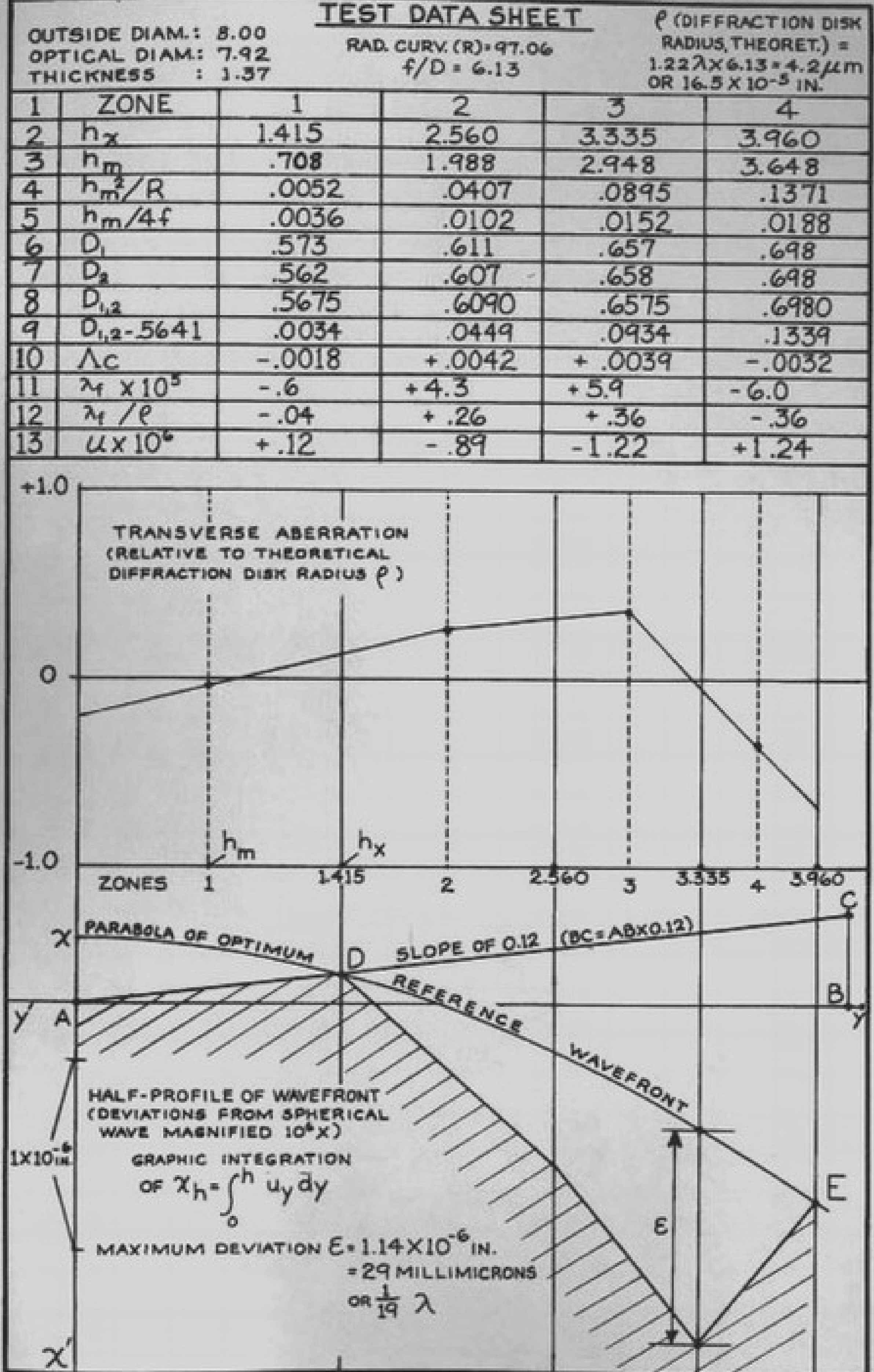
6. Each value is the average of at least four good longitudinal knife-position readings taken at each zone. The mirror remains fixed throughout the readings.

7. Another set of readings like those of line 6, but the mirror has first been rotated a quarter-turn (assuming that readings in row 6 have been taken along an arbitrary mirror diameter D_1, the present readings are taken on a diameter D_2, 90° away).

Note: Regular differences occurring between the values of lines 6 and 7 do not indicate a generally astigmatic mirror; remember that the knife-to-mirror distance has probably changed between the sets of measurements. The relative values could, however, indicate astigmatism within a zone.

8. The averages of lines 6 and 7, which we shall take as representative of the mirror as a whole.

9 to 11. The values in row 9 are obtained indirectly, by subtracting from row 8 a suitable constant, determined by trial and error, that will equalize as much as possible the deviation in either direction from a perfect parabola. *Note carefully:* the selected constant must be such that, comparing lines 9 and 4, we see differences, or residual longitudinal errors (*line 10*, equal to line 9 minus line 4), which, multiplied by the zone factor $h_m/4f$ (line 5), give maximum transverse aberrations λ_f (*line 11*) *equal and opposite*



1	ZONE	1	2	3	4
2	h_x	1.415	2.560	3.335	3.960
3	h_m	.708	1.988	2.948	3.648
4	h_m^2/R	.0052	.0407	.0895	.1371
5	$h_m/4f$	.0036	.0102	.0152	.0188
6	D_1	.573	.611	.657	.698
7	D_2	.562	.607	.658	.698
8	$D_{1,2}$	.5675	.6090	.6575	.6980
9	$D_{1,2}$-.5641	.0034	.0449	.0934	.1339
10	Λc	-.0018	+.0042	+.0039	-.0032
11	$\lambda_f \times 10^5$	-.6	+4.3	+5.9	-6.0
12	λ_f/ρ	-.04	+.26	+.36	-.36
13	$u \times 10^6$	+.12	-.89	-1.22	+1.24

Fig. 46. Facsimile of a test data sheet.

in sign. In effect we "weight" the values in line 10 by the factors of line 5. For example since factor $h_m/4f$ for zone 4 is about five times that for zone 1, a given negative value of Λ_c in zone 1 would be balanced by a positive value in zone 4 only one-fifth as great. Line 11, accordingly, shows adjusted transverse deviation values λ_f as seen at the *circle of least aberration* (see Section II-28).

12. The value of *relative* transverse aberration, i.e., image error relative to the theoretical diffraction spot radius ρ. As shown earlier (Section I-3), the theoretical radius is $\rho = 1.22\,\lambda\,(f/D)$.

13. The angle u, which represents the error of slope for each zone and has a value (in radians) equal to $-\lambda_f/f$ (note the minus sign). We multiply this by a very large factor to represent it conveniently on the graph. The factor of a million used in Fig. 46 suggests the order of magnitude involved.

In both graphs of Fig. 46 the horizontal scale represents the zone radius or "radius of incidence" h. We shall here adopt a more general designation and call this the y axis (consistent with the practice of previous writers). The four parallel, vertical lines mark the boundaries (line 2 of data table) of the four zones.

The upper graph merely depicts the data of line 12. The upper and lower horizontal lines (± 1.0) represent values of λ_f equal, respectively, to plus and minus ρ. Transverse aberrations are thereby directly compared with the theoretical diffraction spot dimensions.

The vertical scale x of the lower drawing depicts the differences (HH' of Fig. 45) between the ideal spherical wavefront Σ' (having its crest at S and center at P) and the actual wavefront Σ (also with crest at S).

At point H, the deviation HH', in mathematical terms, would be given by

$$x_h = \int_0^h u_y dy. \quad (17)$$

That is, the distance HH' is the integral of the slope error u taken from the mirror center to point H. For present purposes, however, it is sufficient to make a simple graphical integration. If we have a sheet of graph paper, even a ruler is unnecessary. The skeptics may raise their eyebrows at this, but we urge them to bear with us.

Within the limits of zone 1 we draw a line whose slope, $u \times 10^6$ (line 13), is $+0.12$ (the "curve" rises when the slope is positive, descends when it is negative) as follows: starting from a point at an arbitrary level at point A on the xx' axis (which coincides with the mirror optic axis), we mark off a convenient horizontal length AB, 4 inches, for example. At B we mark off a vertical height, BC, 0.12 times as long, i.e., 0.48 inch, and join points A and C. We continue this inclined line only to D, of course (the boundary between zones 1 and 2), in order to represent the first slope segment. D is now the starting point for the second slope, -0.89, drawn within the zone 2 limits. We continue this way through zone 4 to the outer edge of the mirror.

Obviously this jagged contour of four lines can only remotely resemble the actual wavefront with its complex, infinitely varied detail. Like certain modern paintings, it is an abstraction. This is no reflection on its usefulness, however; remember that whole continents are represented on a classroom globe! The angular profile does show the maximum limit of error, and if this value is not exact, at least it errs on the conservative side.

We need now only to compare the schematic contour with the particular spherical surface from which it differs by the least possible amount. This surface is not generally the one represented by the wavefront Σ', which in our drawing would be a line parallel to the horizontal or yy' axis (for the same reason, the plane of the circle of least aberration is not necessarily that of the best image). We have the right, of course, to find the center of the *optimum* reference wavefront, or expressed differently, to focus on the plane of the best image. This wavefront, of slightly different radius from Σ', must touch the broken profile at the two highest points; in the case illustrated, at *D* and *E*. The profile of this sphere, which deviates from the ideal surface Σ' as the square of the radius of incidence h, will appear on the drawing as a parabolic curve. The parabola must be such that its axis coincides with xx', and that the curve passes through the points *D* and *E*. The perfectionist could at this point calculate the equation of the parabola that satisfies these conditions; but others will summarily sketch the parabola freehand; it will be a smooth curve that starts at the left perpendicular to xx' and traverses the two high points.

Our evaluation is nearly completed—it remains for us now only to measure the maximum discrepancy between the angular profile and the parabola. Remembering that the vertical scale is magnified a millionfold, we can compare the discrepancy with the wavelength of light. Taking as a reasonable value the wavelength to which the eye is most sensitive, i.e., 560 millimicrons, we note that a vertical inch on the graph represents $^1/_{22}$ wave.

We should add some remarks, finally, about the accuracy of the test data. The actual precision of the knife position readings (Section II-32) does not permit us to obtain average values to better than about 0.0005 inch, assuming an effective "focal ratio" in this test of $f/12$, and a surface free of small, steep defects. The corresponding errors in transverse aberration λ_f are of the order of 1×10^{-5} inch, and for the slopes u about 2×10^{-7}. To avoid accumulation of error, however, in the final mirror data, we have calculated longitudinal aberration Λ_a to 1×10^{-4} inch, λ_f to 1×10^{-6} inch, and u to 1×10^{-8}. But remember that *this precision has no real physical meaning.* In any case, we can determine ϵ, the maximum wave error, to no better than about $^1/_{50}$ wave, but this in practice is already more than sufficient.

For a provisional test data sheet, it is sufficient to calculate Λ_a to 0.001 inch and λ_f to 10^{-5} inch. On the graph showing wave contour, the slopes u would be multiplied by only 10^5—a more convenient value for indicating any defects that have to be retouched.

II-41. Interpreting the Test Data

The meaning of test data such as we have derived is of interest not only to the amateur mirror maker but to anyone who wishes to purchase a finished objective. The purchaser should in fact expect such data from the manufacturer.

Danjon and Couder have pointed out[61] that a good objective must satisfy a double criterion:

1. The radius of the circle of least aberration should be comparable with that of the theoretical diffraction disk and, on the average, the transverse aberrations should not exceed the diffraction disk radius.

2. Maximum wavefront error must not exceed a quarter-wave and, for the major part of the mirror surface, the defects should be appreciably less.

The graphs on our test data sheet tell immediately whether a mirror meets these two criteria. For small mirrors, generally speaking, the first condition is the more difficult to satisfy. A short summary of the test data, giving only calculated λ_f values, can therefore of itself be quite valuable. For the second criterion we often impose an even smaller tolerance. The reasons are discussed in Section I-4. At the workshop of the Société Astronomique, we release a mirror only when final values of λ_f/ρ are less than 1 and the wavefront error is under $^1/_{10}$ wavelength. In fact, the wavelength error usually proves to be much below this value.[62]

If a mirror satisfies these tolerances, it is pointless to look for a defect by observing a star. If an image defect is nevertheless visible with such a mirror, then the mirror is either decentered or poorly mounted.

Those who purchase an objective must be given this word of caution: don't place your trust merely in a Foucault-test photograph supplied by the maker. The contrast of such a photograph can be manipulated at will. If a complete data sheet is provided, check the scale factor applied to the wave profile. For example, if a magnification factor of only 10^5 is used, it gives a much less startling picture of mirror defect slopes. Also, opticians are known to show the profile *on the glass,* rather than on the wavefront, thereby making the defects appear only half as large. If the data are incomplete, for example, if only residual longitudinal aberrations are given, the purchaser should make the simple calculation necessary to obtain the corresponding λ_f values, and compare these with diffraction disk radius. The telescope mirror embodies the amateur's highest hopes; it is not an object to acquire blindly. Visible defects of abrasion, on the other hand, such as grayness, sleeks, scratches, or chips, unless extreme, merely mar the mirror's beauty; their effect on the image is very small.

The most exacting stage in the making of the telescope is now completed. The author would be distressed if any reader, at first attracted to

[61] *Lunettes et Télescopes*, p. 522.

[62] Average wavefront error on the first 18 mirrors was $\lambda/20.4$.

optical glass working, has been turned away by the many details that we have here presented. Surely, not every detail is indispensable for a satisfactory or even a perfect mirror. We have felt, however, that every amateur who has the ability to do so has also, in a sense, the duty to make a perfect mirror, and should be given every opportunity to achieve such a result. The discipline is an excellent one. It makes the amateur both worthy of owning a powerful telescope and better prepared for that far more delicate task: observing the stars to advantage in an atmosphere that is constantly beset with perturbation.

III

THE PLANE DIAGONAL MIRROR

III-1. Mirror vs. Prism—Comparative Requirements

In the Newtonian telescope, the converging beam is deflected to one side in order to make the focal plane more accessible. For this purpose either a total-reflection prism is used or a "diagonal"—a plane mirror usually tilted at 45° with respect to the main beam.

The advantages of a prism (for mirrors of focal ratio equal to 5 or more) should not be minimized. Most important, it eliminates upkeep of a metallized surface that is particularly exposed to the effects of dew. The prism is not an unusual optical element nor is it difficult to obtain. Unfortunately the necessary quality is rarely found in the ordinary prisms used mainly for image inversion in low-power systems. The flatness requirement for the diagonal prism face is approximately the same as that for a diagonal mirror surface. In the prism, unfortunately, these errors are compounded with errors in the entrance and exit faces, errors of angle between the faces, and effects of nonhomogeneity in the glass. In addition, the prism must be rather large: 40 millimeters wide or more at the small face. Such objects are exceedingly rare. The prism moreover behaves like a plane-parallel glass plate of a thickness equal to the width of the small side. For a beam of focal ratio equal to 6 or less, traversing a 40-millimeter glass path, the resulting spherical overcorrection and chromatic aberration are hardly negligible. The plane mirror, on the other hand, introduces no aberration.

Since the diagonal mirror is relatively close to the focus—a distance about one-tenth the focal length—we may in principle tolerate defects ten times as large in slope as those in the main mirror. The essential consideration, as always, is the effect on the wavefront. To satisfy the Rayleigh criterion (taking into account the 45° incidence angle), the error in the glass surface may not exceed about $\lambda/_{12}$. Because the mirror is inclined, we cannot choose, as in the main mirror, from among several reference surfaces or slightly different curvature. The curvature here must be zero; otherwise the reflected beam is astigmatic. If we permit ourselves astigmatism to the extent of $\lambda/5.5$ in the wavefront, then curvature in the mirror, concave or convex, may not exceed $^1/_8\ \lambda$.[1]

Few Newtonian telescopes have been made with a diagonal of this quality. Errors of fully a wave are common. We had occasion once even to see a convexity of nine fringes in a beautiful 12-inch telescope! In part, at least, the poor reputation of commercial Newtonian reflectors stems from this kind of negligence.

III-2. Form and Dimensions of the Diagonal Mirror

If the beam is deflected at right angles, the form of diagonal that obstructs the incoming beam the least is the one obtained by cutting a glass plate with a circular cutter presented to the surface at a 45° angle (Fig. 47*A*). If the short axis of the ellipse is *a*, the length of the long axis is $a\sqrt{2}$. This "sausage slice" is not easy to make in practice, and because the edge at one end is so thin, its surface is rarely as good as that of a piece uniformly thick. The amateur usually confines himself to a mirror with square edges. Depending on the preferred method of cutting, the shape may be octagonal (Fig. 47*B*), rectangular (Fig. 47*C*), or circular (Fig. 47*D*). All these obstruct the beam somewhat more than the ellipse, but even in the least favorable case (Fig. 47*D*), this is a negligible factor compared with the importance of obtaining a better surface.

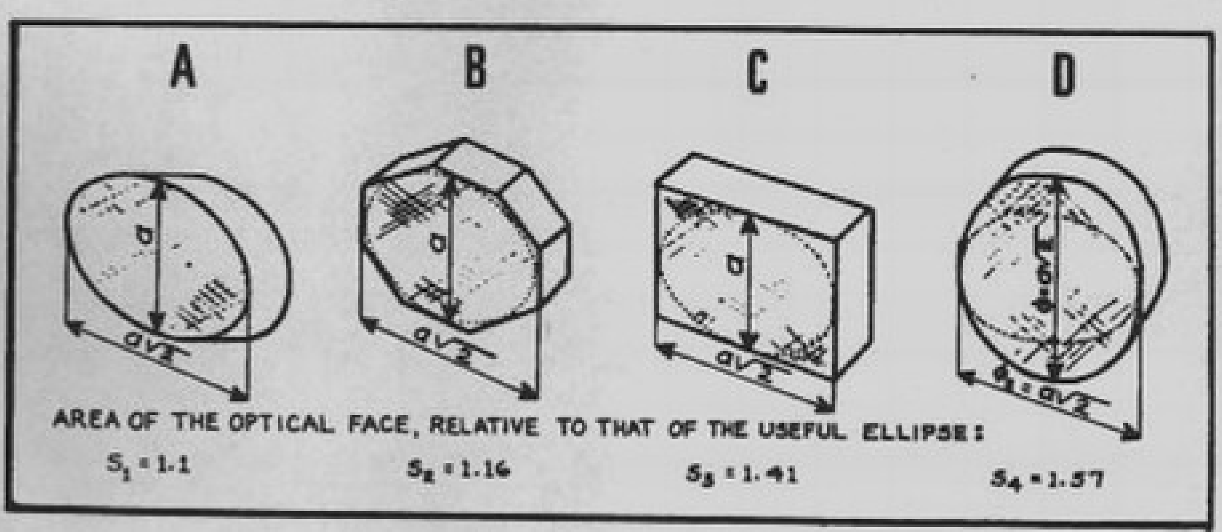


Fig. 47. Various forms of diagonal mirrors.

To determine for any given telescope the required mirror dimension *a*. we must know the following (Fig. 48):

a. optical diameter *D* of the primary mirror;
b. focal length *f* of the primary mirror;

[1] A. Couder, Thesis, "*Recherches sur les déformations des grands miroirs employés aux observations astronomiques*," p. 10.

c. distance *l* between the center of the diagonal mirror face and the focal plane; and
d. diameter *d* of the fully illuminated field we wish to cover.

The distance *l* is the sum of the following: (*1*) outside radius of the telescope tube (or half the width of the side, if the tube is square); (*2*) overall length of the eyepiece holder assembly (Figs. 58, 60) when fully collapsed; and (*3*) a certain amount of clearance between the end of the collapsed eyepiece holder and the focal plane. Allowing such clearance makes the focal plane externally accessible if desired and is now more or less standard practice, especially to permit direct photography at the focus. If

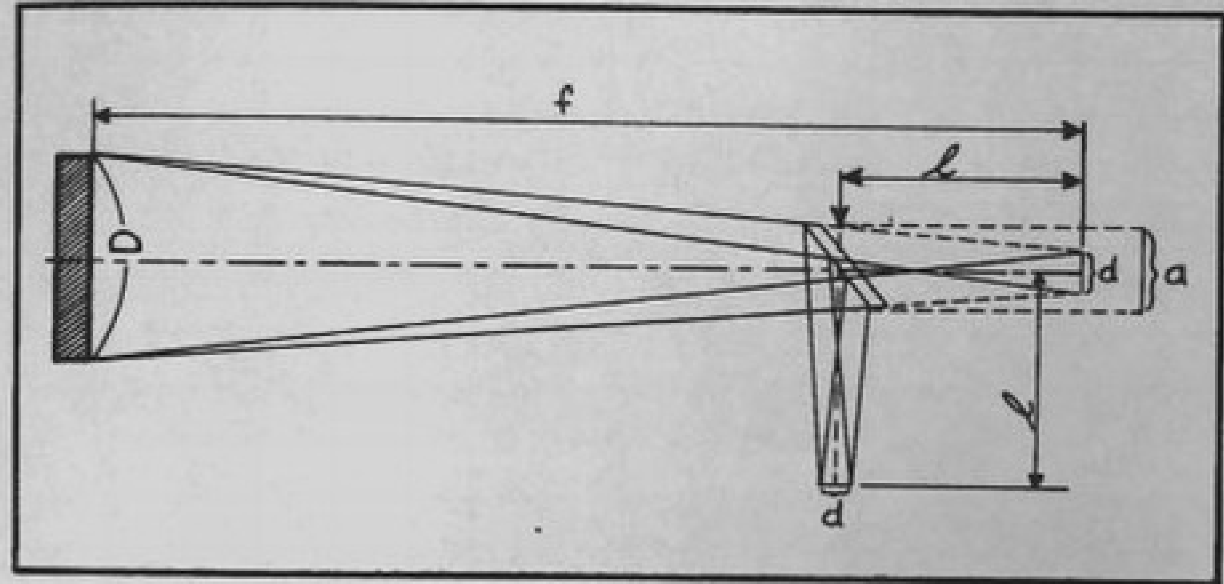


Fig. 48. Dimensions of the diagonal mirror.

only visual work is anticipated, the clearance need be only enough to permit focusing with the strongest negative eyepieces. In mountings that take the usual slip-fitted eyepieces, a clearance of $^3/_8$ inch or $^1/_2$ inch is sufficient. To allow for photography at the focus, however, we must take account of the depth of the camera. Generally speaking, attaching any accessory shortens the main telescope tube and calls for increased clearance between the eyepiece mount and focal plane. Attaching such items as a polarizing helioscope or an inverting prism should not be attempted, however, without a diverging lens to increase the focal length by the required amount.

We need now only to determine the diameter *d* of the fully illuminated field that we wish to cover. For most visual work, a field angle equal to the moon's diameter (31 minutes) is sufficient. The diameter of the moon's image in the focal plane is 0.009 times the focal length *f*. For $f = 48$ inches, this is 0.43 inch. In photographic work, however, one often strives for maximum field angle (note that the usual field of a medium-size telescope does not even cover a large nebula). In this case the practical limit is set by off-axis aberration of the parabolic mirror. The diameter of the faintest photographic star image attainable at the focus of a medium-size telescope is about 25 to 35 microns. At the edge of the field, however, we must accept poorer definition, for here we must cope with astigmatism and coma. If we set a limit of 100 microns on the permissible radial "fanning" or elongation of the image, due to coma and astigmatism, we derive the data of Table VI, giving the maximum allowable field diameter *d*, for various amateur-size mirrors, both in minutes of arc and inches at the focal plane.

TABLE VI
PERMISSIBLE FIELD DIAMETERS
(In minutes of arc and inches at the focal plane)

Mirror diam., inches	Focal ratio (f/D)			
	5	6	7	8
6	103′ 0.85 in.	116′ 1.20 in.	130′ 1.60 in.	138′ 1.90 in.
8	80′ 0.90 in.	92′ 1.25 in.	102′ 1.65 in.	110′ 2.00 in.
10	66′ 0.95 in.	76′ 1.30 in.	86′ 1.75 in.	92′ 2.10 in.
12	55′ 0.95 in.	64′ 1.35 in.	73′ 1.80 in.	80′ 2.20 in.

For small mirrors of relatively large *f* number, this criterion may lead to an excessively large, obstructive diagonal. To do both visual and photographic work in this case, it is best to have interchangeable diagonals, a larger one for photography, and a smaller for visual work.

Having now the four necessary dimensions, we may sketch the telescope to half scale in the manner shown in Fig. 48, tracing out the rays that define the useful field limits.

The *minor* ellipse axis *a*, or *width* of the diagonal mirror, is obtained merely by measuring the beam diameter at a distance *l* from the focal plane. The larger or *major* ellipse axis, is 1.414 times as large.

The small dimension *a* may also be calculated from the formula*

$$a = \frac{(D - d)l}{f} + d. \tag{18}$$

Example 1: Determine the required diagonal mirror dimensions in a telescope characterized as follows: primary mirror diameter $D = 8$; $f/D = 6$ (therefore $f = 48$ inches); $l = 6.30$ inches (telescope tube is standard and visual work only is contemplated); $d = 0.43$ inch (diameter of the moon's image at the focal plane).

Substituting in the formula, we obtain:

$$\text{Minor mirror axis: } a = \frac{(8 - 0.43) \times 6.30}{48} + 0.43 = 1.42 \text{ inches.} \tag{19}$$

Major mirror axis: 1.414a, or 2.01 inches.

Example 2: Determine the diagonal mirror dimensions for a telescope designed as follows for long exposure photography at the focus: the mirror is a 12-inch, $f/7$ (therefore $f = 84$ inches); the outside telescope tube diameter is 14 inches; the length of the focusing mount, fully collapsed, 2 inches; additional depth allowed for a camera supported on the mount, 1.60 inches; extra (working) clearance for the focal plane, 0.40 inch.

For the dimension *l*, we obtain:

$$l = 7 + 2 + 1.60 + 0.40 = 11.0 \text{ inches.} \tag{19a}$$

From Table VI of "Permissible Field Diameters" we obtain:

$$d = 1.80 \text{ inches.}$$

Substituting in the formula, we find for the small ellipse axis:

$$a = \frac{(12 - 1.80)\,11.0}{84} + 1.80 = 3.14 \text{ inches.} \tag{20}$$

and for the large axis:

$$3.14 \times 1.414 = 4.44 \text{ inches.} \tag{21}$$

III-3. Interference Test for Flat Mirrors

Consider an air layer of thickness *e* (Fig. 49*A*) between two glass plates, and a light ray *S* incident on the plates at an angle *i*. The ray is in part

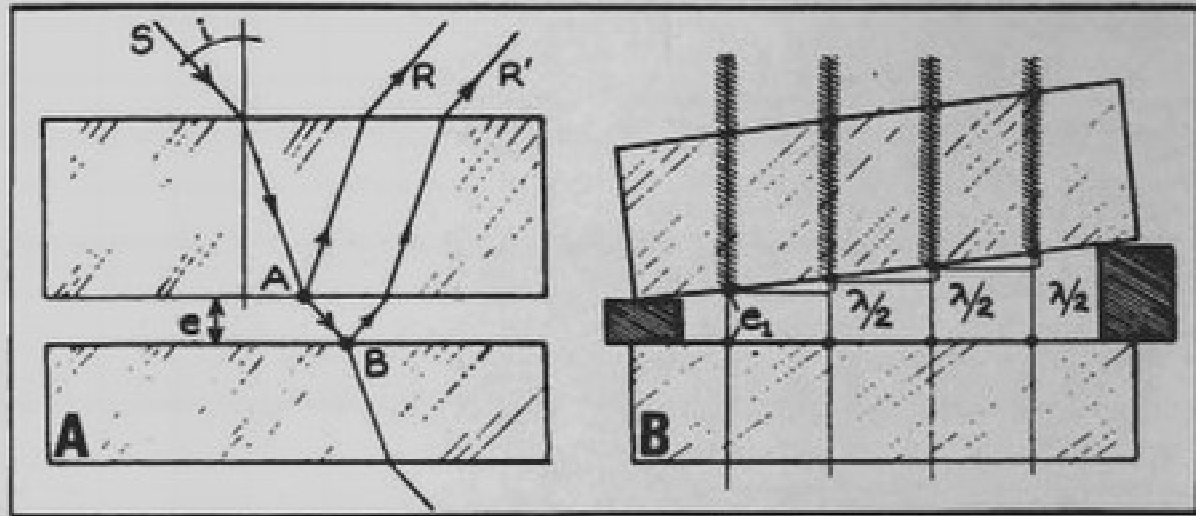


Fig. 49. Interference produced in an air space.

reflected at *A* on reaching the air layer; in part it is transmitted and impinges on the second plate at *B*. The reflection at *A* gives rise to beam *R*; reflection at *B* gives rise to beam *R′*. If properly phased, the beams *R* and *R′* interfere (Section I-2). The difference in the nature of the reflection at *A* and *B* (one internal, the other external) in itself results in a phase difference of a half wavelength. To this we add the extra distance traversed by ray *R′*, equal to $2e \cos i$. If the total path difference is a half wavelength, or any odd number of half wavelengths, interference is complete. If the air layer varies in thickness, then at points of appropriate thickness the layer appears dark. *We see a fringe pattern localized in the air layer.*

The case of immediate interest is that in which the faces bounding the air layer are flat, and inclined to each other at a very small angle. We have then an *air wedge* (Fig. 49*B*). If the rays impinge vertically, then starting at any point e_1 at which interference is complete, we see an additional fringe each time the wedge increases by $\lambda/2$ in thickness, since the path difference is then increased by a whole wavelength λ. Each fringe is, of course, a straight line parallel to the apex of the wedge. If between any two points on the glass we count k fringes, the difference in thickness is $k \cdot \lambda/2$. If we know that one face is flat (for example, it is an optical flat tested by some other method), we can directly interpret any departure of the fringes from straight lines as an error in flatness of the second face. The fringes therefore give us a precise measure of the flatness of a surface, provided only that a reference flat is available.

III-4. Making the Interference Test

In industrial workshops, the interference test is often made simply under white or daylight illumination. Under these conditions, fringes are visible only when the air wedge is extremely thin; they are the characteristic, vividly colored bands known as "Newton's rings." The surfaces must be perfectly clean, and brought together carefully without sideslip. Even the expert cannot always avoid scratching if the surfaces are more than about 2 inches across. A further difficulty is that as the air film becomes extremely thin, very objectionable adhesion effects arise that mechanically distort the pieces. If one considers also that in industry the pieces are rarely examined at a fixed viewing angle, and that usually neither the reference (following handling) nor the mirror (still cemented to the mounting block) is cooled sufficiently before testing, it is not surprising that the technique as ordinarily used cannot be relied on to better than a half wavelength.

A more accurate method is to use a broad source of radiation that is dominantly monochromatic (a mercury vapor lamp, for example) and to illuminate the plates perpendicularly. Even without isolating the green line of the mercury spectrum, we easily see the characteristic fringes of the wedge when we interpose paper spacers between the plates. However, it is better and far less expensive to use a simple neon glow lamp.[2] The optical arrangement shown in Fig. 50 is that devised by Fizeau. The practical details are borrowed largely from A. Couder. The glow lamp N is mounted at the focus of a simple plano-convex lens L. The flat lens surface faces the source. The focal length should be moderately long, say 15 to 20 inches for a 4-inch diameter lens. If the lamp is somewhat bulky, it may be positioned to one side, and a prism used to deflect the beam downward toward the lens, as shown (the quality of the prism is unimportant). The downwardly directed beam is slightly displaced from the perpendicular, so that the reflected rays are made easily accessible. By providing means for tilting the reference and mirror plates, the angle of incidence on the plates and the position of the reflected beam can be easily adjusted. For this purpose we either place shims under the mirror or use leveling screws as shown in Fig. 50.

Three shims for the air wedge are cut from the same sheet of paper, and may be about 0.003 or 0.005 inch thick, and $1/4$ to $3/8$ inch wide. News-

[2] These are available from electrical supply houses with a convenient standard screw base.

print, being a relatively compressible material, is especially suitable. The test flat is brought into contact first with one of the shims, then with the other two, without touching the mirror. At first we usually see a large number of fringes, indicating an appreciable wedge angle and an excessive difference in thickness between the shims. By partially withdrawing a thick shim or by compressing it, we cause the fringes to spread and appear across the surface in smaller number. When only ten or so remain, there is no advantage in equalizing the shims further. If we produce a too uniform or "flat field" appearance, defects even of as much as one- or two-tenths of a

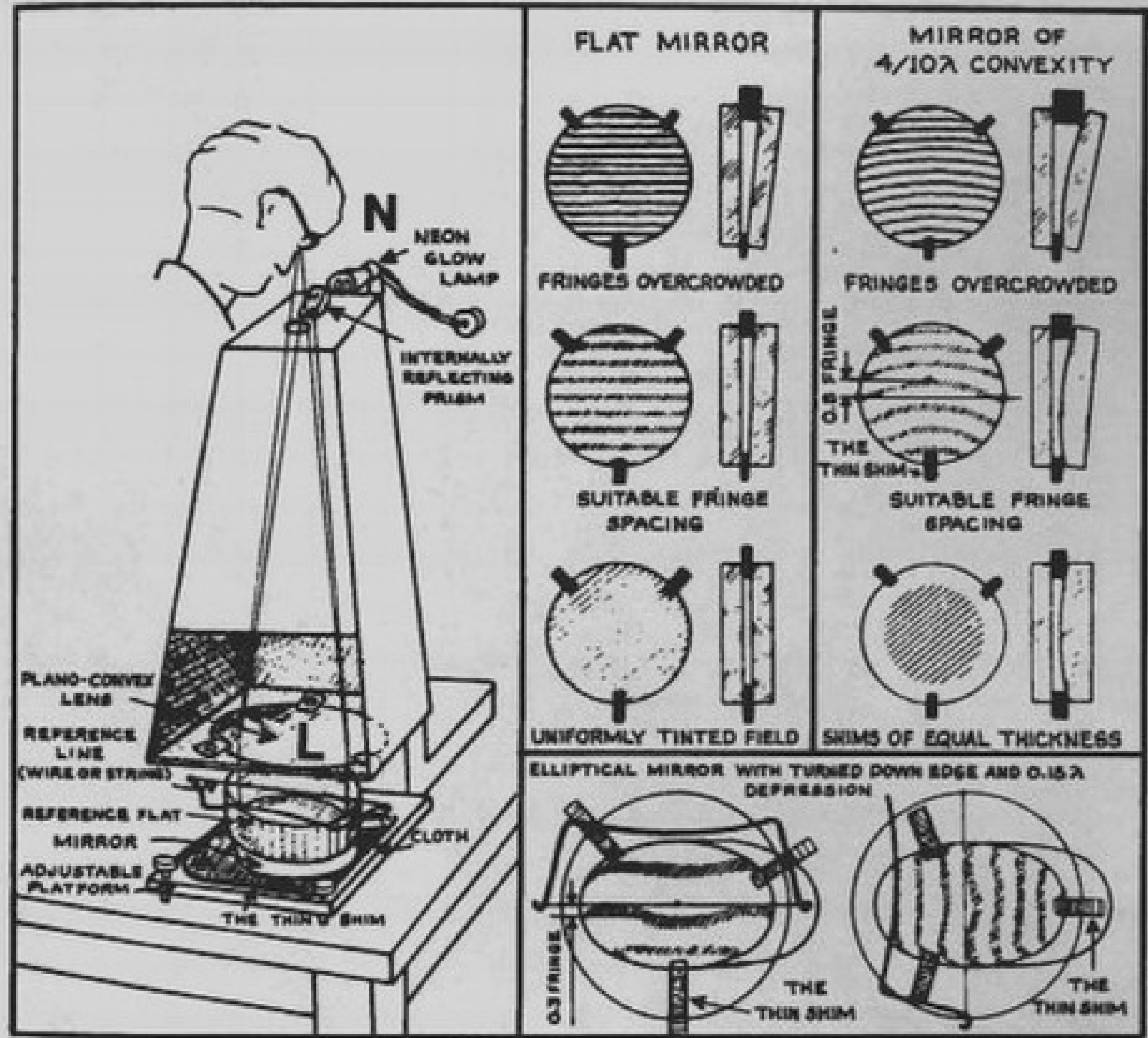


Fig. 50. Interference test on a flat mirror using the Fizeau apparatus.

fringe may remain unnoticed, but if the spacing between the fringes is about a centimeter, then a fringe curvature or irregularity of a half millimeter, representing $1/20$ fringe or a surface error of $1/40$ wave, is still quite visible.

Usually, either zonal defects are present or the mirror as a whole exhibits some curvature. To avoid errors of interpretation, we first identify and mark the thinnest shim. This is the shim which, compressed by light local pressure on the overlying glass, will cause the fringes to appear in greater number, more closely spaced across the surface (since the wedge angle has increased). It is convenient now to turn the plates to bring this thinnest shim nearest the operator (Figs. 50, 51). Note that *the central fringe depicts the cross section of the surface under test, at such magnification that one interfringe space corresponds to about 0.3 micron (the effective half wavelength for neon light).*

Figures 50 and 51 illustrate how the method is applied. Errors are measured by noting the deviation of the fringes from a straight line and comparing this deviation with the inter-fringe spacing. A thread stretched across a wire bow forms a convenient straight-line reference. If the defective surface is other than a figure of revolution, interpretation may be difficult.

Fig. 51. Interference test on a flat mirror. Note: Reference line near the central fringe is formed by a taut wire or string. White spot is reflection of the neon lamp. The thin shim is marked T. The extreme edge is turned down.

In this case the direction of maximum slope of the wedge should be changed, for example, by interchanging two spacers, in order to bring out the surface shape along several different diameters. This is particularly helpful on noncircular mirrors (Fig. 50).

It is essential that the plates be uniformly at room temperature, and that we avoid heating them during the test. Ordinarily, after handling the reference and mirror, we wait several hours before making the test; or better, we allow the pieces to settle overnight to a uniform temperature. We avoid leaning over the apparatus longer than necessary, and shield the plates from body heat by enclosing them in a chimney, for example, a corrugated paper collar that extends up to the height of the lens.

The interferometric method is easy to apply and can be interpreted directly, without calculation. Its only disadvantage, as we have mentioned, is that it assumes that we possess a reference flat at least as large as the

mirror blank, and that the quality of the reference is beyond question. In a group of amateurs, one of the first obligations should be to acquire such a reference flat. The isolated worker may, if necessary, avoid at least the more serious errors by obtaining a set of three mirror plates (the backs of the plates being allowed to remain clear), and testing these against each other two at a time. Assuming that any errors present are purely errors of curvature, each test indicates the difference of curvature between two of the surfaces. In this way one may obtain three equations, containing three unknowns, that are easily solved to give the magnitude and sign (i.e., whether concave or convex) of the curvature of all three mirrors. Unfortunately, if the surface errors are more complex, as occurs often in plate glass, the method is inadequate. A better method in this case is the one described below.

III-5. Testing by Combination with a Spherical Mirror

We require a spherical concave mirror of diameter at least equal to the small axis of the mirror to be tested. Even for testing very small mirrors, however, the diameter may be 4 inches or larger, and the radius of curvature 80 inches or more. For the dedicated mirror maker, a sufficiently large, perfectly spherical mirror is a highly valued test piece. But for the amateur who will only once, or at rare intervals, construct a telescope, a special mirror is unnecessary. We recommend instead that he use his main telescope mirror, even if already parabolized. This is entirely satisfactory; the mirror need only be free of small, sharply localized defects near the center. An 8-inch mirror, of $f/8$ or even of $f/6$, may be checked in this respect by masking all but a central area 2 inches in diameter, and determining by a Foucault test whether this approximates a small sphere.

We then examine the mirror, covered with its mask, in the arrangement described in Section II-33 for detecting astigmatism in the main mirror. Using a strong eyepiece, we verify that no astigmatism (due, for example, to the positioning of the parts) is present. Next, using a special support, we alter the optical arrangement to introduce the flat into the beam. The support, as shown in Fig. 52, may comprise three boards. Three nails driven in the lower surface of the base provide a 3-point support. The two vertical boards form a niche of suitable angle, for example 45°.[3] Nails are driven in these upright boards also—three nails behind each mirror to form a back rest, two nails below each mirror to act as a support. The large mirror is, of course, accurately aimed at the center of the flat. To assure sufficient light despite the three reflections (note that the diagonal still lacks a reflective coat), the concave mirror should be silvered or aluminized.

If we should apply the Foucault test under these conditions, any zonal defects in the diagonal would at once be evident. A slight general convexity

[3] A. Couder has shown (thesis cited in Section II-3) that an optimum angle for testing flats is 54°45′. In practice, an angle of 60° is also often used.

or concavity, on the other hand, would not be apparent. Such general curvature will however give an astigmatic image, and this may be detected by examination with an eyepiece. The plane of incidence on the diagonal being horizontal in our setup, curvature in the diagonal is evidenced by two *line foci* slightly displaced from each other, one of these lines being horizontal, the other vertical. The *sagittal focus* lies in the plane of incidence and is therefore the horizontal line; the *tangential focus* is the vertical.

If a vertical knife edge is brought into the tangential focus, the mirror surface darkens uniformly, just as with a perfect or "stigmatic" beam. If we wish, we may use a knife edge (and a slit source) to detect and measure the astigmatism very precisely, provided both the knife and the slit are made

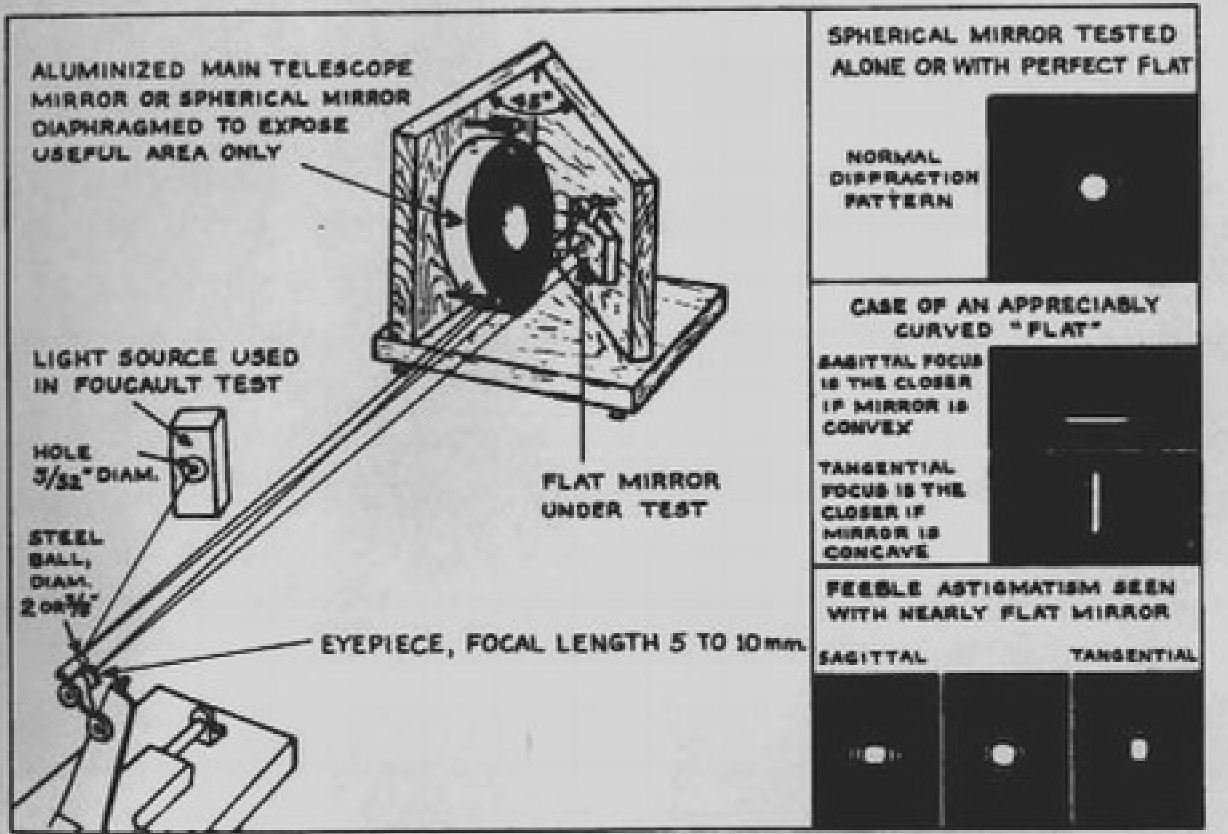


Fig. 52. Testing a flat surface with the aid of a spherical mirror.

rotatable around the beam axis. Having first located the tangential focus and noted the knife position, we set knife and slit horizontal and find a second knife position where again the mirror is uniformly darkened. The change of knife position is the "astigmatic difference," from which may be calculated the curvature of the diagonal (see below).

Taking knife-position readings is not essential, however; we can merely focus a strong eyepiece successively on the two line images formed from the point source (Fig. 52), and measure the difference of position. This method is less precise, but adequate. Moreover it gives us a chance to see the appearance of an image affected by pure astigmatism. Since the polished ball is secured next to the eyepiece, and the angular aperture of the arrangement is small, astigmatism contributed by the positioning of the elements is

negligible. If the *sagittal* (*horizontal*) focus is the one nearer to the mirror, the diagonal mirror is *convex;* if the *tangential* focus is the nearer, the diagonal is *concave*.. The radius of curvature is given by the following formula of A. Couder:[4]

$$R = \frac{4p^2}{l}\left(\frac{1}{\cos i} - \cos i\right), \qquad (22)$$

where p is the distance from the diagonal to the image plane viewed at the eyepiece; l is the astigmatic difference; and i is the angle between the upright supports.

In the arrangement shown, $i = 45°$; therefore $\cos i = 0.707$ and the formula reduces to

$$\mathrm{R} = \frac{2.83p^2}{l}. \qquad (23)$$

The "sagitta," i.e., the depth (or height) of curvature of the small axis of the elliptical area lying in the beam is given by

$$\epsilon = \frac{l}{22.6}\,\frac{D^2}{p^2}, \qquad (24)$$

where D is the effective diameter of the beam at the diagonal (assuming, as above, that $i = 45°$).

Example: Given a distance between the two foci of 0.080 inch, the sagittal focus being the farther from the mirror; $p = 122$ inches (using an 8-inch mirror, $f/8$, as the spherical surface); and $D = 2.00$ inches, determine the radius of curvature, whether the surface is convex or concave, and the depth of the curve.

The sagittal focus being the farther from the mirror, the curvature is concave. Substituting in the formula for R, the radius of curvature is given by

$$R = \frac{2.83 \times 122^2}{0.080} = 5.27 \times 10^5 \text{ inches} = 8.33 \text{ miles}. \qquad (25)$$

The depth ϵ of the mirror curve is

$$\epsilon = \frac{0.080}{22.6} \times \frac{2.00^2}{122^2} = 9.52 \times 10^{-7} \text{ inches} = 0.024\mu \;=\; \frac{\lambda}{23}. \qquad (26)$$

The method is very sensitive, first, because of the large distance between the diagonal and the image (p here being 20 times the working distance used in the telescope), and second, because the beam is reflected twice from the diagonal.

[4] *Lunettes et Télescopes*, p. 501; Couder thesis, p. 9.

III-6. The Diagonal Mirror Blank

Plate Glass. Experimental physics texts and books on amateur telescope making often extol the flatness of plate glass. Its flatness is no doubt remarkable for so commonplace a commercial material. Given a sufficient stock of fragments and an adequate interference test apparatus (Section III-4), it is not difficult to find a piece large and perfect enough to make a diagonal with a minor axis equal to 20 or 30 millimeters. An utterly inadmissible practice, however (only too frequent among amateurs), is that of accepting, without test, the first piece of glass that comes to hand. The chances of obtaining an adequate diagonal this way are less than one in a hundred. Almost invariably astigmatic defects are present (which are, moreover, difficult to interpret), and these may be of a magnitude easily reaching 5 to 10 fringes in a space of 2 inches. *Resurfacing of the glass is indispensable.* A thickness of $^{5}/_{16}$ inch is sufficient, if need be, for a diagonal having a minor axis up to about $1^{1}/_{2}$ inches. But if the thickness is $^{3}/_{8}$ inch or $^{5}/_{8}$ inch (which serves also for a minor mirror axis as large as 2 inches or $2^{1}/_{2}$ inches), so much the better.

Second-Hand Optics. The photographic filters made for the early, large aviation cameras, notably by Carl Zeiss and Goerz, have been a mine of diagonal mirror flats. These have been obtainable at very low cost from second-hand supply sources. The filters comprise two plates, each flat and parallel, measuring 150 millimeters in diameter and 11 millimeters thick (or better, 180 millimeters in diameter and 14 millimeters thick), and cemented together by an intermediate, tinted gelatine layer. The metal mounting ring is usually sawed apart, and the plates separated in warm water. The interior, cemented faces commonly have two or three fringes total error from edge to edge. But the outer faces are often flat within a fringe, and if studied carefully, show areas large and flat enough to yield a diagonal that is precise to $^{1}/_{10}$ wave. The Paris Observatory group is currently obtaining four mirrors of faultless quality from a single 150-millimeter filter plate at a total cost equivalent to 30 cents! Those who lack the courage to make an optical test still stand a fair change of obtaining a good diagonal by using *the middle of an outside face* of one of these filters; a far better chance at any rate than with unselected plate glass. In any case, the filter plate is much the easier to retouch, if this proves necessary.

We should mention also certain rectangular mirrors obtainable from range finders that are usually precise to $^{1}/_{10}$ fringe. The statement of such a specification must not be taken on faith, however; the mirrors must always be tested. Commercial optics of such precision are very rare indeed; and in totally reflecting prisms, a similar precision is virtually unknown.

III-7. Resurfacing the Flat Mirror

Whether we refigure a piece of plate glass (or a filter disk) or use the piece "as is," we never abrade the rear surface. This would result in a concavity at the optical face of several fringes, owing to elastic effects in the abrasive (so-called "Twyman effect").

Usually the diagonal does require retouching, and we can consider one of two alternative retouching techniques:

a. The mirror is cut from the blank, trimmed to the desired final shape, then "block-mounted," i.e., cemented to a base with pitch and surrounded with pieces of plate glass that serve to restore an approximately circular outline (Fig. 53*A*). *Disadvantage:* detaching the mirror inevitably releases strains in the glass; usually necessitating final retouching on the demounted piece. Such retouching is difficult on a noncircular element.

b. The mirror is cut roughly to a circular shape, of diameter somewhat larger than the desired major ellipse axis, for example, 4 inches for a major axis of about 2 inches to 3 inches.[5] The plate is then reworked to

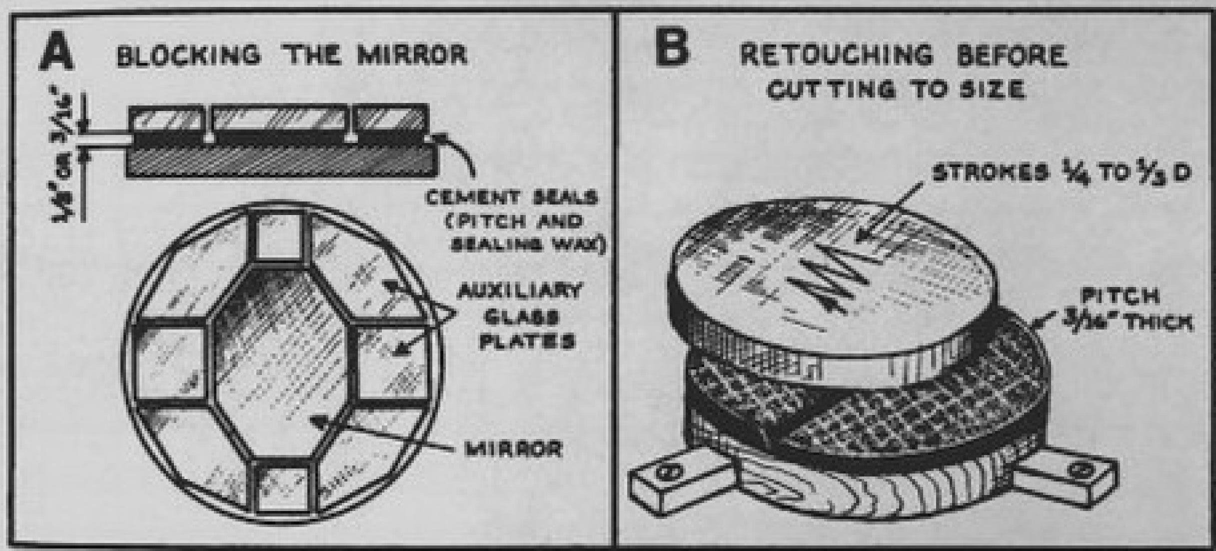


Fig. 53. Two methods of improving the surface figure of a flat mirror.

make it rather precisely flat (Fig. 53*B*), and the mirror is cut to final shape. *Disadvantage:* if the disk (particularly in the case of plate glass) is internally strained owing to imperfect annealing, stresses may be relieved during final cutting and unexpectedly cause a defective surface.

Despite its disadvantage, we prefer the second method. In relatively thin plates, such as those used for our diagonal, effects of internal strain are usually much less serious than those resulting from release of cementing strains. The method permits us to discard the outside zone after figuring, this portion almost always being defective.

For a flat mirror 4 to 6 inches in diameter, the lap may be cast in a single piece. Its diameter is made slightly larger (10 per cent) than the mirror. The procedure is as follows:

Use a metal or glass disk, or a disk of paraffined wood (flat, with parallel faces), as a support for the lap. Fit a heavy paper collar around the

[5] If the blank is a 150-millimeter filter plate, preliminary cutting is unneccessary.

edge of the disk, level the disk carefully, and pour in a pitch layer about $^{3}/_{16}$ inch thick. The pitch when cool should be rather hard, yielding only slightly under pressure of the fingernail at room temperature. Before the lap has cooled completely, press it down on a sheet of tracing paper, using a plane, sufficiently large backing surface such as a glass plate, then press with rouge as described in Section II-16. At some point in the pressing process, cut a groove along a diameter of the lap, and if necessary add a few shallow knife cuts to improve contact. Remember that a uniform temperature near 20° and a prolonged, uninterrupted working spell are indispensable.

As a rule, we work with the mirror on top, using a stroke of varying length, as for the usual concave mirror. Our earlier remarks on this subject could largely be transposed here. The stroke amplitude should not exceed $^{1}/_{3}$ the mirror diameter. The tendency to form a concave surface is counteracted by the excess tool diameter, but if the mirror surface is already concave at the start, it is worked briefly with the tool on top, the mirror being cushioned below on several layers of flannel.

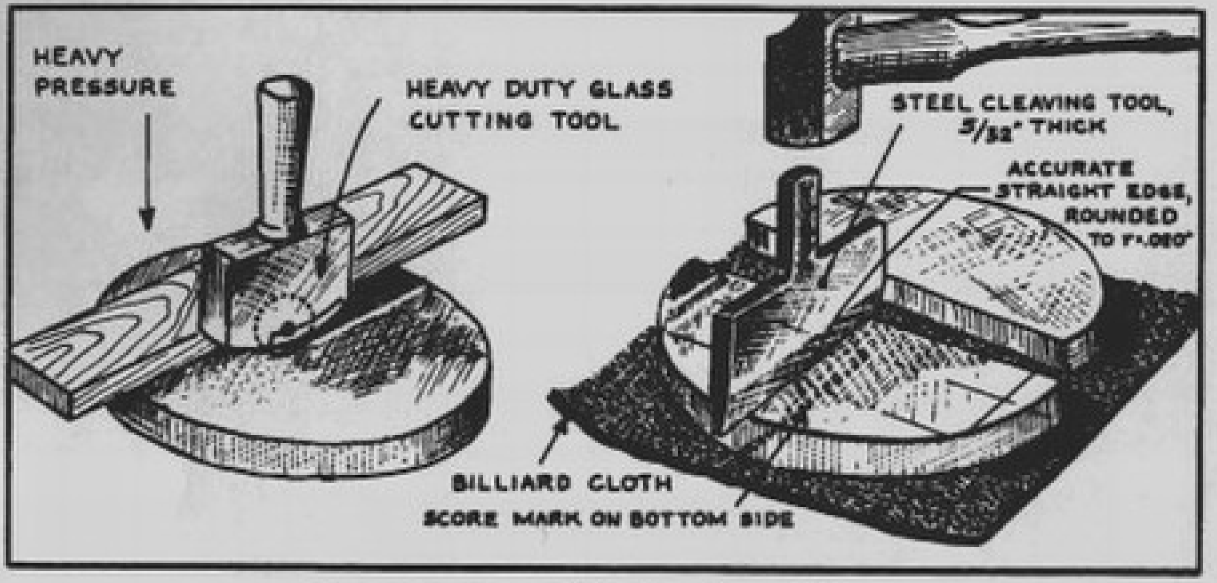


Fig. 54. Cutting a thick glass plate to shape.

If the disk has a turned-down edge—even a rather wide one—it will not matter; this disappears with the trimmings when we cut the mirror. Seriously irregular defects, often found in plate glass, are eliminated automatically if polishing continues long enough. Three or four hours are usually enough. It remains then only to reduce the general surface curvature and zonal defects in the useful, center portion to less than $^{1}/_{10}$ fringe. The outer zone may be masked during testing by an apertured card or paper placed against the disk.

III-8. Cutting the Mirror

Cutting the mirror with the edges square to the face is by far the easiest method. For fairly thick glass, the author prefers a special heavy-duty cutter such as shown in Fig. 54, in which a journaled cutting wheel is mounted in a

router-type handle. This permits the application of heavy pressure for making a deep score mark. Verify that the glass lies on a flat surface. Guide the tool against a straight edge (preferably clamped to the disk), and in positioning the cutting wheel remember, of course, to allow for the half width of the tool.

To part the glass correctly, proceed as follows (Fig. 54): set the piece, scored face downward, on a felt pad or piece of billiard cloth at least the size of the glass. The support should be flat and relatively massive; a machinist's surface plate is ideal. The steel parting tool may be either of the form shown in Fig. 54 or a wide chisel; in either case the working edge is blunted by forming the edge into a half-cylindrical surface of small radius. The aim is to induce the break by flexure. Set the parting tool exactly over the score mark and rap it sharply with a light hammer. When possible, separate the glass always into pieces of more or less equal size. Thus, when cutting several mirrors from the same disk, make the first cut approximately across the middle. The form easiest to cut, of course, is the rectangle (Fig. 54). If slightly chipped edges or sharp projections remain, it may be necessary merely to apply a small chamfer to the edge to remove them, for example, by grinding at 45° against another piece of plate glass with 5-min. emery or 1-F Carborundum. Scratching of the optical surface can be avoided by coating it with a layer of rosin or shellac.

Octagonal mirrors may require more work at the edges, since diagonal cuts do not always part well. If a lapidary wheel is accessible, or its equivalent can be improvised, this operation presents no difficulty.

To cut an *oblique* elliptical mirror, the glass may be cemented between two additional, protective glass plates, the assembly then mounted securely with optical cement against a cylindrical support cut at 45°, and roughly ground to shape against a lapidary wheel or metal plate. The edges are then fine-ground on a lathe against an iron plate fixed to the tool carriage (Fig. 55*A*). An alternative method is to use a "biscuit cutter" mounted in a drill press as shown in Fig. 55*B*. A similar arrangement is used also for piercing Cassegrainian mirrors. The cutter is a tube of soft metal, e.g., brass or mild steel. The inside diameter should be about $^{1}/_{16}$ or $^{3}/_{32}$ inch larger than the desired small mirror axis; the wall thickness about $^{1}/_{16}$ or $^{1}/_{32}$ inch. The tube is fitted to the shoulder of a supporting piece that permits mounting in the drill press, and is slotted at the bottom for better access of the abrasive. As before, the glass is preferably cemented between protective plates to prevent chipping. A suitable cement comprises three parts rosin to one part beeswax. The assembled plates may be potted in a cube of plaster of Paris at 45° to avoid direct, oblique presentation of the tool to the glass. A simpler procedure consists in propping the glass at 45° in a paraffin-coated box which serves also to catch the water and used abrasive (Fig. 55*B*). The box is clamped firmly to the drill press. Water and Carborundum (No. 120, for example) are applied liberally to the cutter, and the tool is raised frequently from the work in order to make efficient use of the abrasive and to prevent overheating.

Remember that Carborundum is an unwholesome material near any machine tool. Handle the abrasive with one hand only, the machine with the other; and cover as much of the machine as possible with pieces of oil-cloth. After cutting and separating the elliptical mirror, apply a small chamfer to the edge immediately, or the sharp edges may very easily be chipped.

Final retouching. Tests made on the diagonal mirror after cutting to shape are not without surprises. In an elliptical mirror, we may expect at

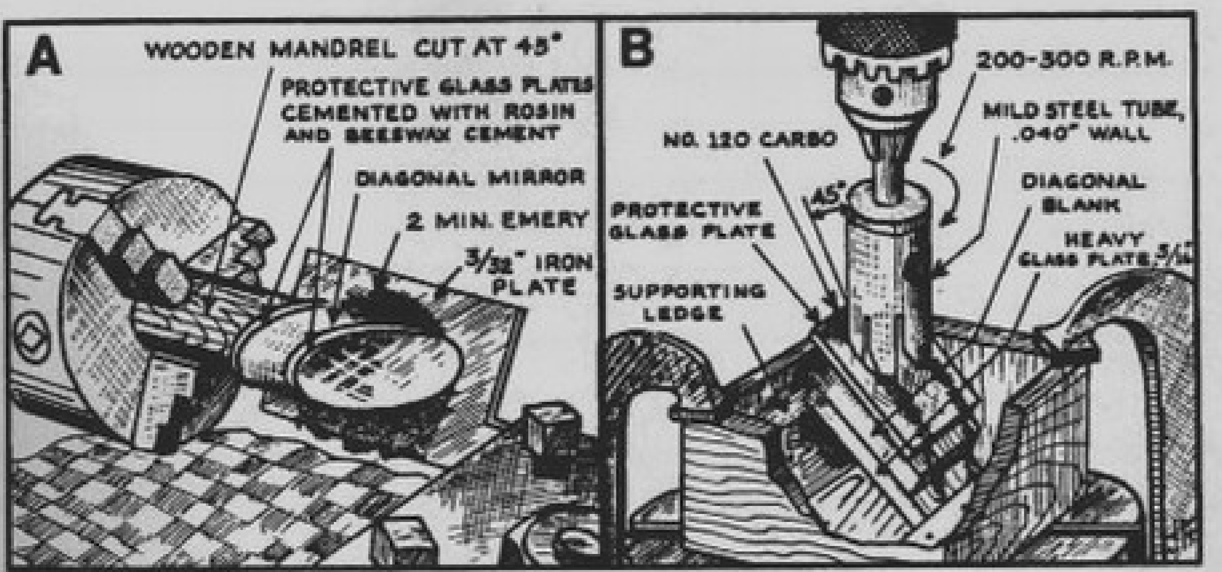


Fig. 55. Producing an elliptical mirror contour.

least a slightly turned-up edge at the acute end. This is due to the action of the Twyman effect on the thin portion. The defect is usually very small and localized and thus may be neglected. If it is as much as $^2/_{10}$ fringe or larger, however, it may be retouched with the fingertip. In an occasional severe case, release of strains may necessitate more than simple local retouching. If the defect exceeds one fringe (fortunately this is rare), we may use a polishing tool equal in diameter to the large ellipse axis. What we fear most in this procedure is a turned-down edge. For a truly impeccable mirror, it is in this event probably more economical in the long run to cut a new diagonal from a flat of high-quality, annealed optical glass.

IV

MECHANICAL STRUCTURE

IV-1. Choice of a Standard Design

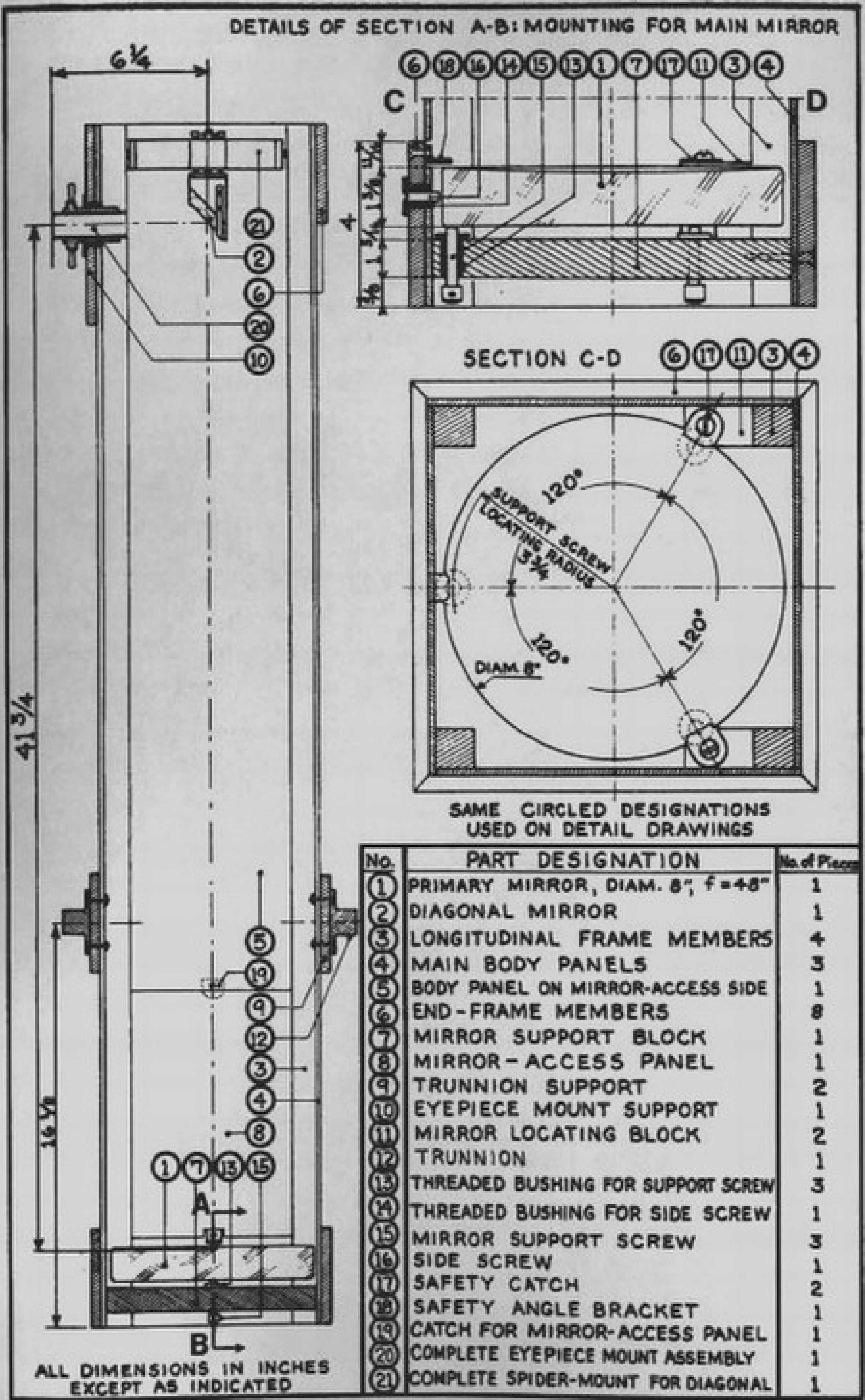
The standard telescope mount that we describe below was selected because of its low cost, its simplicity, and its ease of construction. Our aim was a design that could be accepted and used as widely as possible. The construction is derived from a model conceived and built by André Couder[1] in 1926. It provides the basically necessary features without sacrifice of good principles of design. Taking as a premise that the telescope is *first of all* an instrument for astronomical observation, we have omitted all complications that are based merely on esthetic considerations and not directed in some way toward improving the performance.

Figures 56, 57, and 58 differ only in details from the original design. The dimensions and certain of the details are subject, of course, to considerable latitude, if merely to accommodate differences (in focal length aperture, etc.) in the actual optics used. In particular, the longitudinal position of the eyepiece on the telescope tube may be changed, and it will be optional whether to mount the eyepiece on the right or left telescope panel, depending on whether the finder, which adjoins the eyepiece, will be more convenient for the left eye or the right. Depending also on the amateur's experience and available raw materials further changes of design may be made with entirely happy results. But we must warn the worker with an inventive bent that even minor details of the standard mounting have evolved from long practical experience. Below, we shall stress in particular certain points that cannot be entrusted merely to mechanical "common sense."

IV-2. Important Details

Mounting of the Main Mirror. It is *essential* that the mounting impose no restraint whatever on the mirror disk. The mirror position must nevertheles be well defined and adjustable. For an 8-inch mirror (see Section II-3) this is quite simple, but perhaps for this very reason we fear the measures and compli-

[1] A. Danjon and A. Couder, *Lunettes et Télescopes*, p. 322. Editions de la Revue d'optique théorique et instrumentale, Paris, 1935.



No.	PART DESIGNATION	No. of Pieces
1	PRIMARY MIRROR, DIAM. 8", f = 48"	1
2	DIAGONAL MIRROR	1
3	LONGITUDINAL FRAME MEMBERS	4
4	MAIN BODY PANELS	3
5	BODY PANEL ON MIRROR-ACCESS SIDE	1
6	END-FRAME MEMBERS	8
7	MIRROR SUPPORT BLOCK	1
8	MIRROR-ACCESS PANEL	1
9	TRUNNION SUPPORT	2
10	EYEPIECE MOUNT SUPPORT	1
11	MIRROR LOCATING BLOCK	2
12	TRUNNION	1
13	THREADED BUSHING FOR SUPPORT SCREW	3
14	THREADED BUSHING FOR SIDE SCREW	1
15	MIRROR SUPPORT SCREW	3
16	SIDE SCREW	1
17	SAFETY CATCH	2
18	SAFETY ANGLE BRACKET	1
19	CATCH FOR MIRROR-ACCESS PANEL	1
20	COMPLETE EYEPIECE MOUNT ASSEMBLY	1
21	COMPLETE SPIDER-MOUNT FOR DIAGONAL	1

Fig. 56. Telescope body and mirror assembly.

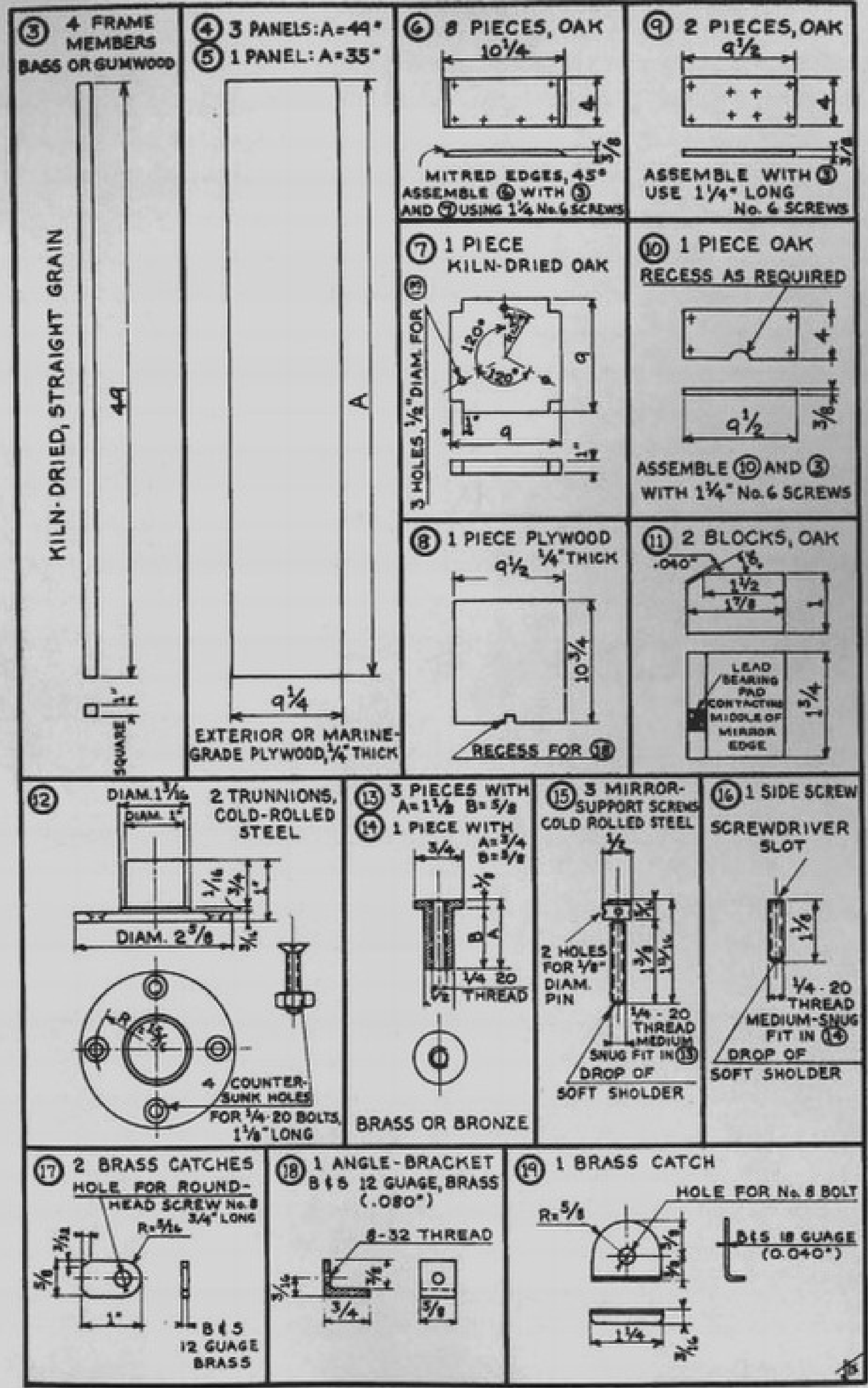


Fig. 57. Details of telescope parts.

cations that overcautious readers may resort to. The mirror rests at all times against five selected points (Fig. 56). These are the tinned tips of three positioning screws (15) which form an equilateral triangle just inside the mirror edge[2] and against which the back of the mirror rests, and two positioning blocks (11) spaced 120° apart, against which rests the mirror edge. If the instrument is to be employed exclusively in an altazimuth mounting, the positioning blocks may be as close as 90°. This minimizes rubbing against the blocks at inclined positions of the tube. The side-pin (16) and three tabs (17 and 18) are a safety provision. They *do not* touch the glass when the mirror is in working position. A clearance at the pin of 1/32 inch and a clearance of at the tabs of 1/16 inch may be considered normal. Before using the telescope it is necessary only to verify that a previous shock or an abnormal inversion of the tube has not caused the mirror to leave one of the five contact points and that the instrument is accordingly in working order.

The following serious errors must be avoided at all cost:

Cementing the mirror against a glass or metal "reinforcing" disk. Result: severe image deterioration, caused by the resulting serious mechanical strain, as evidenced by total destruction of the diffraction image.

Mounting the mirror in a close-fitting, machined barrel or cell. Stresses applied to the glass by the mounting at temperatures slightly below the fitting temperature can produce extraordinary deformation and introduce even the hazard of fracture.

Mounting the mirror directly on a turned metal disk. In terms of the scale we use to represent mirror deformation (of the order of tenths of microns), the mirror would contact at most only at three points, appearances notwithstanding. Unfortunately, the position of the contact points in such a case is a matter of pure chance. Assuming that the support plate is convex by 0.0005 inch, and that the mirror rests on top of this curve, a corresponding bulge in the wavefront is inevitable. There will be visible undercorrection, and the position of the optic axis will be unstable. Assuming the base is concave, it would be rare indeed to find that the disk bears at three points equally spaced on the periphery. As a result, the image becomes astigmatic. A ring or disk of flannel inserted between the mirror and the turned surface improves the situation; but the position of the optic axis is still somewhat unstable; moreover the flannel insulates the mirror to some extent, so that it accommodates itself less rapidly to ambient temperature change. The use of three selected support points avoids these difficulties.

A metallic mirror cell is acceptable if relatively light in weight (reinforced with ribbed walls) and completely closed (or closed except for removable vents), in order to minimize air currents moving past the mirror. The bore

[2] Note: The screws should *not* bear on a circle at 0.7 or 0.8 of the mirror radius, as is often done. When the support points are near the edge, slight sagging of the disk changes only the curvature of the spherical wavefront, and this can be accommodated automatically in focusing. When the supports are nearer the center, the total absolute change in mirror depth may be less, but the departure from a spherical wave is greater.

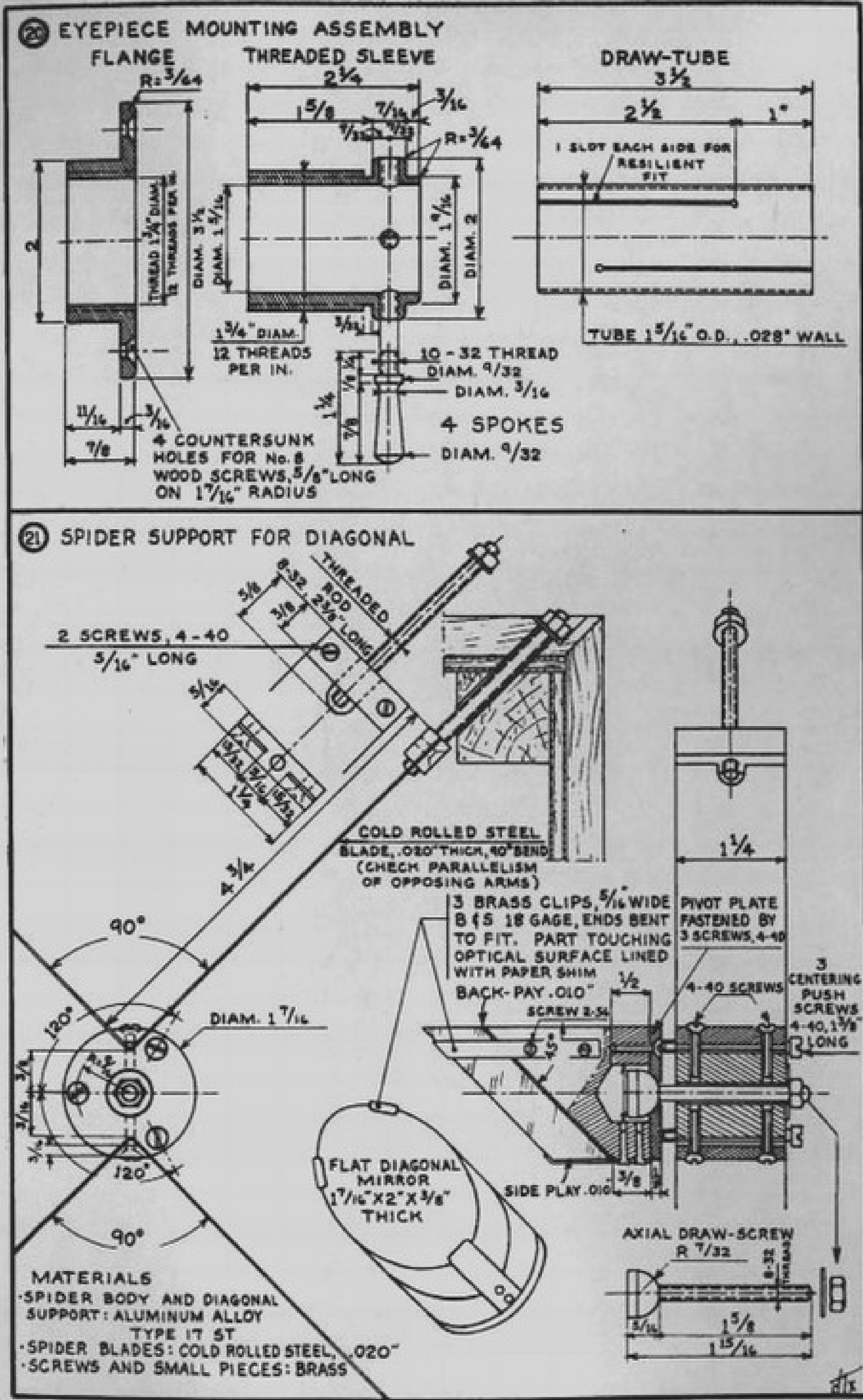


Fig. 58. Details of eyepiece mount and spider support for diagonal mirror.

should be at least 3/8 inch larger than the disk diameter, and the positioning pins at the side and back should space the disk at least 3/16 inch from the metal.

Diagonal Mirror Mounting. Despite its small size, the diagonal is mounted with no less care than the large mirror. In the arrangement shown in Fig. 58, three clips serve both as side supports and positioning points for the front face. In an alternative design, the mount may comprise a diagonally cut tube with three small tongues projecting at the diagonal edge. These are bent inward to retain the mirror within the tube and to position the optical face. The inside tube diameter is at least 0.010 inch larger than the projected circular contour of the diagonal. For an octagonal or rectangular mirror, however, the illustrated arrangement using the three side clips is more reliable. If the telescope mount is of the altazimuth type, the clips are adjusted to allow a forward play of the diagonal mirror not exceeding 0.010 inch. Some side play is equally necessary. In a flat mirror, side play obviously does not affect the operation in any way. To verify that the mirror is without constraint, the operator may jar the support slightly and listen for the sound of the glass against the clips. If the instrument is an equatorially mounted, photographic type, the diagonal may in certain positions of the telescope leave one of the three positioning points. In this case one may cement three spacers of blotting paper on the mirror-supporting surface just behind each of the three clips. The clips are adjusted, after mounting the mirror, so that the spacers are compressed by the weight of the mirror only; pressure from the clips themselves should be nil.

Spider Mount for the Diagonal Mirror. The design illustrated in Fig. 58 is that described by Morse[3] and by Hargreaves.[4] The steel blades do not radiate from the axis of the telescope tube, but are offset—an arrangement which even for much lower blade tension gives greater rigidity than the classic design. We take advantage of this improvement by replacing the hardened steel blades with mild steel or, much better, with stainless steel; this permits putting 90° bends in the blades and simplifies the assembly. We must be careful, of course, to position the opposing blades parallel; otherwise diffraction at the blades produces additional flare lines in the star image. Some workers eliminate flaring by avoiding straight blades altogether, either by using diaphragms so patterned as to provide curved support arms or by using curved spider arms.[5] In an 8- to 12-inch telescope, the tendency of such special supports to be weak is not insurmountable. We have encouraged amateurs with good shop facilities to make curved, reed-braced supports that do not exceed 3/32 inch in thickness at any point.

Eyepiece Support. A suitable design must provide, first, a means for rapid, coarse adjustment of sufficient range to accommodate the required eyepieces. Except for the Plössl eyepieces mentioned earlier (Section IV-2),

[3] *Publ. Astron. Soc. Pacific*, 53 (No. 12), 128 (April, 1941).
[4] *J. Brit. Astron. Assoc.*, 56, 115 (1946).
[5] *Amateur Telescope Making II*, p. 620; R. R. LaPelle, *Sky and Telescope*, 8, 152 (1949).

whose mountings have been especially adapted, the differences in focusing position are considerable. Second, the fine-focus adjustment, as such, must be *extremely* smooth. A fine adjustment with some inherent play is better than a stiff one that jars the telescope every time it is used.

For an $f/15$ objective, where focusing tolerance is of the order of 0.010 inch, a rack and pinion can be used to good advantage. But with our standard mirrors, $f/6$ and $f/8$, focusing tolerance is of the order only of 0.002 inch. A focusing arrangement that has proved quite practical is one that uses a threaded eyepiece tube fitted with a small capstan (Fig. 58). Rotation of the eyepiece is properly centered. Only for certain accessories, a camera, for example, is a nonrotatable mount necessary.

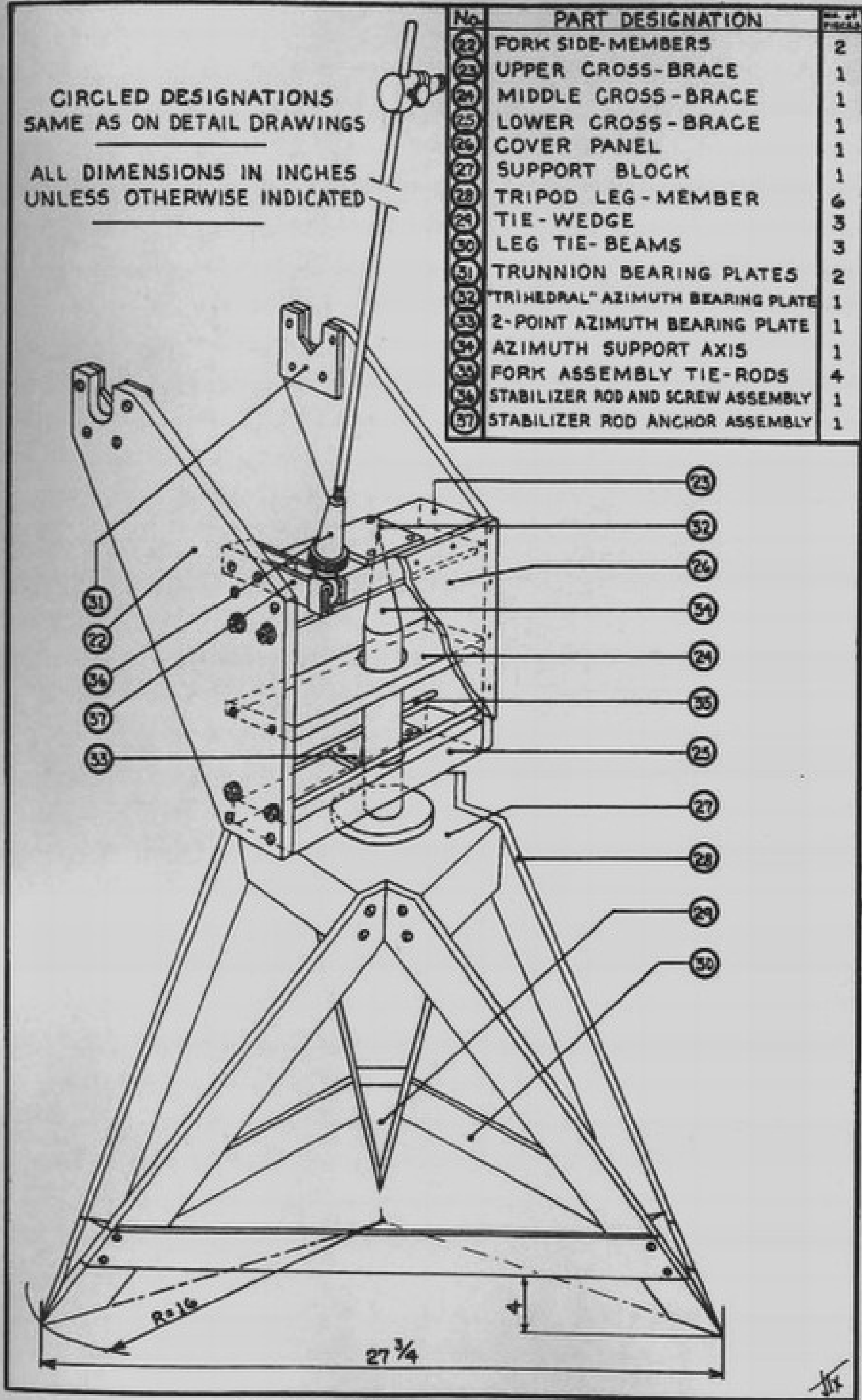
THE ALTAZIMUTH MOUNTING

V-1. Principles of Design

The Couder altazimuth mounting that we adopt for our standard construction (Figs. 59–61) is of kinematic design; that is, each member capable of motion with respect to other members bears upon the least possible number of points necessary to define the desired motion. The basic principle is that *every rigid body possesses six degrees of freedom*. These may conveniently be represented as the possibilities of translation along any of three mutually perpendicular axes, and of rotation about these axes. In the present case, to provide rotation of the telescope tube in *azimuth* (i.e., about a vertical axis), we mount the telescope tube in a fork (Fig. 59) which is adapted to rotate on a vertical shaft (34). The upper, conical end of the shaft is seated in a conical hole in a bearing plate (32), and eliminates three of the possible degrees of freedom of the fork, namely, those of translation (the conical hole serves as a practical equivalent of the ideal trihedral socket). In addition, the weight of the telescope tube applies a torque, or tilting moment, to the fork and causes the notched plate (33) to bear forcibly against the lower, cylinder portion of the vertical shaft. Two additional points of contact are thus defined, and two more degrees of freedom eliminated (i.e., those of rotation about two mutually perpendicular horizontal axes). A single degree of freedom remains, that of rotation in azimuth.

The advantage of kinematic design is that is provides the desired motion with complete freedom from play or blacklash and without need of adjustment or takeup. The crudest workmanship is practically as effective as that of an expert machinist.

Similarly, rotation of the telescope in *elevation* is effected by tilting the tube in the two V-notched support plates (31). The trunnion bearing points (numeral 12, Fig. 57) on these plates provide four points of contact; we have, therefore, one degree of freedom in excess—that of horizontal translation, or play, across the V-plates, which we deliberately permit to be quite large. Such movement in translation is without effect, of course, on the direction in which the telescope tube is aimed and is therefore inconsequential.



No.	PART DESIGNATION	No. of PIECES
22	FORK SIDE-MEMBERS	2
23	UPPER CROSS-BRACE	1
24	MIDDLE CROSS-BRACE	1
25	LOWER CROSS-BRACE	1
26	COVER PANEL	1
27	SUPPORT BLOCK	1
28	TRIPOD LEG-MEMBER	6
29	TIE-WEDGE	3
30	LEG TIE-BEAMS	3
31	TRUNNION BEARING PLATES	2
32	"TRIHEDRAL" AZIMUTH BEARING PLATE	1
33	2-POINT AZIMUTH BEARING PLATE	1
34	AZIMUTH SUPPORT AXIS	1
35	FORK ASSEMBLY TIE-RODS	4
36	STABILIZER ROD AND SCREW ASSEMBLY	1
37	STABILIZER ROD ANCHOR ASSEMBLY	1

Fig. 59. Altazimuth mounting assembly.

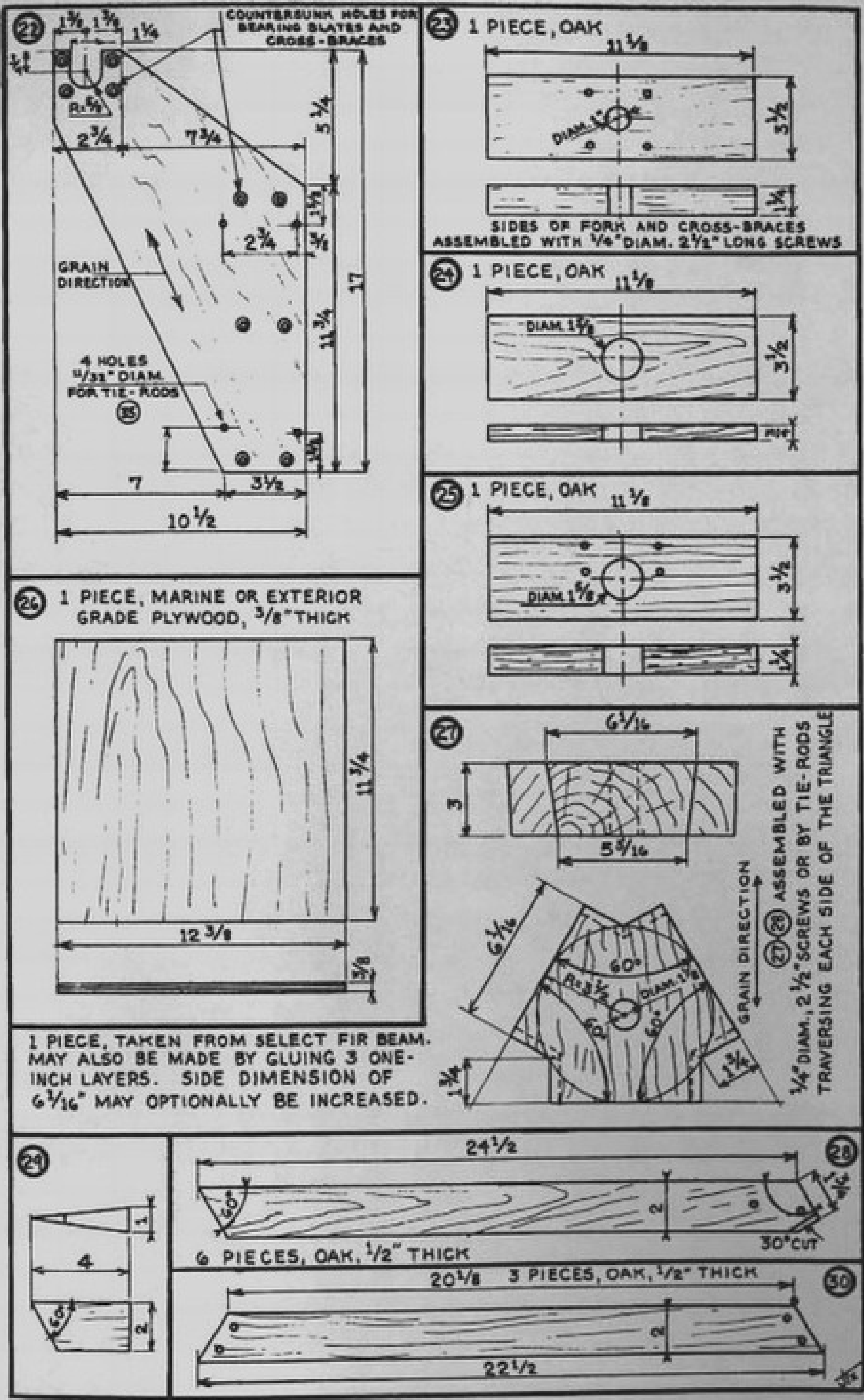


Fig. 60. Details of wooden parts of mounting.

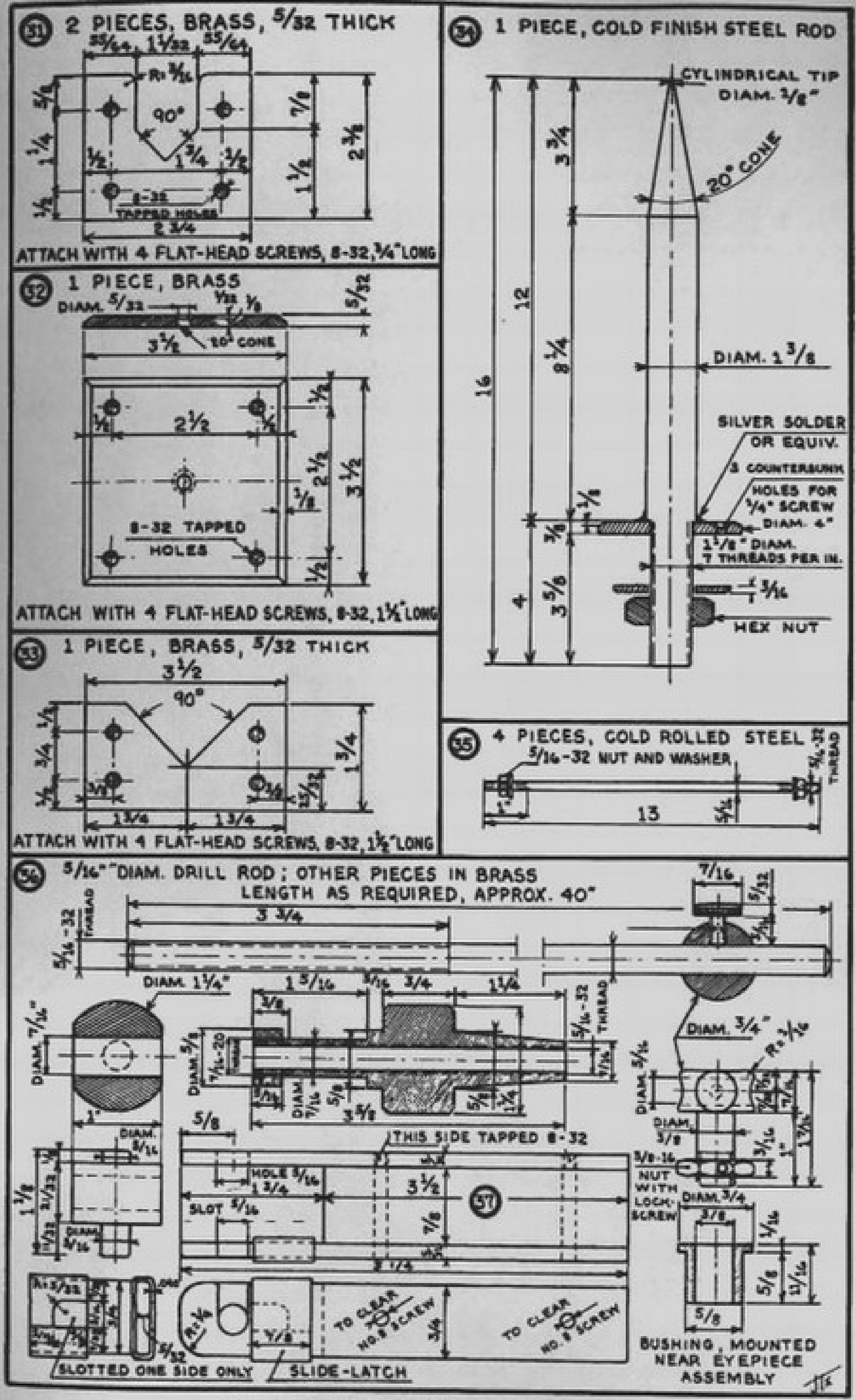


Fig. 61. Details of metal parts of mounting.

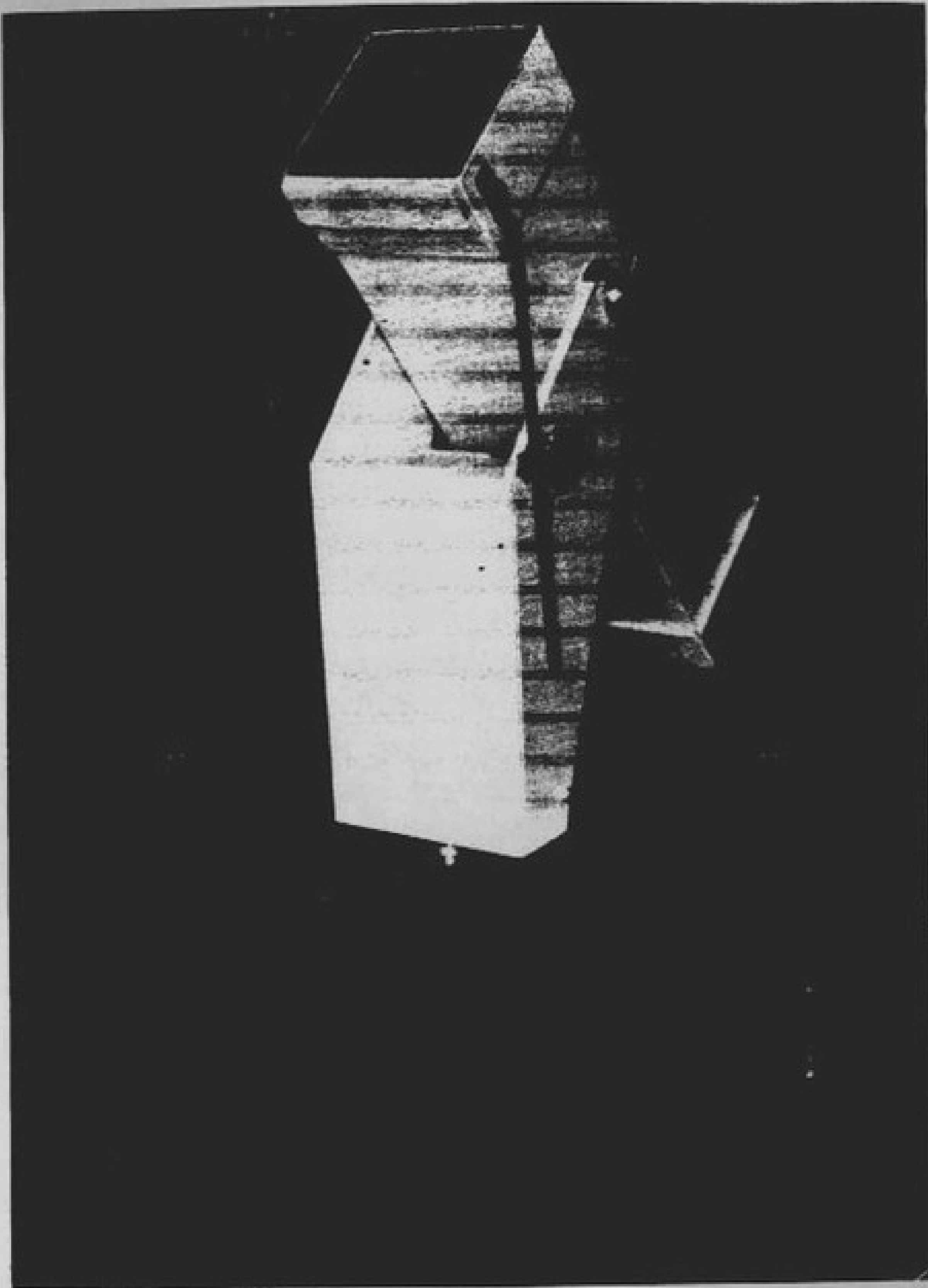


Fig. 62. Example of modified Couder mounting: a "richest-field" telescope (R.F.T.) with eyepiece at fixed height. Mirror diameter 157 mm., $f/3.9$; magnification as R.F.T.: 25 diameters. A slightly modified eyepiece mounting replaces one of the trunnions. The telescope is balanced by the extended upper portion of the body upon which is mounted a lead frame. The elevation adjustment bar is fitted with a rack and pinion.

V-2. Details of Importance or Interest

The Azimuth Axis. The vertical shaft (34), being heavily loaded at the free, upper end, is the weak point of the mounting. The variable additional loading caused by wind may not produce perceptible vibration at the end of the shaft, but at the eyepiece, at 300 or 400 diameters magnification, the effect can be considerable. The longer and heavier the telescope, the more slowly these vibrations are damped. The amateur who is tempted, after a simple calculation of the rigidity, to reduce the shaft diameter to say ¾ inch, must pause to consider the real nature and magnitude of the problem. No single characteristic of a telescope mounting compares in importance with that of stability. The calculated static deflection, however small, is of little importance compared with considerations of vibration, i.e., the attainable vibration amplitude, the frequency, and the damping period. Note that a mere displacement of 0.0008 inch at the upper end of the shaft, corresponding to angular flexure of 10 seconds of arc, produces an intolerable motion at the eyepiece.

The safe course is to accept the recommendations of those who have learned the hard way—sometimes changing the shaft three or four times before reconciling themselves to a sufficiently heavy shaft and the added cost involved. The following are the minimum recommended diameters based on experience with several hundreds of telescopes of similar design:

For a 6- or 7-inch telescope, *f*/6, lightly built, weight of telescope tube less than 20 pounds: 1¼ inches diameter.

For the standard 8-inch telescope illustrated in the drawings, tube weight about 25 pounds: 1⅜ inches diameter.

For heavier-than-average 8-inch telescope, made with thick panels or built to larger dimensions, tube weight not in excess of 45 pounds: 1⅝ inches diameter.

For a 10-inch telescope, tube weight not exceeding 70 pounds: 2 inches diameter.

For telescopes of larger size, the offset-fork structure is not recommended; it would not have the necessary rigidity. To use larger instruments effectively requires a carefully designed equatorial mounting the final cost of which can be justified only in a relatively permanent installation. It would be shortsighted indeed for an amateur to undertake a 12-inch or larger mirror unless he could meet the inevitably high cost of a sturdy mounting of this type.

Fork Assembly. The tie rods (35), traversing the full width of the fork, are an important feature. This is far sturdier than relying merely on the wood screws in the ends of the crossbeams. If looseness develops at any time, the turn of a wrench is all that is needed to restore the original rigidity. Additional rigidity is given by the cover panel (26).

Azimuth Clamp and Fine Adjustment. Users of the standard mounting in the past have sometimes complained that the telescope moves too freely on the azimuth axis; that they must therefore set the instrument up with its

azimuth axis rather accurately vertical, and shelter the telescope from the wind. To improve this, we have increased the friction at the "triple" point by reducing the cone angle on the shaft to 20°. The worker can in addition easily devise an adjustable clamping bar to bear against the shaft opposite the V-plate contacts. A more perfect solution is a clamp (made of wood, for example) mounted on the shaft and caused to bear at one end against a screw mounted on the telescope fork. This provides a fine adjustment in azimuth. But there is little need to elaborate on details. Each worker will want to adapt the design to his own needs and preferences.

Support Block and Tripod. We require a relatively massive mounting block (27) in order to assure firm support of the aximuth axis. Note the width of the sides of the block, forming the base of each triangular tripod leg. The advantage of this tripod design is that the leg members (28 and 30) act almost exclusively in compression and tension. Even when the individual boards are themselves quite flexible, the assembly as a whole is extremely rigid.

MAKING A CASSEGRAINIAN TELESCOPE

This chapter assumes that the reader has had the experience of making a good primary mirror for a 6- or 8-inch Newtonian telescope.

VI-1. The Classic Cassegrainian: Configuration and Notation

The large, main concave mirror (Fig. 63) is of diameter D_1 and radius of curvature r_1. It therefore has a focal length of $f_1 = r_1/2$. The secondary mirror is

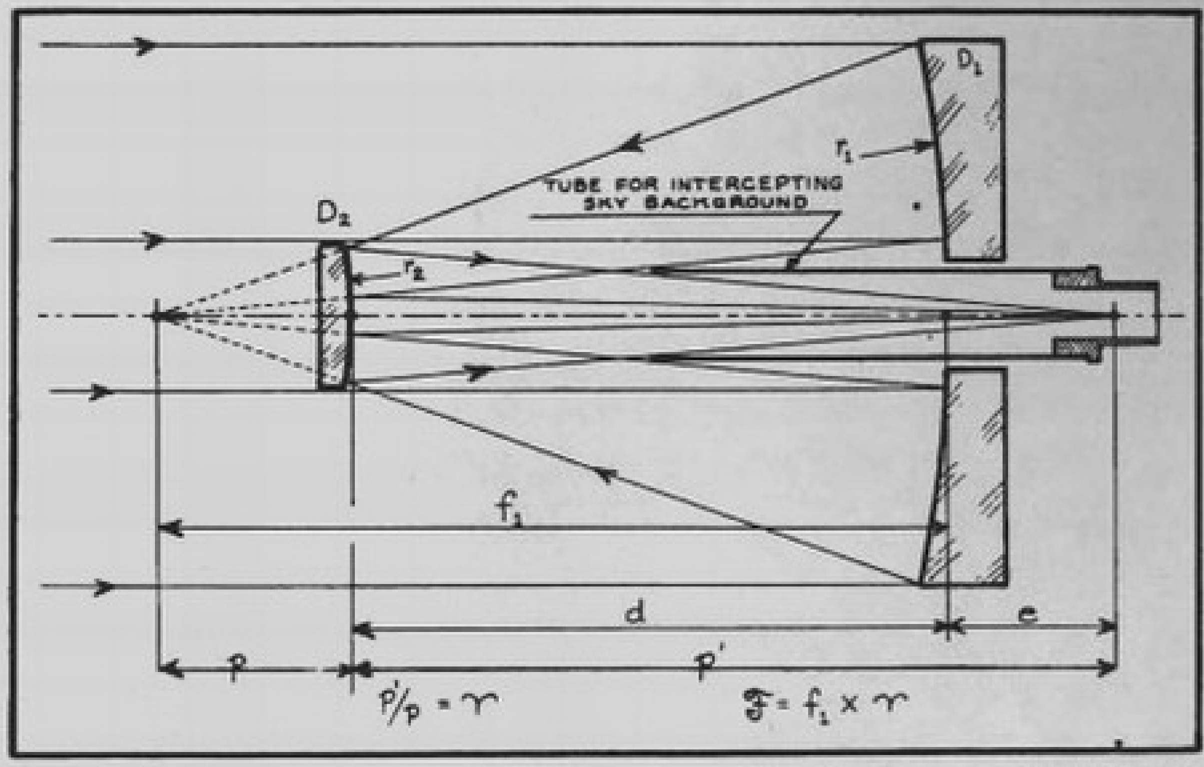


Fig. 63. General arrangement of a Cassegrainian combination. Transverse dimensions are exaggerated.

convex, of diameter D_2, and radius of curvature r_2. Positioned within the beam of the large mirror and inside its focal plane, the secondary mirror reshapes the beam of the large mirror into one of a narrower aperture that passes through a hole cut in the main mirror. The resulting beam corresponds to an equivalent focal length $\mathcal{F}$ for the mirror combination. The ratio $\mathcal{F}/f_1$, designated as γ, expresses the magnification due to the convex mirror as well as the ratio between the distances p' and p separating the crest of the convex mirror from the final focus and from the focus of the large mirror. The midpoints of the mirror surfaces are separated by the distance d. A clearance distance e, measured from the center of the large mirror, is provided to make the final focal plane accessible.

VI-2. Advantages and Disadvantages of the Classic Cassegrainian

The eyepiece section points toward the sky, as in a refractor. Overall, this is more convenient than the Newtonian arrangement with its lateral eyepiece at the top of the tube, particularly when the instrument is mounted equatorially. Thanks to its convex mirror, the Cassegrainian makes available a telescope with a focal length as long as one may wish, without increasing the overall length, which is fixed by the focal length f_1 of the main mirror. This is particularly valuable in planetary photography or, more generally, for high resolution work[1]. Correspondingly, planets and double stars can be observed with eyepieces of convenient focal length, and these need not be highly corrected types such as the Plössl or the orthoscopic.

In the Cassegrainian, the eyepiece or the photographic plate is directly exposed to background light from the sky or from any source near the field. This lowers the contrast and is a very serious disadvantage. The remedy consists in elongating the eyepiece support tube sufficiently to eliminate the stray light without vignetting. Unfortunately, the elimination cannot be complete except on the axis; off axis, the aperture is vignetted and sky background is reintroduced unless the central obstruction is increased considerably. But this is inadmissable, as we shall see; nor can we excessively elongate the eyepiece tube. Not only may the ratio $\mathcal{F}/D_1$ be large in the Cassegrainian, but logically it should be. Without doubt, the Newtonian, aside from being easier to build, is the preferred telescope for ratios of $\mathcal{F}/D$ of the order 6 to 8. One can even add a Barlow[2] lens to extend this advantage to an $\mathcal{F}/D$ of the order of 15 to 20. In the Newtonian, as in the Cassegrainian, obtaining a wide field with good clearance from the telescope tube must be paid for by a large central obstruction. In the Cassegrainian, this reduces the possibility of choosing a small γ and should not be considered lightly. The large central obstruction is objectionable not because of the light loss, in most cases translating into only hundredths of a magnitude, but because the normal diffraction pattern (Fig. 64) is altered. The energy diffracted into the rings is increased at the expense of intensity in the central disk. Table VII shows the extent of this loss for various obstruction ratios.

Figure 64 shows the intensity ratios up to the second diffraction ring relative to the central disk for a completely unrestricted pupil and for obstruction ratios of 0.2 and 0.5. The corresponding visual appearances show

[1] *Astrophotographie d'amateur*, Sections 21 & 26 Editions Revue d'Optique, 1954.
[2] See section XI-3

TABLE VII
EFFECT OF CENTRAL OBSTRUCTION
ON DIFFRACTION DISK

Relative Obstruction	0.0	0.1	0.2	0.3	0.5
Relative % of Energy in:					
Central Disk	83.8	81.8	76.4	68.2	47.8
1st Ring	7.2	8.7	13.7	21.8	35.2
2nd Ring	2.8	1.9	0.7	0.5	7.2
3rd Ring	1.5	2.4	4.0	2.5	0.2
All Rings	16.2	18.2	23.6	31.8	52.2

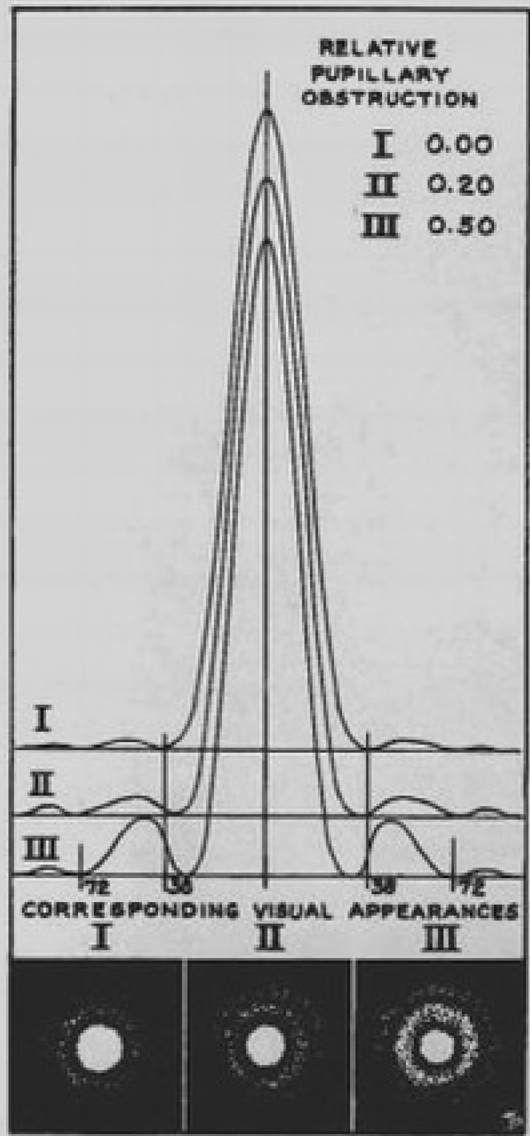


Fig. 64. Diffraction figure changes caused by a central obstruction.

the seriousness of the change for an obstruction ratio of 0.5; the first ring is so reinforced that with the slightest added residual zonal aberration, or the least turbulence, it is no longer the radius of the first dark ring, but that of the second which fixes the resolving power. Thus, a 16-inch telescope with an obstruction of 0.5 will hardly be better than an unobstructed 6-inch, and may even be much worse if turbulence increases appreciably. In practice, we may say that an obstruction of 0.1 causes no appreciable change in the image. An obstruction of 0.2 causes visible but tolerable reinforcement in the first ring. An obstructon of 0.3 is not advised, particularly in an instrument intended for viewing planetary surfaces or observing the close companion of a double star. Above 0.4 the obstruction is admissible only in photographic wide-field telescopes.* A Cassegrainian should have an $\mathcal{F}/D_1$ greater than 15, and consequently it will be poorly adapted for visual or photographic observation of pale, extended objects such as nebulae and comets which require the largest of exit pupils (5 to 7 mm), low magnifications and wide fields, characteristics which are impracticable on such an instrument.

VI-3. The Coudé or Nasmyth Modifications

Instead of perforating the main mirror, Nasmyth made the focal plane accessible by a plane diagonal mirror P, analogous to that of a Newtonian telescope, to transpose the secondary focus F to F′ (Fig. 65). A notable example

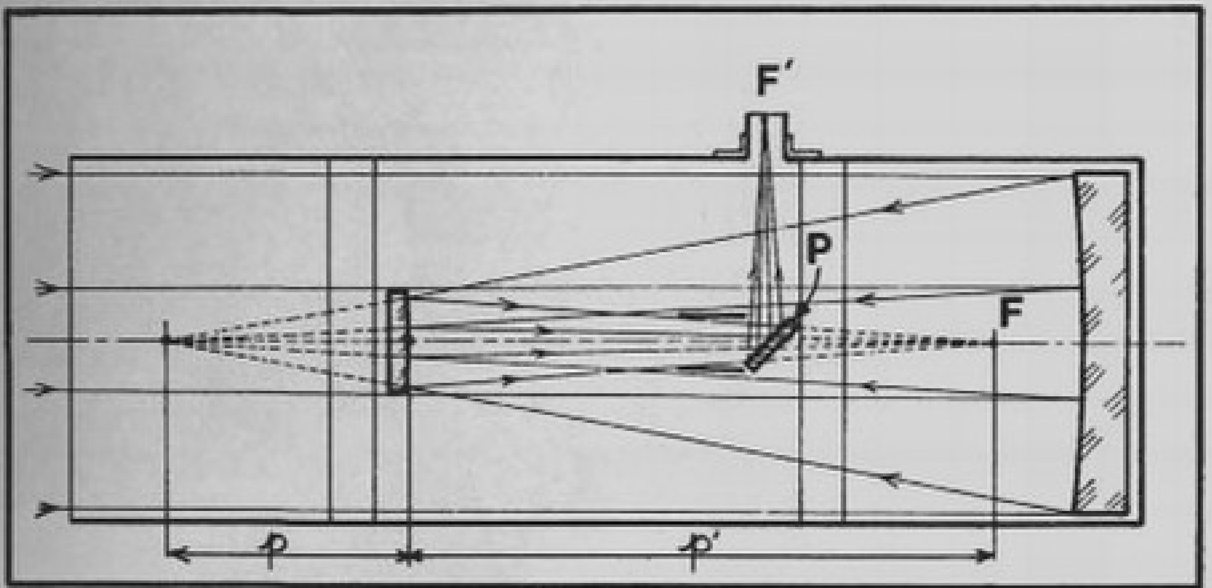


Fig. 65. General arrangement of a coudé Cassegrainian.

of this arrangement was its use by Ritchey for the 60-inch and 100-inch Mount Wilson telescopes. However, it can be applied to equal advantage in a modest amateur instrument with an equatorial fork mount (Fig. 66). The most frequent orientations of the instrument correspond to comfortable viewing angles for the eyepiece mount, comparable to that of a microscope. Further, Figure 65 shows that for a given obstruction, we can reduce the distance p' and that consequently a rather high value of γ is no longer obligatory. Finally, the unperforated mirror is much easier to make and avoids thermal effects at the central aperture always seen in a Foucault test on a normal Cassegrainian, regardless of its dimensions. This takes the form of slow-moving spirals of air rising radially from the hole and forming a permanent vein of convection, at

* For a more complete description of this subject see: "The Perfect Point Spread Function," by D. Stoltzmann, Chapter 4., *Vol. 9 of Applied Optics and Optical Engineering*, Academic Press (1983).

Fig. 66. Small coudé Cassegrainian.

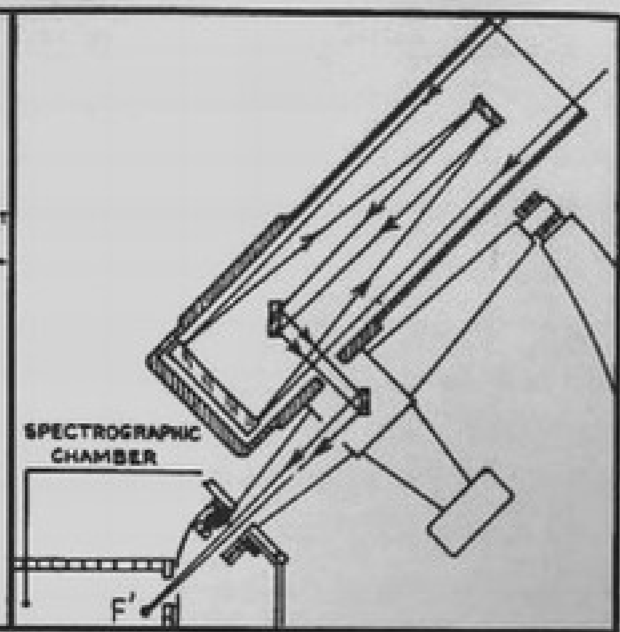


Fig. 67. Large coudé Cassegrainian.

times very marked. The principal disadvantage of the system is that the odd number of reflections leads to an image reversed with respect to reality. When referring to a map, or identifying details in a planetary drawing, one would need to use a mirror. This can be remedied by replacing the diagonal mirror with a roof prism of *prime quality* (in view of the power of the eyepieces). Protection against background light from the sky may be very difficult for certain telescope proportions, but on the contrary may be better if the distance between the diagonal and the convex mirror is reduced sufficiently. Almost inevitably, there is an accumulation of diffraction effect from the two sets of spider support blades, and even with alignment of the blades along the axis, the improvement expected in theory may not be realized. We should again mention briefly the coudé arrangement used in large observatory telescopes, where a *fixed final focus* passes through the polar axis and permits installation of a large spectrograph in a temperature controlled chamber. Figure 67 shows the beam arrangement for a reflector in a simple English equatorial mount. We note that a fourth mirror is necessary and that p' is lengthened considerably, resulting in a high value of γ and an enormous equivalent focal length. These factors must be taken into account in designing the slits and collimators for the spectrographs.

VI-4. Selection of Design Constants

The diameter D_1 of the large mirror establishes the overall scale. On this point we leave the builder's ambition to its fate, though if excessive, it may cause trouble later. The overall instrument length is tied to the focal length f_1 (Fig. 63) of the mirror. There is legitimate interest in reducing this as much as possible, but a high quality parabolic mirror of aperture ratio $f_1/D_1 = 4$ requires an optician of the first order. Preferably, the aperture ratio should not be less than 5, even if one has had considerable advanced experience. On the other hand, a ratio higher than 6 would lead ultimately to too long a working focal length $\mathcal{F}$. The clearance distance e is the sum of dimensions that are difficult to reduce: the thickness of the mirror and its mount, the eyepiece mount, and additional allowance for possible accessories with their own clearance requirements—a coudé eyepiece, a helioscope, or a camera. For an amateur instrument, e will be about 8- to 10-inches. A needless increase in this allowance will lead to an increase in γ or in the central obstruction. We are thus at the point of making our most important decision, i.e. the choice of γ, since f_1 cannot vary over any great range. This is no problem for those who, at any price, want the best possible instrument for studying planetary surfaces. They will choose a maximum γ value which reduces the obstruction to a minimum, but which sacrifices field width and the possibility of low magnifications. To compensate for the latter has not been easy because commercial sets of eyepieces of long focal length have not been readily available[3]. Assume that the weakest available ocular has a focal length of 75 mm. We forego exit pupils larger than 1.5 mm. The ratio $\mathcal{F}/D_1$ may be as large as 50 and γ equal to 10, given a primary of $f_1/D_1 = 5$. The lowest possible magnification will then be 133 for an 8-inch instrument, and 200 for a 12.5-inch instrument. For a less specialized instrument, we would not want to exceed $\mathcal{F}/D_1 = 20$ to 25. Assuming again a primary aperture ratio of 5, γ will be 4 or 5 and the maximum pupil will be 3.75 or 3 mm. Assuming again in each case that the weakest eyepiece, i.e. 75 mm, is used, the magnification is reduced to 53 or 67 for the 8-inch instrument, and to 80 or 100 for the 12-inch. With the latter instrument we can no longer see the moon in its entirety without cutting a rather large hole in the primary mirror. Values of γ less than 3 are not advised in Cassegrainians intended primarily for visual use.

VI-5. Calculating Related Design Constants

It is useful to think basically in terms of the parameter γ. In the elementary formulas below we assume that all quantities are positive, so as to to avoid errors of sign that may occur with variously arranged optics.

Position of the secondary mirror (notation as in Figure 63):

$$p = \frac{f_1 + e}{\gamma + 1} \tag{27}$$

$$p' = p\gamma \tag{28}$$

Radius of curvature of the secondary:

$$r_2 = \frac{2p\gamma}{\gamma - 1} \tag{29}$$

[3] As a result, even normal astronomical refractors of $f/15$ cannot be used with equipupillary magnification. At our request, the firm of Clavé is now making Plössl eyepieces in focal lengths of 40, 50, and 75 mm in a 50 mm diameter slide tube (see Section XI-4).

Diameter of the secondary:

$$D_2 = \frac{D_1 p}{f_1} \tag{30}$$

To the latter we may add ⅛ inch if we wish to cover a fully illuminated, finite field. We should provide an additional 1/16 inch for the outside diameter of the glass. The actual obstruction is determined by the outside diameter of the mounting, which can hardly be less than 1/32 inch greater than that of the glass in the case of a small mirror.

The opening in the main mirror should, of course, remain less than the diameter of the secondary obstruction. It will be seen that in a small instrument it is not always possible to use the entire field of a long focal-length eyepiece.

VI-6. Deformation Coefficients and Off-Axis Aberrations

Schwarzschild, in 1905[4], described a general theory for two-mirror reflectors permitting direct calculation of all third-order aberrations and exact determination of the deformation coefficients b_1 and b_2 of the large and small mirror, respectively (See sections II-28 and -29).

If we postulate that spherical aberration has been corrected and introduce the parameter γ (magnification by the secondary, or G1 in the corresponding BASIC statement—See Appendix C for program), we obtain practical expressions in which (except for special mentioned cases) the variables r_1, r_2 and d (R1, R2, D) are to be introduced with positive sign.

1. *Stigmatic mirror combinations.* If the deformation of either of the mirrors is known, for example, an existing primary which we do not want to refigure, we can theoretically always obtain stigmatism with a secondary from which;

$$b_2 = (1 + b_1)\frac{r_1}{r_1 - 2d}\left(\frac{\gamma}{\gamma - 1}\right)^3 - \left(\frac{\gamma + 1}{\gamma - 1}\right)^2 \tag{31}$$

B2=(1+B1)*R1/(R1−2*D)*(G1/(G1−1))^3−((G1+1)/(G1−1))^2

On the other hand, if the deformation of the secondary is known, and the primary is to be refigured, we have

$$b_1 = \frac{r_2}{r_1}\left(\frac{\gamma - 1}{\gamma}\right)^4\left[\left(\frac{\gamma + 1}{\gamma - 1}\right)^2 + b_2\right] - 1 \tag{32}$$

B1=R2/R1*((G1−1)/G1)^4*(((G1+1)/(G1−1))^2+B2)−1

The particular case of a true Cassegrainian with a separately useful parabolic mirror is the most interesting one in practice. Here we have

$$b_1 = -1 \text{ (paraboloid)} \tag{33}$$

[4] Untersuchengen zur geometrischen optik II. Theorie der Spiegeltelescope. Astronomischen Mitteilungen, Göttingen, Vol. 9, 1905.

$$b_2 = -\left(\frac{\gamma + 1}{\gamma - 1}\right)^2 \qquad (34)$$

2. *Off-axis coma* $\mathcal{B}$ or B

$$\mathcal{B} = \frac{\gamma^2}{2}\left[\frac{1}{\gamma^2} - (1 + b_1)\frac{d}{2d - r_1}\right] \qquad (35)$$

B=G1*G1/2*(1/(G1*G1)−(1+B1)*D/(D*2−R1))

For the radial length of the plume (tangential coma) at a distance Θ from the axis expressed in radians, we have

$$\mathcal{B}'' = \tfrac{3}{4}\Omega^2\Theta B \qquad (36)$$

where,

$$\Omega = \frac{D_1}{\mathcal{F}} \qquad (37)$$

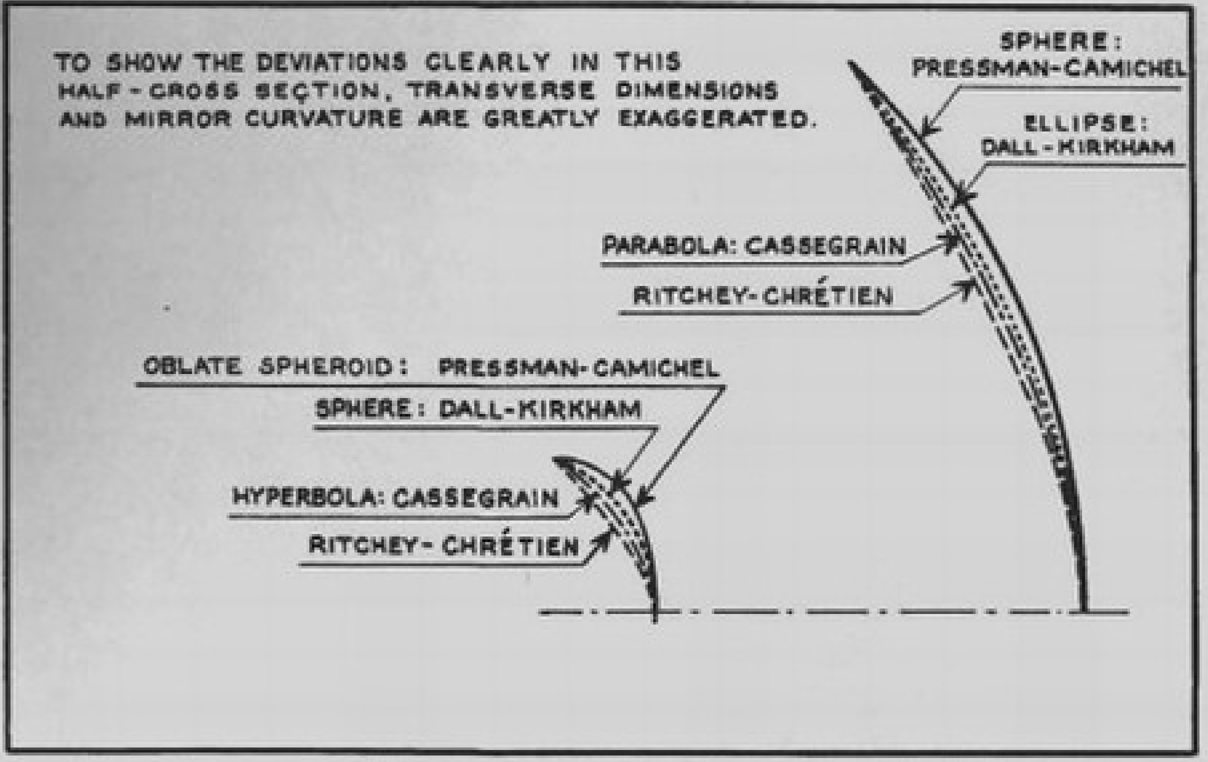


Fig. 68. Deviations relative to the sphere for various designs of paired mirrors.

Actually, the spreading of the diffraction spot that can be seen by the eye or photographed is much smaller.

For the true Cassegrainian, $\mathcal{B} = 0.5$, i.e. exactly the same as for a paraboloid of the same diameter *and of a focal length identical to that of the combination*. The positive sign of $\mathcal{B}$ indicates exterior coma; if on the other hand the sign is negative, the plume is directed toward the axis of the field.

To facilitate figuring one of the mirrors, some authors have proposed combinations in which one of the mirrors is spherical:

Dall and Kirkham[5] made the secondary spherical on the basis that this is more easily tested:

$$b_2 = 0 \qquad (38)$$

$$b_1 = -\left[1 - \frac{r_2}{r_1}\cdot\frac{(\gamma^2 - 1)^2}{\gamma^4}\right] \qquad (39)$$

B1=−(1−(R2/R1)*(G1*G1−1)^2/G1^4)

The primary is ellipsoidal, a little less deviant from the sphere than a paraboloid. It is not usable separately and the chief disadvantage is accentuation of the coma, which becomes 2 to 6 times as large as in a true Cassegrainian for the usual values of γ. This is not too serious an objection in a visual instrument that is always of limited field width.

Pressman[6] and Camichel[7], on the other hand, proposed a spherical primary:

$$b_1 = 0 \qquad (40)$$

$$b_2 = \frac{r_1}{r_2}\left(\frac{\gamma}{\gamma - 1}\right)^4 - \left(\frac{\gamma + 1}{\gamma - 1}\right)^2 \qquad (41)$$

B2=R1/R2*(G1/(G1−1))^4−((G1+1)/(G1−1))^2

This time b_2 is positive; thus the radius of curvature diminishes toward the edge. The deformation relative to the sphere is unfortunately quite large, so that obtaining a truly satisfactory surface quality by retouching is not feasible. But more serious, the coefficient of coma is enormous—4 to 12 times that of the true Cassegrainian—which requires very precise alignment, a condition not easily maintained if the mechanical design of the instrument is not excellent.

3. *Aplanatic reflector*—Schwarzschild in his 1905 paper showed that spherical aberration and coma could be corrected simultaneously by an appropriate choice of b_1 and b_2. This aplanatic condition is given by

$$b_1 = -\left(\frac{2p}{d\gamma^2} + 1\right) \qquad (42)$$

B1=−(P*2/(D*G1*G1)+1)

$$b_2 = -\left[\frac{r_1\gamma}{d(\gamma - 1)^3} + \left(\frac{\gamma + 1}{\gamma - 1}\right)^2\right] \qquad (43)$$

B2=−(G1*R1/(D*(G1−1)^3)+((G1+1)/G1−1))^2)

These values are valid for all reflectors. At the time that Schwarzschild wrote his paper, the slow photographic emulsions would suggest relative apertures, $\mathcal{F}$/D, of the order 3. His telescope had a *concave secondary* (thus r_2

[5] Scientific American, vol. 185, 1951, p 118.
[6] Journal of the British Astronomical Association Vol. 57 Dec. 1947, p. 224.
[7] l'Astronomie, Vol. 68, Oct. 1954, p. 387.

enters in our equations with negative sign), a magnification γ of less than unity and a focal plane ahead of the primary ($e<0$). One could also (if it were worth the trouble) similarly calculate a Gregorian aplanatic (r_2 and p negative). But the most interesting form of aplanatic reflector is that proposed by Ritchey and Chrétien[8]. It is simply a Cassegrainian in which the mirror deformations satisfy this aplanatic condition.

The suppression of coma, the most serious of off-axis aberrations, eliminates a disturbing source of error in astrometric measurements with a photographic telescope, but the Ritchey-Chrétien is not the panacea that the current literature makes it out to be. Off-axis astigmatism not only persists, but is somewhat increased, and the same applies to curvature of the field. To give a specific example, consider the case of a 12-inch amateur reflector with a primary of $f/3$, $f_1 = 36$, $\mathcal{F} = 90$, and $e = 8$. The value of γ then is 2.5. If we examine the 2-degree field that can be covered without vignetting by a 5-inch secondary, then at 1-degree from the axis the Cassegrainian will exhibit a coma of 12 seconds of arc and an astigmatism of 8.9 seconds. The radius of curvature of the focal surface will be −14.92 inch. The Ritchey-Chrétien suppresses the coma, but the astigmatism amounts to 10.44 seconds of arc and the radius of focal curvature is −13.28 inch.

If we take into account the intensity of a photographic image needed to show the coma, the recordable plume length will not even be half the calculated length. We can in fact say that no one will see the improvement, since an approximately round image 0.001 inch in diameter is still considered satisfactory, and finer images of stars at best have a halo of aberration that does not attain the sensitivity threshold of the photographic emulsion.

For a large telescope, for example ten times larger, we can no longer in a comparable case do without a multiple-lens field corrector. For a long time it was believed that such correctors were more easily made and more effective on a Ritchey-Chrétien, but this is no longer true. The three-lens Wynne correctors likewise provide a perfectly flat field on an ordinary Cassegrainian. This is important because the parabolic mirror, which can always be used separately with a reduced field and without involving refraction, is an attractive possibility with devices that are unavoidably small, such as cameras using charge-coupled detectors.

In the Ritchey-Chrétien, not only can the primary not be used separately, but the aplanatic combination prescribes a fixed $\mathcal{F}$/D ratio. For visual observation we want a larger ratio and less obstruction by the secondary but, in this case, the coma would be seriously increased.

Finally, it is evident that the more deformed mirror surfaces of the Ritchey-Chrétien are more difficult to figure, at any rate if we want the diffraction-limited quality taken as a standard in this book.

[8] *Revue d'Optique*, Vol. 1, 1922, January and February.

4. *Astigmatism* A or AS

$$A = \gamma \left[\frac{2d - \gamma r_1}{\gamma^2(2d - r_1)} - \left(\frac{d}{2d - r_1}\right)^2 (1 + b_1) \right] \tag{44}$$

AS=G1*((D*2−G1*R1)/(G1*G1*(D*2−R1))−(D/(D*2−R1))^2*(1+B1))

Between the two foci we have a minimum "circle" of confusion of a diameter in seconds of arc equal to

$$A'' = \Omega\Theta^2 A \times 103132 \tag{45}$$

As in the case of coma, $\Omega = D_1/\mathcal{F}$ and the angular distance Θ from the axis is in radians.

5. *Anastigmatic reflector*—A. Couder[9] in 1928 designed the optics of a reflector of 31.5-inch aperture in which correction was made not only for spherical aberration and coma, but for astigmatism as well. The system has a mechanical constraint that makes it resemble a Schwarzschild aplanatic, namely the condition that

$$d = r_1 \times \gamma \tag{46}$$

The deformation coefficients become

$$b_1 = \frac{2\gamma - 1}{\gamma^3} - 1 \tag{47}$$

$$b_2 = \frac{\gamma(\gamma^2 + \gamma - 1)}{(1 - \gamma)^3} \tag{48}$$

The radius of curvature r_2 of the concave secondary has to be introduced in our equations with a negative sign. This instrument may be compared with the Schmidt. The correction of off-axis aberrations is the same. The overall instrument size is unfortunately the same. The focal plane is equally inaccessible. The curvature of the field has the same positive sign (convex toward the incident light), but in the present case is unfortunately considerably more pronounced. The two concave mirrors are strongly deformed, but nevertheless easier to make than a Schmidt corrector plate and can be tested easily at their centers of curvature. The absence of the Schmidt corrector could be considered a decisive argument favoring this design, since it eliminates such plate effects as filtering, chromatism and possible inhomogeneity. On the other hand, the advantage of thermal stabilization in a tube closed by a plate is lost. Another disadvantage is the obstruction by the secondary, which rapidly becomes unacceptable when an unvignetted field of 3 degrees or more is attempted. Here, for example, are the specifications of an anastigmat of 50 cm aperture, $f/2.7$, which might be used for supernova searches.

[9] *Lunettes et Télescopes*, 1935, 1979, p. 206.

The unvignetted field is 2 degrees and could in practice be extended to a plate 3 inches (7.62 cm) on a side covering 3 degrees 26 minutes of arc. The deviation of the plate from flatness by only 0.043 inches (0.11 cm) makes it possible to use films cut to circular shape and bent to conform to this radius in a suitable holder. All measurements are in millimeters (1 inch = 25.4 millimeters).

$D_1 = 500/594$	$D_2 = 200/294$
$f = 4500$	$r_2 = 1542.86$ (concave)
$p = 1800$	$\gamma = 0.3$
$p' = 540$	$\mathcal{Z} = 1340$
$d = 2700$	Convex field, $r = 658.5$
$b_1 = -15.8148$	$b_2 = -0.533528$
$\epsilon_1 = 2.65 \mu m$	$\epsilon_2 = 1.06 \mu m$
Slopes at edge: 8.47×10^{-5}	6.9×10^{-5}

6. *Curvature of field.*—We must first calculate the Petzval curvature ($\mathcal{P}$; P3):

$$\mathcal{P} = \gamma \left[1 + \frac{r_1 (\gamma - 1)}{\gamma (2d - r_1)} \right] \qquad (49)$$

P3=G1*(1+R1*(G1−1)/(G1*(D*2−R1)))

The curvature of the surface containing the sagittal astigmatic focus is

$$CS = \mathcal{P} - \mathcal{A} \qquad (50)$$

That of the surface containing the tangential focus is

$$CT = \mathcal{P} - 3\mathcal{A} \qquad (51)$$

By convention, the curvature of the field at which the image is more or less round is

$$C = \mathcal{P} - 2\mathcal{A} \qquad (52)$$

Using our sign convention, a positive C value indicates a focal surface that is concave toward the incident light and its radius of curvature is simply

$$CR = \frac{\mathcal{Z}}{C} \qquad (53)$$

7. *Completely corrected telescope.*—Theoretically, there is no difficulty in postulating an astigmatic telescope with a flat field. The added condition to be satisfied is that P become zero, or

$$\gamma = \pm \frac{\sqrt{2}}{2} \qquad (54)$$

However, it is easily seen that the four possible solutions are impractical, leading either to virtual images or a totally defeating central obstruction. This instrument concept is therefore no more than a curiosity.

VI-7. Judging the Difficulty of Figuring

As explained in sections II-20 (p.59) and II-28 (p.77) the accurate testing of concave mirrors is easily done by measuring the longitudinal aberration at the center of curvature and comparing the result to the theoretical value given by formula (15) page 77.

On the other hand, to evaluate the difficulty of figuring as well as testing a convex mirror against a concave reference (as we shall see), we need equations describing the curve of the mirror itself by X and Y coordinates. The same coefficient of deformation b is used and three terms of the development are sufficient to give a proper accuracy even for big or wide aperture mirrors

$$X = \frac{y^2}{2r} + (1 + b)\frac{y^4}{8r^3} + (1 + b)^2 \frac{y^6}{16r^5} \qquad (55)$$

X = Y*Y/(R*2) + (1 + B)*Y^4/(R^3*8) + (1 + B)^2*Y^6/(R^5*16)

Now the equation of the sphere being

$$X\,(Sp.) = r - \sqrt{r^2 - y^2} \qquad (56)$$

If the two curves osculate each other on the axis, the departure on edge is e (see fig 12c page 17)

$$e = X\,(sp.) - X \qquad (57)$$

As mentioned in section II-1 the departure of interest for the mirror maker is very close to a quarter of this (see figure 12b page 17).

A simple and sufficiently accurate way for amateur size mirrors to obtain the departure on a given zone radius y is given by

$$\Delta x = \frac{b}{8} \times \frac{y_{max}^2 y^2 - y^4}{r^3} \qquad (58)$$

(y max is the extreme optical radius on edge)

As illustrated in Figure 69, the maximum departure from the sphere, ϵ, at $y = 0.707 y_{max}$, has the value

$$\epsilon = \frac{b}{32} \times \frac{y_{max}^4}{r^3} \qquad (59)$$

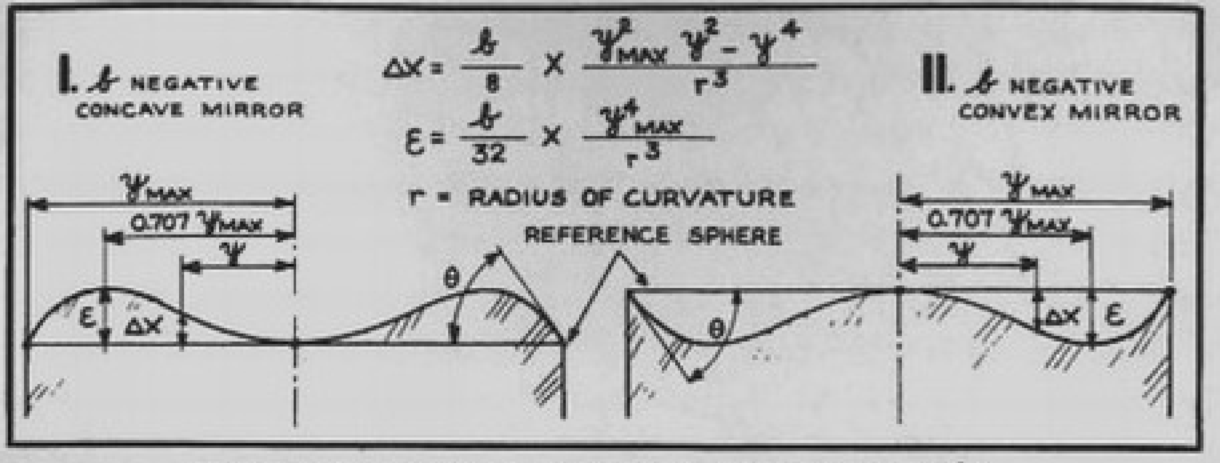


Fig. 69. Mirror surface deviations compared with the sphere.

In the most frequent case, where b is negative, we see that the cross-section has the familiar central cavity, and a down turned edge[10] in the case of a *concave* mirror (Fig. 69-I). If the reference is compared with a *convex* face, the increasing radius of curvature as we go towards the edge translates into a cross-section with a central prominence, an annular depression and a raised edge (Fig. 69-II).

The value of the slope at the edge, where it is a maximum, is especially important in judging the difficulty of figuring a convex secondary, because here we are dealing with a raised edge, which is more difficult to obtain. The slope at the edge relative to the sphere is given by the value of the derivative of equation (59) for $y = y_{max}$:

$$\Theta \text{ (radians)} = \frac{dx}{dy} = \frac{b\, y^3_{max}}{4r^3} \tag{60}$$

Let us consider the magnitudes of some of the slopes of interest. The actual surface of a finished optical element exhibits millions of defects of every lateral dimension. Those seen under phase contrast range from 0.0004 to 0.25 inch, for example, and those more particularly visible in the Foucault test vary from 0.080 inch up to the diameter of the disk. We have shown that on a correctly worked and retouched astronomical optical element all of these defects have about the same slope, i.e. 0.5 to 1×10^{-6} with respect to the ideal geometric surface. Small defects of this weak slope are generated automatically if one adopts a correct polishing technique[12], but the overall form cannot be finished to this approximation except at the cost of retouching steps that become increasingly prolonged and numerous as slopes such as Θ (Fig. 69) become large. The following are some results for mirrors of interest to us. A primary parabolic mirror of $f/5$ will have a slope of 3×10^{-5} near the edge with respect to a sphere, a value that can be realized to the approximation cited above. This is a challege for the dedicated amateur but quite feasible because it

[10] Figure 37.
[11] *Ciel et Terre*. 66th year (LXVI), numbers 3–4 March-April 1950.
[12] Section II-34 and Figure 41C.

is rather easy to take advantage of the natural deforming tendency of a large tool which with long strokes tends as a first approximation to give the cross-section of Figure 69-I. On the other hand, a parabola of $f/4$ with slopes twice as steep, i.e. 6×10^{-5}, will require delicate and numerous local retouching steps.[13] The convex secondary hyperbola to be used with the $f/5$ primary will likewise have slopes of 3×10^{-5} at its edge. Given its small dimensions this requires only light retouching: unfortunately, Figure 69-II indicates that it is of the *raised edge* type, whereas the surfaces commonly generated on a small mirror can easily have a *turned-down edge* with a slope of 5×10^{-5} or even 1×10^{-4} relative to the sphere, especially if the operator fears that stretching out the working time will overheat the disk. To reverse this tendency and obtain a good sphere requires much more experience than forming a hyperbola with a true sphere as a starting point.

VI-8. Design Examples for Two Cassegrainian Telescopes

For the reader who may be intimidated by the preceding detailed discussion, we present the calculations for two interesting instruments that are quite feasible to build.

First example: A not too-specialized Cassegrain of 10-inch aperture. Main mirror $D_1 = 10$ inch; $f_1 = 50$ inch; $f_1/D_1 = 5$

We specify that the minimum available magnification shall be equal to 100 (pupil 2.4 mm or 0.1-inch) with an eyepiece of 75 mm (3 inch) focal length. This gives $\mathcal{F} = 300$ inches, $\mathcal{F}/D_1 = 30$ and $\gamma = 300/50 = 6$. The required clearance distance, e, is taken as 8.66 inches.

$$\text{Equation (27) gives:} \quad p = \frac{50 + 8.66}{6+1} = 8.38 \tag{61}$$

$$\text{Equation (28) gives:} \quad p' = 8.38 \times 6 = 50.28 \tag{62}$$

$$\text{Equation (29) gives:} \quad r_2 = \frac{2 \times 8.38 \times 6}{6-1} = 20.11 \tag{63}$$

$$\text{Equation (30) gives:} \quad D_2 = \frac{10 \times 8.38}{50.28} = 1.67 \tag{64}$$

The optical diameter of the secondary is increased to 1.77 inch and its outside diameter to 1.85 inch. The fractional obstruction for a mounting of 1.89 inch will therefore be 0.19, a value that does not seriously degrade the diffraction spot (Fig. 64). One may cut a 1.77 inch hole in the main mirror and use an eyepiece drawtube of 1.61 inch I.D. (1.69 inch O.D.). The field will not exceed 18 arc minutes at most (advice to observers of the entire lunar disk: do not give up your Newtonian option).

$$\text{Equation (34) gives:} \quad -b_2 = \frac{(6+1)^2}{(6-1)^2} = 1.96 \tag{65}$$

[13] Section II-37, Method C.

$$\text{Equation (60) gives:} \quad \epsilon = \frac{1.96}{32} \times \frac{(0.89)^4}{(20.11)^3} = 0.0000047 \text{ or } 0.12\mu \qquad (66)$$

The slope at the edge of the secondary is 4×10^{-5} relative to the sphere. No special difficulty there: this slope diminishes rapidly as we move away from the extreme edge.

Second example: A 12.5 inch diameter Cassegrain for planetary surfaces. Main mirror $D_1 = 12.5$; $f_1 = 62.5$; $f_1/D_1 = 5$.

The largest pupil is limited to 1.5mm or minimum magnification = 200 with an eyepiece of 75 mm focal length. This gives $\mathcal{F} = 590$ inch; $\mathcal{F}/D_1 = 50$; and $\gamma = 10$. The clearance distance e is taken as 9.45 inches.

$$\text{Equation (27) gives:} \quad p = \frac{62.5 + 9.45}{10 + 1} = 6.54 \qquad (67)$$

$$\text{Equation (28) gives:} \quad p' = 6.54 \times 10 = 65.40 \qquad (68)$$

$$\text{Equation (29) gives:} \quad r_2 = \frac{2 \times 6.54 \times 10}{10 - 1} = 14.533 \qquad (69)$$

$$\text{Equation (30) gives:} \quad D_2 = \frac{12.5 \times 6.54}{62.5} = 1.30 \qquad (70)$$

The optical diameter of the secondary is taken as 1.30 inch; the outside diameter as 1.38 inch. The secondary mounting has a diameter of 1.42 inch, the fractional obstruction is 0.12; thus perturbation of the diffraction spot will be negligible (Fig. 64). We shall cut a 1.34-inch hole in the main mirror, and use an eyepiece drawtube of 1.26 inch I.D. (1.30 inch O.D.) We have to reconcile ourselves to a maximum field of 7 arc minutes; in practical terms, this dictates an equatorial mount for the instrument and a clock-driven polar axis.

$$\text{Equation (34) gives:} \quad -b_2 = \frac{(10 + 1)^2}{(10 - 1)^2} = 1.49 \qquad (71)$$

$$\text{Equation (60) gives:} \quad \epsilon = \frac{1.49}{32} \times \frac{(0.65)^4}{(14.53)^3} = 0.0000027 \text{ or } 0.07\mu \qquad (72)$$

The slope at the extreme edge is 3.6×10^{-5}; but because material to be removed is so slight, hyperbolization is very easy if we start from a sphere. This instrument is almost impossible to equip with a complete series of eyepieces (see section XI-4).

VII

MAKING THE PRIMARY CASSEGRAINIAN MIRROR

Making a parabolic mirror has been discussed in detail in Sections II-1 to II-41. Some supplementary instructions will be useful for making a perforated mirror.

VII-1. Rough Check for Strain

It must be recognized that cutting a hole in a thick glass disk unavoidably releases mechanical strain that may be quite severe and may cause the glass to shatter. Testing for strain is therefore recommended, especially on a disk that

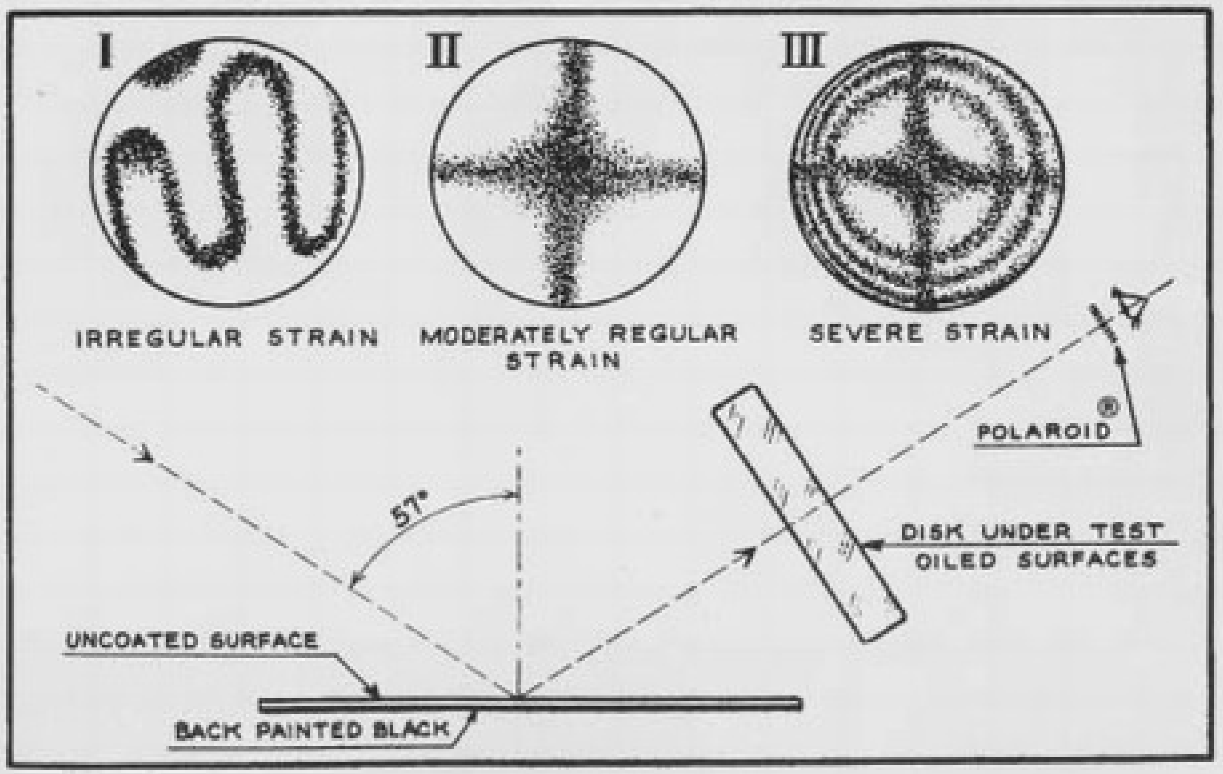


Fig. 70. Simple test for strain.

may have been cast some years ago, and is relatively thick. Even if the disk has been well annealed, it is a near-certainty that attempting to pierce a finished high-quality mirror will destroy its overall figure. Perforation can therefore only be contemplated prior to precision figuring.

Strain is easily detected in polarized light with a simple test set-up (Fig. 70). The polarizer, which should provide a field covering the entire mirror disk, may be a sheet of ordinary polished plate glass without any reflective coating. We use the light reflected from this plate at the Brewster angle (57 degrees from the normal). To prevent depolarization of the light by the rough surfaces of the raw disk, they may be coated with castor oil or lubricating oil. The analyzer, placed in front of the eye, may be a small piece of polarized film, or simply a Polaroid® sun glass lens. Before inserting the mirror disk in the beam, the Brewster angle is determined by trial and error. With the Polaroid first rotated so that its polarization axis exactly crosses the polarization plane of the glass, the viewing angle is found at which light reflected from an extended source such as a cloudy sky is almost completely extinguished. When inserted in the polarized light path, the mirror may show bright zones or even colored fringes in areas of appreciable compression or tension.

A porthole disk cut from a casually annealed slab of glass will present an irregular appearance as shown in Figure 70-I. An individually annealed disk shows tension lines crossing regularly from the center to the edge, forming a more or less centered black cross (Fig. 70-II). A hole can be cut in such a disk without too much risk of breakage. On the other hand, old thick disks often have strain corresponding to optical path differences of several wave-lengths, manifested by a series of colored, higher-order rings (Fig. 70-III)

One should avoid piercing such a disk. As the cutting tool enters the layer of greatest tension, about a third of the way through the disk, it will probably cause the glass to shatter[1].

VII-2. Cutting the Hole

In industry, the cutting tool is a hollow cylinder, the cutting edge of which is diamond-charged. The amateur cannot readily amortize such a tool, but with the "biscuit-cutter" fed with 80 or 120 carbo, he can cut a 2 inch hole through 1.5 inches of glass in less than a hour. An ordinary drill press may be used, provided the spindle velocity can be set as low as 100 to 200 rpm. The set up shown in Figure 71 is self-explanatory. The cutter is conveniently guided by means of a disk that is about 1/8 inch thick, attached with rosin precisely at the center. The mirror, its rim coated with vaseline, serves as the bottom of a dish whose sides are formed simply by a few turns of heavily paraffined wrapping paper. This container will hold enough water and carborundum to assure constant renewal of the abrasive. Nevertheless, it is best not to bear down too hard or persist too long on the used abrasive, but to raise the cutter frequently to prevent dangerous overheating.

Polishing a perforated mirror is hardly possible without forming an appreciable turned-down edge next to the central hole. To avoid this, we may use one of the following two methods:

[1] This mishap occurred, despite every meticulous precaution during piercing of the old 36-inch Common mirror of the Crossley Telescope at the Lick Observatory.

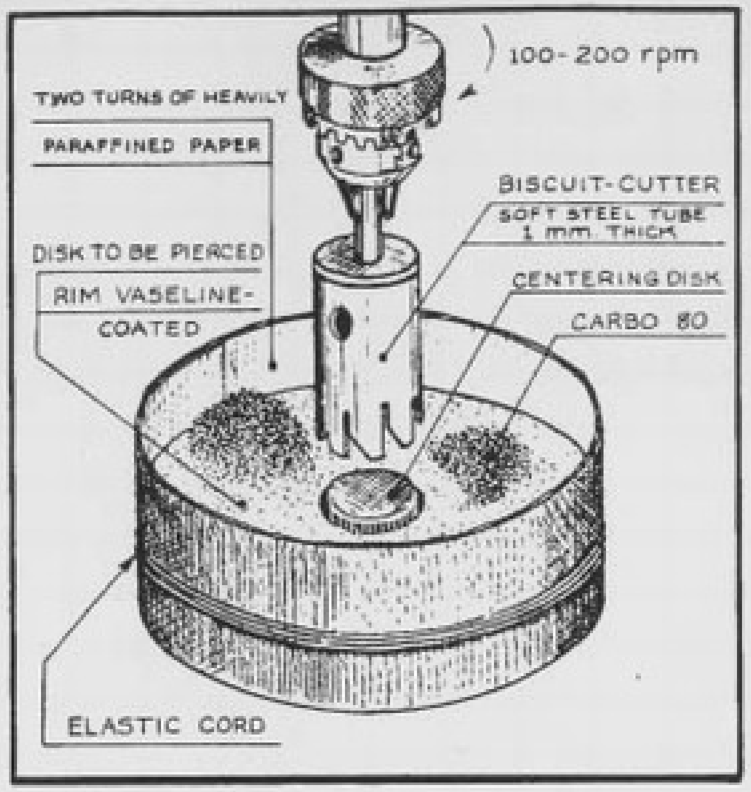


Fig. 71. Cutting the hole in a Cassegrainian primary mirror.

Henry Brothers Method—We begin by cutting the disk from the side that will be the back, but we stop before reaching the face (Fig. 72). A thin, narrow steel rule inserted to the bottom of the cut will confirm that the remaining thickness of glass equals the depth of the intended mirror curvature (note that we do this before rough-grinding the concave face) plus about 0.10 to 0.15 inches. If the disk was well annealed, we may hope that residual strains have been nearly completely liberated, and we then entirely finish the mirror like an ordinary disk. The circular cut at the back is filled with wax or plaster for the remaining course of the work. With the optical surface free of any discontinuity, no zone will be discerned opposite the circular cut at the back; only a faint anomaly is sometimes seen, due to disturbance of heat flow near the cut. When removing the central core from the the completely finished mirror, we observe several precautions. To avoid chipping of the edges, cutting is resumed on the second face which is now the polished surface of the mirror. It is advisable first to coat this surface with a protective layer, for example, with wax or lacquer. Precise alignment of the biscuit cutter with the original cut will be assured by again using a guide disk cemented with rosin to the glass. The remaining 0.10 or 0.15 inches are abraded away under gentle pressure, using 5 min. emery. To reduce the risk further, one may complete the cut by turning the biscuit-cutter by hand without forcing or bearing down too heavily. After the central core is removed, the inner edge of the hole must be chamfered on both sides. This can be done rapidly and precisely with a spherical tool fed with 5 min. emery, the tool being of such radius that it contacts the edge of the hole at an angle of about 45 degrees.

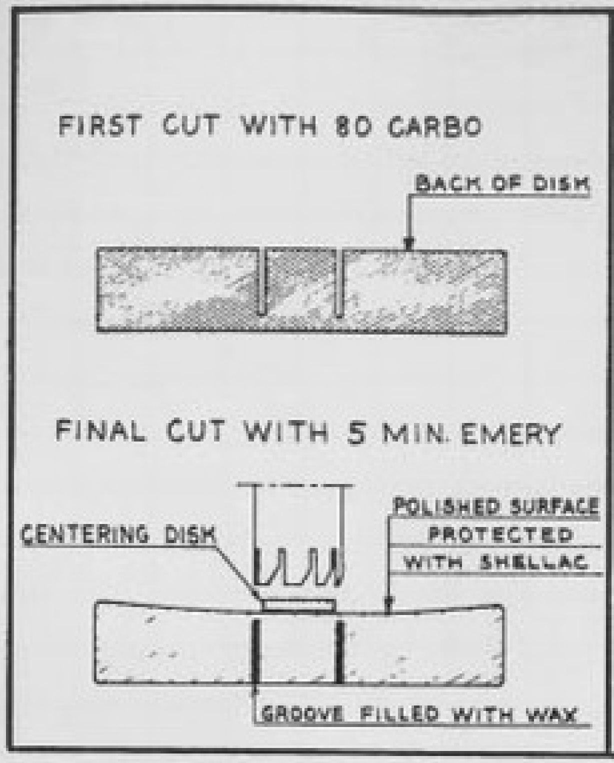


Fig. 72. Henry method.

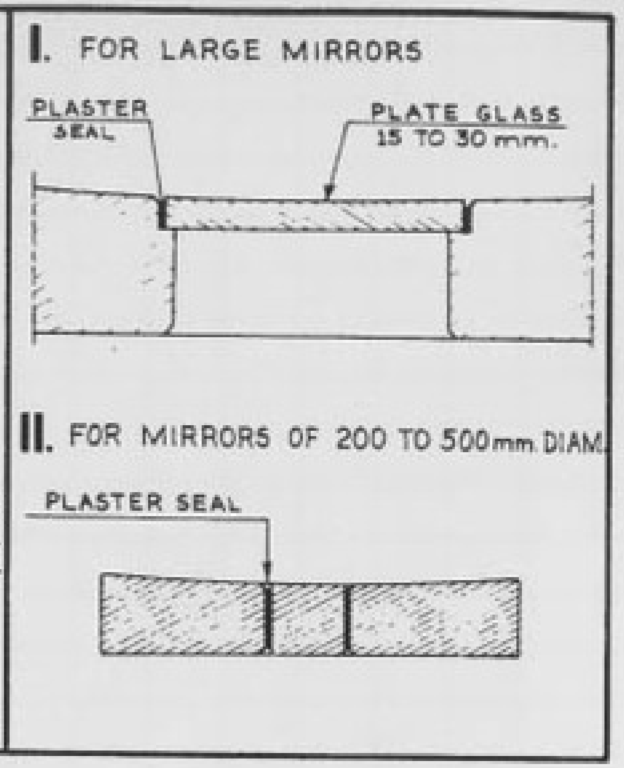


Fig. 73. Ritchey method.

The principal hazard in the Henry method is that one cannot be sure that the mirror deformations will be negligible when the core is finally removed. For example, at our optical group's workshop, where three 7.87 inch disks were made by this method, and where we had confirmed that residual strain was negligible, two of the disks remained practically unchanged while the third slumped in the central zones to show an over-correction of a full fringe (half wave). Retouching such a hyperbola, once the central core has been removed, is difficult. It may even be impractical if the mirror has also lost its symmetry of revolution.

The Ritchey Method—The preceding method is in any case too risky for a large mirror, and the hole in any event would be formed at the factory during casting to avoid risk of breakage. In this case the biscuit-cutter is used only to enlarge the hole to the desired diameter. A second cut, slightly larger in diameter, forms a shoulder in which is placed a glass insert 5/8 to 1 1/4 inches thick. This insert is secured throughout the surfacing procedures by a plaster seal around its edge (Fig. 73-I). For the amateur's mirror, one simply uses the central core. The core is cemented into the disk with plaster in a rather liquid state, since the channel will be barely 1/16 inch wide (Fig. 73-II). After prolonged drying of the plaster and rough grinding of the mirror to its concave shape, the plaster in the channel is scraped down to about 1/32 inch below the surface, then painted with several layers of lacquer to prevent penetration of water into the plaster and to facilitate removal of abrasive between the various grades of emery. The Ritchey method is less effective than the Henry method in avoiding thermal effects at the inner edge. However, it does greatly reduce the risk of deformation after removing the core. We should

remember, though, that setting of the plaster is sometimes accompanied by a volume change—it may expand. On one occasion, using this method at the workshop, we had to retouch a 12 inch mirror after removing the plaster mounted core.

VII-3. Finishing the Perforated Mirror

Most of the information in Sections II-8 through II-19 is directly applicable here. We should mention only that when smoothing a mirror with a re-inserted core or an inserted plate (Ritchey method) we should clean the groove meticulously with each change of emery. It is wise also to coat the groove with shellac to fix any abrasive grains that escaped cleaning, at the same time preventing water penetration into the plaster. In polishing (considering still the mirror with a replaced core or insert), a small zone of pitch should be trimmed away on the polishing tool where it tends to bulge directly above the groove in the mirror during pressing. One may even completely remove a circle of pitch from the center of the tool equal to the diameter of the hole, to better ensure that a bulge in the lap will not form an inside turned-down edge.

VII-4. The Apertured Couder Screen

In deciding on screen window dimensions, the important thing is to have areas that are easily readable, when making knife adjustments, as zones of equal brightness (Sec. II-31). The width of the windows should not be less than 5/8 inch for an observer at 10 feet. We prescribe an arithmetic progression of h_m^2 values merely to indicate the general trend in relative zone widths. One need not hesitate to adjust the theoretical values somewhat if they lead to poorly proportioned windows. For example, a central window may be too wide and may contain a small zone making it impossible to decide when the overall zone is of uniform brightness. In the Cassegrainian, the central hole is naturally eliminated, so that this difficulty is reduced. In any event, measurements made with an apertured screen are valid only if the figure of the mirror is relatively regular and free of narrow zones. Figure 74 gives the proportions for a 5-zone screen adapted for a 10-inch diameter Cassegrainian of $f/D = 5$. Similar proportions could be used for mirrors not too different in diameter or in their departure from sphericity. Likewise, one may modify the inside radius of the central zone to fit a central hole of different size. If the mirror is not parabolic, i.e. if b differs from -1, we will naturally replace the values of h_m^2/R by those of bh_m^2/R without otherwise changing the calculations for reducing the data.

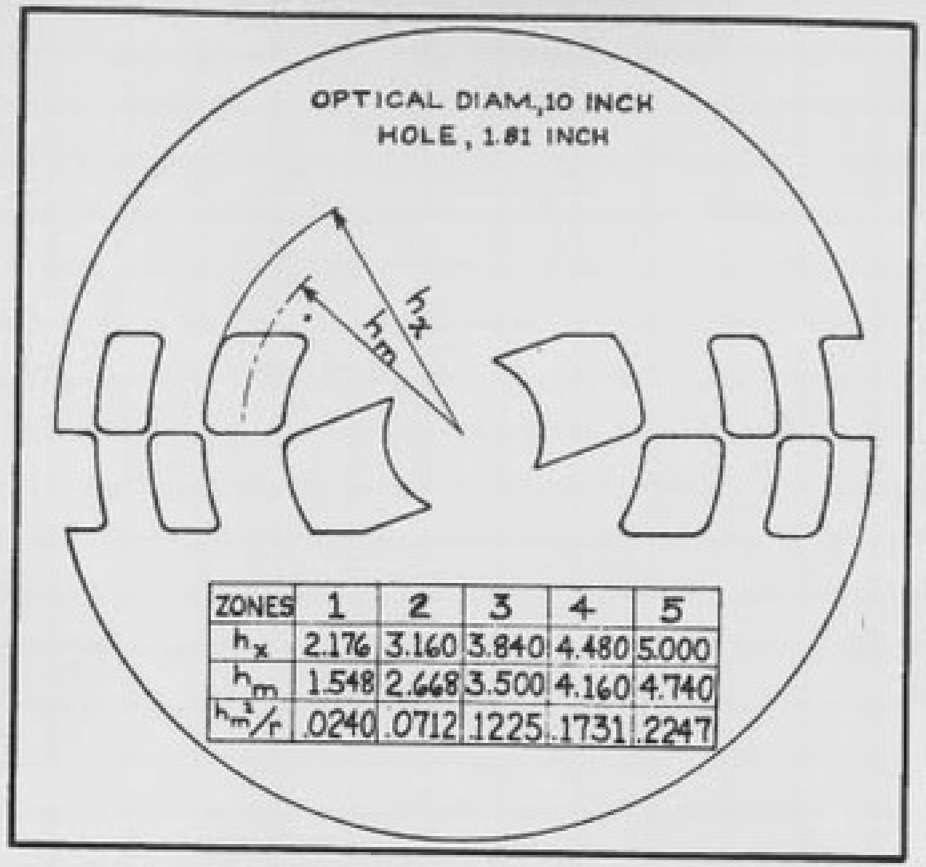


Fig. 74. The couder screen for a 10-inch Cassegrainian mirror.

VII-5. Parabolizing Mirrors of Large Relative Aperture

One may always start parabolizing by the classic method (Section II-37, Fig. 43-A) provided that changes in the mirror cross-section are monitored with each successive correction step. In most cases a mirror that deviates markedly from a sphere, such as a parabola of $f/D = 4$, or, even more so, a Ritchey Chrétien, cannot be completed in this way. Beyond a certain point, the pitch resists these larger deformations. Still, one would always try to finalize the form with a large tool and a decidedly eccentric stroke (Fig 43-C).

Local polishers will be of little use except for a turned-down edge or a faint zone. Final retouching is done after the central core is removed. For a mirror of $f/D = 5$, the radius of the theoretical diffraction spot is only 3.4μ, and for $f/D = 4$ decreases to 2.7μ. Extremely careful retouching is necessary to assure that all emerging rays converge within this image. Poorly performing Cassegrainians have often been made because their makers insisted on a primary of $f/D = 4$ and were not careful or skilled enough to properly figure the objective. In a word, we cannot realistically count on the secondary to compensate for negligent work on the primary. As always, the quality of the principal mirror is critical if the project is to make any sense.

VIII

MAKING THE SECONDARY CASSEGRAINIAN MIRROR

The principal difficulty in a Cassegrainian telescope is that the secondary mirror is convex, and consequently cannot be tested by the Foucault method without using additional optical elements.[1] Since the selected test method greatly affects the entire course of the work, we shall examine closely the four methods that are valid and practical.

VIII-1. Testing Combined Mirrors on a Star

This method (Fig. 75-A) is applied under the normal conditions of telescope use, with a bright star serving as the source. It is assumed that the complete instrument is available, that it is mounted equatorially, and is provided with a carefully made polar drive. The large mirror, which has been separately tested and completed, is aluminized. The secondary to be tested has not yet received its reflective coating. It takes considerable experience to correctly interpret small defects by the Foucault method on an actual star. Because of atmospheric turbulence, matching brightness in the mask windows may be deceptive. However, a Foucault shadowgram of a bright star will show the magnitude of the defect and an enlargement will enable one to measure the precise radius of the crest of a zone[2]. This technique requires careful guiding for about one minute to average out atmospheric effects. When figuring is nearly complete, the Hartmann Test with its numeric results should be used[3]. In this photographic technique, a bright star such as Vega serves as the source, and two separate extra-focal exposures are made in planes separated by a known distance. This records the positions of narrow light beams isolated by a perforated screen placed over the opening of the telescope. A 1-minute exposure is sufficient for plates of average sensitivity even if only one of the mirrors is aluminized. A measuring device, readable within a

[1] Except by a method proposed by J. H. King, *Scientific American*, Febuary 1935, page 100 and A.T.M. Vol 2, page 269, in which the polished back of the mirror is immersed in a tray filled with liquid of the same refractive index as the glass. In practice, it would be difficult to keep the index of the liquid sufficiently uniform during measurements.

[2] See Figure 144

[3] A very complete description of this technique is given in *Lunettes et Téléscopes*, section 115, page 504.

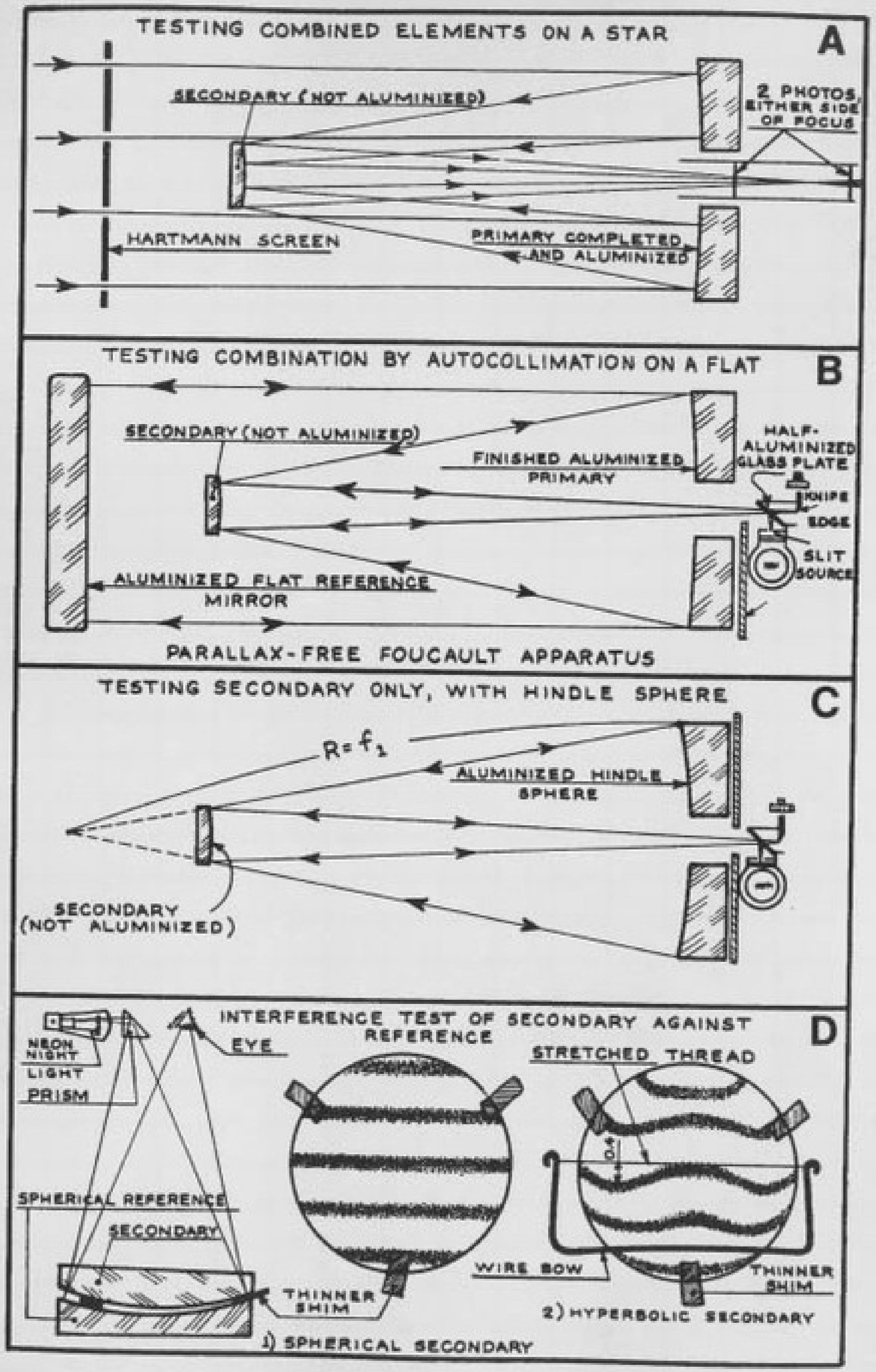


Fig. 75. Test methods for Cassegrainian optics.

micron, is needed to measure on each plate the distance between beams derived from the same mirror zone. Knowing the axial distance separating the two exposures, one can easily deduce the position of intersection for each zone. Details of the method are given in the cited reference.

The data reduction procedure (Sections II-39 and -40) must be modified somewhat to avoid certain mistakes. In the present case, with the source at infinity, we are obviously seeing the aberrations directly at the normal focal position. It is therefore unnecessary to subtract the values of h_m^2/R, line 4 (Fig. 46), which is done only when reducing data taken at the center of curvature. The same applies to adjustment of the values to correspond to the plane of the circle of least aberration. Since we are observing the longitudinal aberrations Λ_F *at the focus*, line 5 (Fig. 46) will comprise the values of $h_m/\mathcal{F}$ and not the values $h_m/4f$. Finally, transverse aberrations will be given by the values of the expression:

$$\lambda_{\mathcal{F}} = \Lambda_{\mathcal{F}} \times \frac{h_m}{\mathcal{F}}$$

The rest of the calculations are unchanged. The advantage of direct study of the combined primary and secondary mirrors under conditions of use is that it automatically incorporates thermal aberrations that enter in the real situation, and which can be substantial in a large instrument. Unfortunately, the cycle of testing and retouching is hostage to the weather. Using only this method, it took six months to complete the secondary of the 24-inch Cassegrainian at the Meudon Observatory, whereas at the observatory of Haute Provence a month was enough for the Cassegrainian secondary of the 76-inch telescope, although the diameter of this secondary was 20.5 inches.

For an instrument of modest size, this difficulty is avoided if a large, well-enclosed area is available, so that an artificial star can be positioned at least 33 yards from the telescope. The visual Foucault method is then again of value to the extent that the air in the enclosed space can be kept homogeneous, but this is not usually easy. A small apertured screen may be placed against the secondary to localize the zones needing retouching. With the source no longer at infinity, the wave front from an ideal parabolic mirror will not be perfectly spherical, and some longitudinal aberration will appear. This will be much smaller than the horizontal aberration h_m^2/R in a parabolic mirror tested at the center of curvature, but will not necessarily be negligible. The combination is tested by increasing slightly the separation d of the two mirrors (Figure 63) so as to leave both the initial separation e and the magnification γ approximately unchanged.

VIII-2. Testing the Combined Mirror with a Plane Mirror

As Leon Foucault has expressed it[4], *the flat mirror in experimental optics is an artificial sky*. If one owns a flat mirror that is free of defects and at least as

[4] Leon Foucault. *Oeuvres de Foucault*, p. 287.

large as the principal Cassegrainian mirror, it may be used to test the mirrors by autocollimation. A notable example of the method was its use by G. W. Ritchey to test the Cassegrainian combination of the 60-inch Mount Wilson telescope. A Foucault test set-up is used with the source and knife-edge as close together as possible. Better, the arrangement is made completely free of parallax by using a semi-reflective plate (Fig. 75-B). In effect, if the source is off-axis, then with the flat unavoidably a fair distance away, the beam reflected symmetrically from the flat would impinge on the two mirrors at considerably offset positions. We note that there is a total of five reflections. With the source at the focus, the Cassegrainian mirror serves first as a collimator to form parallel rays. These are reflected back to the Cassegraininan mirror which then becomes a telescope. Any observed mirror defects are therefore doubled. To minimize light loss, both the flat and the large mirror are aluminized. Short of having professionally finished mirror mounts, fine screw adjustments should be provided on all three mirrors. Even so, the collimation procedure is a challenging exercise for a beginner. Unlike the preceding method, the procedure allows only the axial beam to be tested. If part of the secondary lies outside this beam as in the case where one wishes to extend the field, this portion cannot be tested at the same time. Few amateurs will have access to a good enough flat. We note, however, that whereas zonal defects on the flat are troublesome, slight curvature is of no consequence in an autocollimator setup. It means merely that the source would appear to be at a large finite rather than an infinite distance.

VIII-3. Method of Hindle[5]

Here (Fig. 75-C) in conjunction with the convex secondary mirror to be tested, we use a special, large *spherical* mirror whose *radius of curvature* is equal to the *focal length* f_1 of the principal telescope mirror. The distance d between the centers of the mirror surfaces is the same as in the telescope.

This time, we have only three reflections. The beam is reflected twice from the secondary, so that the observed defects in the latter are doubled in apparent magnitude. The spherical mirror employed in this way gives a stigmatic beam, the same as that of the paraboloid with the source at infinity. The Foucault test therefore directly reveals the twice-magnified defects of the secondary, as in the preceding method. Measurements are made with a small apertured screen, and calculations for reducing the aberration data are the same as with a parallel incident beam. If the Hindle sphere is slightly larger than the main telescope mirror, one can test a secondary that has been increased in diameter to give a wider field. The obvious practical disadvantage of this method is that one has to make a second large mirror. Though the specifications on this mirror are not the most stringent, they are sufficiently so that one would need a collection of such mirrors to avoid making one specifically for each job. On the other hand, the Hindle sphere would be

[5] J. H. Hindle, A New Test for Cassegrainian and Gregorian Secondary Mirrors, *Monthly Notices of Royal Astronomical Society*, March 1931, reproduced in A.T.M. Vol 1, page 225.

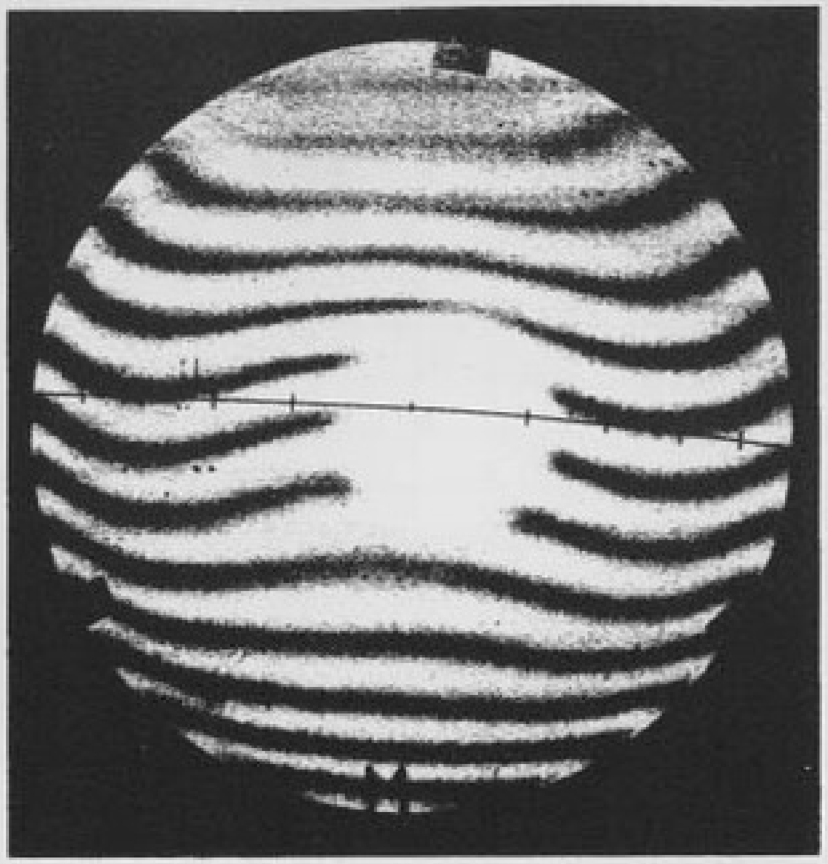


Fig. 76. Fringe pattern for hyperbolic surface. D = 97mm; r_2 = 1312mm; $b_2 = -3.13$; ϵ = 0.25μ.

justified where a standardized Cassegrainian telescope is being produced commercially, or where the secondary under test is that of a large instrument.

VIII-4. Testing the Secondary Against a Concave Reference

This method (Fig. 75-D) was developed and taught by A. Couder in 1945–1946 at the Optical Laboratory of the Paris Observatory. It was independently reported by J. P. Hamilton who published a good description of it in 1952[6]. Since we have already discussed interference testing of mirrors (Sections III-3 and -4) we shall be brief in the following. We begin by making a *small spherical concave mirror* at least as large as the desired convex mirror and of the same radius r_2. Confirming the sphericity of this mirror by the Foucault method presents no difficulty, of course. With such a small mirror, we need only to be careful about off-axis aberrations, which can be troublesome if a source is not very close to, or coincident with the returned image. This spherical mirror serves as the *interferometric reference*. It is assumed that the back of the convex secondary is polished (as is usual when a mirror is made from Saint Gobain plate glass). The interference fringes are observed with the light source and the eye near the center of curvature of the reference. Three paper shims separate the two elements, and as usual the thin

[6] J. P. Hamilton, *A Test for the Cassegrain Secondary*, The Journal of the Astronomical Society of Victoria, Feb. 1952, page 7.

shim and the narrow end of the air wedge are positioned toward the observer. Assuming that our convex mirror is *spherical and of the same radius as the reference*, the fringes formed by the air wedge will be straight lines, the same as would be seen with flat plates (Fig. 75-D1). We know that the central-fringe simulates the cross-sectional form of the surface deviations on the disk being tested. Wherever the deviation relative to the straight line amounts to one fringe spacing, we can deduce a deviation from sphericity of $\lambda/2$, equal to 0.3μ if we assume the effective wavelength of neon light. More specifically, if we want to verify that the secondary is hyperbolic, we need only to confirm that the shape of the central fringe is close to that shown in Figure 69-II when the thin spacer is positioned as indicated in Figure 75-D2. Also, deviation ϵ of the zone at 0.7 h (where it should be maximum), may be estimated to a tenth-fringe and compared with the deviation calculated by equation (60). For example, the form of the fringes shown in Figure 75-D2 would be appropriate for the secondary mirror in the combination proposed as our first example of a Cassegrainian (Section VI-8) in which $\epsilon = 0.12\mu$, equivalent to $0.12/0.3 = 0.4$ fringe spacing.

We observe that the method as described here requires that we make a convex mirror of precisely defined radius, i.e. equal to the radius of our concave reference. If we try to adhere to this equality while at the same time trying to hyperbolize, i.e., aim for patterns of the form shown in Figure 75-D2, hyperbolization often becomes quite difficult. Actually, we can test for hyperbolic form even when there is a curvature difference of several fringes between the mirror and the reference. We need only calculate the contour of the newly added fringes representing equal thickness increments.[7] If we prefer to work with shims of equal thickness, we can calculate the changes of diameter of the resulting Newton rings which correspond to the deviations. However, we prefer to adjust the radii of the surfaces to better than one fringe before hyperbolizing, for a more direct, reliable measurement of the deviations. Besides estimating to a tenth-fringe is quite sufficient for the secondary of a modest instrument.

If the desired secondary mirror surface differs considerably from a sphere, it may be advantageous first to hyperbolize the concave reference. The reference can be tested by the Foucault method and the data reduced in the same way as for a parabola, but with $\Delta p'$ value calculated by equation (56), and taking account of the coefficient b_2 of the secondary. The secondary is considered finished when the fringes seen against the reference appear as straight lines, these being much easier to interpret than curved fringes such as those of Figure 75-D2.

For the amateur without laboratory test optics, making and using a reference disk is the most practical method of testing the secondary.

We now give practical details for the worker who selects the general method of testing the secondary against a concave reference.

[7] This family of curves is given for up to ± 2 fringes in the article by J. P. Hamilton, cited earlier.

VIII-5. General Procedure for Small Mirrors

The secondaries of amateur telescopes of 8- to 12-inch aperture are usually between 1.20 and 3.15 inches in diameter. Making a very precise mirror of this size is more difficult than might be supposed by those who have not tried it. The *fixed post* method, so simple and effective when working with an 8 by 1.38 inch disk, becomes increasingly touchy and uncertain when the diameter goes below 6 and particularly below 4 inches. With mirrors this small, involuntary hand pressures lead to some unpleasant surprises. The job is simplified considerably if the operator works in a seated position in front of the mirror disk or tool, with the latter turning slowly on its vertical axis. The classic optician's foot-operated lathe[8] is considered the machine best adapted for working with small precision optics (Fig. 77). If one can secure such a

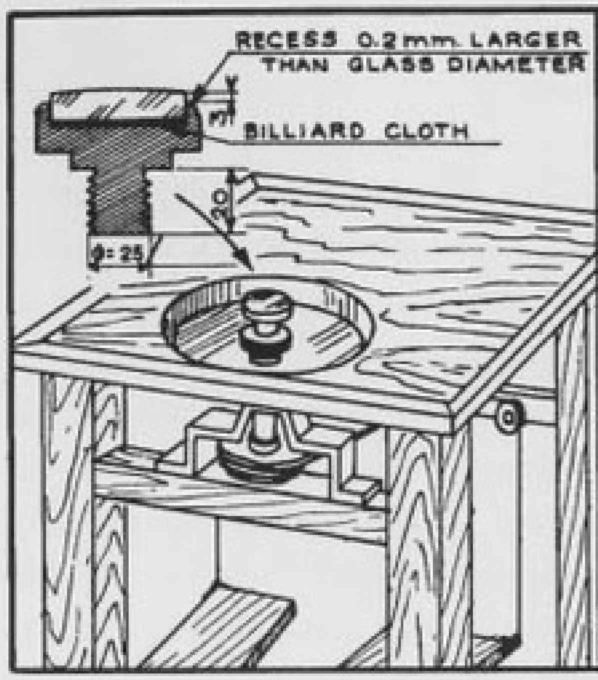


Fig. 77. Pedal-operated lathe.

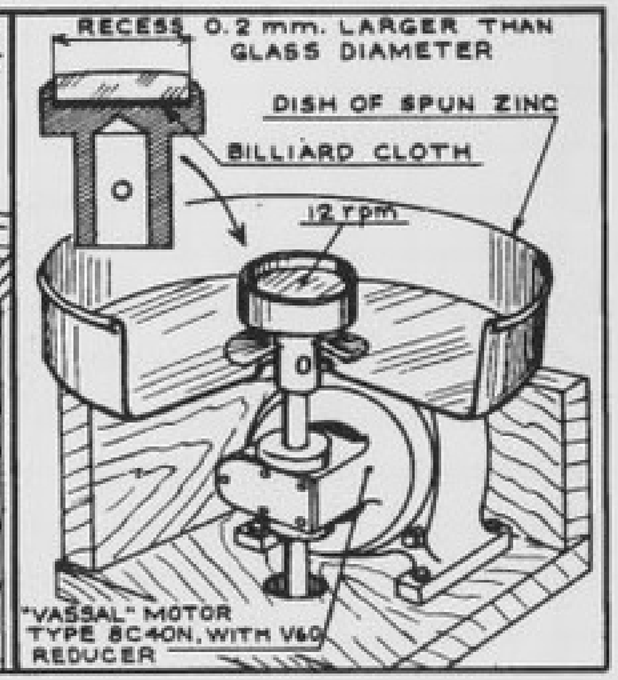


Fig. 78. Motor-driven lathe.

lathe, the drive belt should be positioned for the lowest operating speed, and the pedals worked as slowly and uniformly as possible, at least during precision polishing. For occasional use, such a lathe can be improvised by using directly the slow-turning output shaft of a motor fitted with a right angle reduction gear box (Fig. 78) provided the speed does not exceed 15 r.p.m. The equipment used in the optical industry has a threaded spindle and pan to catch spent abrasive, water, and polishing compound. Tools or the glass to be worked, suitably mounted on a holder, are attached either directly to the threaded spindle or via adapters. Usually separate spindles are available for rough grinding, smoothing, and polishing, and the glass elements are secured on blocking tools with optical cement or rosin[9].

[8] CLAVÉ, 9, rue Olivier Metra, Paris 20ᵉ

[9] For details of these classic methods consult Le *Travail des verres d'Optique de Précision*, Colonel Dévé.). Also available in English as *Optical Workshop Principles*, 1954, Hilger & Watts Ltd. London.

We prefer to support the glass without restraint by using special adapters (Figures 77 and 78) in which the glass lies on a felt disk without any lateral pressure. This arrangement also allows testing or interchanging of the glasses without having to unfasten and re-cement them. The receptacle adapters are machined from a light-weight alloy, or simply in a hard wood. They are either mounted directly on the lathe axis, or merely cemented on a flat disk already provided with the machine.

VIII-6. Edging

The raw material for the mirror and tool may be a piece of Saint-Gobain plate glass 0.40 to 0.60 inch thick. After cutting to approximate shape with the heavy duty cutting tool (Fig. 54) or with the *biscuit-cutter* (Fig. 55) the glass is cemented with rosin on a cup screwed onto the lathe (Fig. 79). Before the rosin

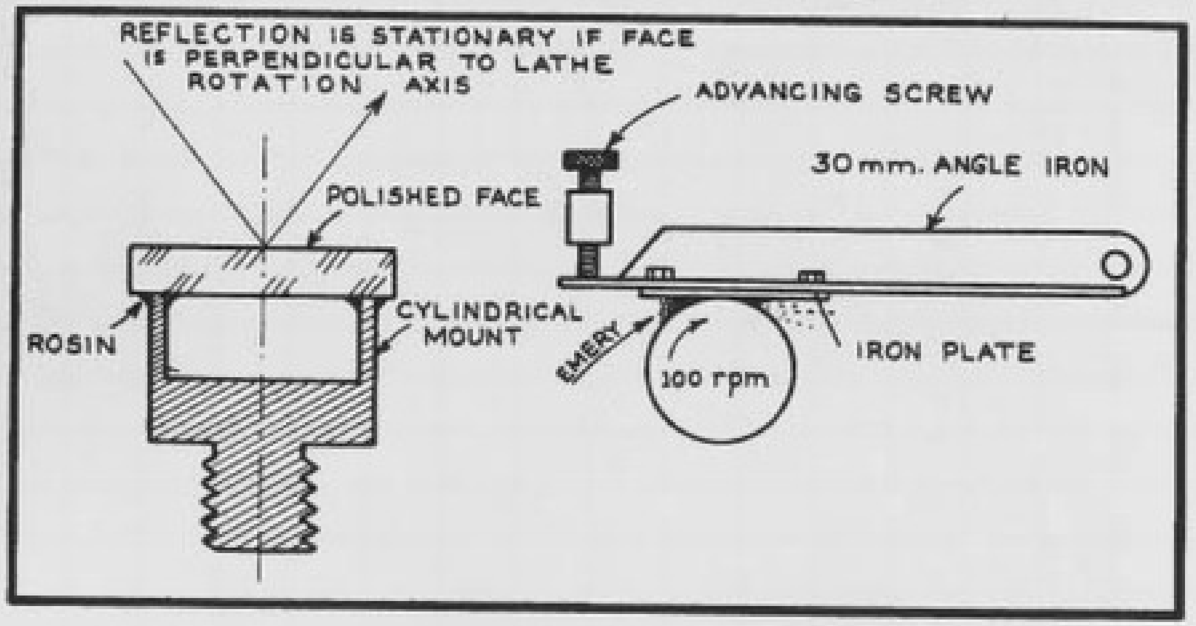


Fig. 79. Edging of small mirror positioned on a cylindrical mount by reflection test.

cools completely, the glass is repositioned for optimum centering of its irregular contour and to ensure that the polished faces are perpendicular to the machine axis. The classic way to confirm this perpendicularity is to verify that the reflection of a lamp or window, seen on the upper surface of the glass, remains stationary. Such centering *by reflection* is done with great care on lenses that will be inserted in strongly convergent systems, and where the elements are centered mechanically. In the present case, approximate verification is quite adequate. The rosin must cool completely before we start to grind the edge. If the edge is irregular, it can first be evened out somewhat by the technique shown in Figure 17A, using 1 min. emery and turning the foot-powered lathe at about 100 r.p.m.. To make the glass exactly cylindrical, a tool like that illustrated in Fig. 79 may be used. This is hinged on a fixed pivot and brought tangentially against the disk by pressure applied with an adjusting screw. The 1 or 2 min. emery is used as long as the noise of abrasion indicates

unevenness or discontinuity when the iron plate, wetted with emery, lightly contacts the glass edge. When the emery is changed, the iron plate can be shifted to change the position of wear on its surface, or it may be replaced with a brass plate to produce a beautiful grain with 10 min. emery. This tool may also be used for gentle chamfering of the fragile edges. If the rim of the glass is not square with the faces, the angle can be corrected by tilting the iron plate.

VIII-7. Rough Grinding

As we work here with glass on glass, we are shaping two useful elements, both of which will be polished so that we can apply the interference test (Section VIII-4). The convex glass is the mirror, the back of which should remain polished and protected by a layer of shellac. The concave tool will later be polished to become the reference. It is advisable to make the reference disk about 10 percent larger in diameter than the mirror. This has no adverse effect on the grinding operations and allows us to overlook a turned-down edge, should the latter occur. Rough grinding proceeds the same as with a fixed post, the glass to be made convex being of course in the lower position, i.e. supported in the holder on the lathe spindle. Given the small amount of glass to be removed, 1 or 2 min. emery used with long, slightly decentered strokes of about $4/5$D is enough to rapidly produce the desired curvature. A sheet metal template cut to the calculated radius of curvature r_2 will suffice to check the rough grinding. We will remember also to regularize the curvature by reducing the stroke amplitude to $1/3$D at the end of rough grinding, and if necessary interchange the disks (which requires having two adapters). After cleaning and taking the normal precautions, we may move on to 5 and 10 min. emeries. We now use somewhat shortened, normal strokes since the concave tool, with its larger diameter, may tend to turn down the mirror edge. Switching the disks is useful not only to correct too-long or too-short a radius of curvature, but can be done systematically following each wet to make the glasses conform as exactly as possible to the same curvature.

VIII-8. Spherometry

Precision testing with a simple sheet metal template (Fig. 20A) leaves something to be desired in verifying the radius of curvature of a Cassegrainian secondary. The effective focal length of the system and positions of the conjugate points are very sensitive to this parameter.

To measure the curvature precisely, we may use a ring spherometer of the form shown in Figure 80. The ring, machined in hard steel, has a diameter slightly less than the glass to be tested. Its contact face is made flat, after tempering or case-hardening, by grinding with 5 or 10 min. emery on a cast-iron plate. The edge defining the radius of the circle of contact on the sphere should be quite sharp. Using a sliding caliper we can measure this radius with precision both for a convex element where $d_1/2 = h_1$ or a concave element where $d_2/2 = h_2$. The hollow upper stem on the ring is slotted at 120 degree

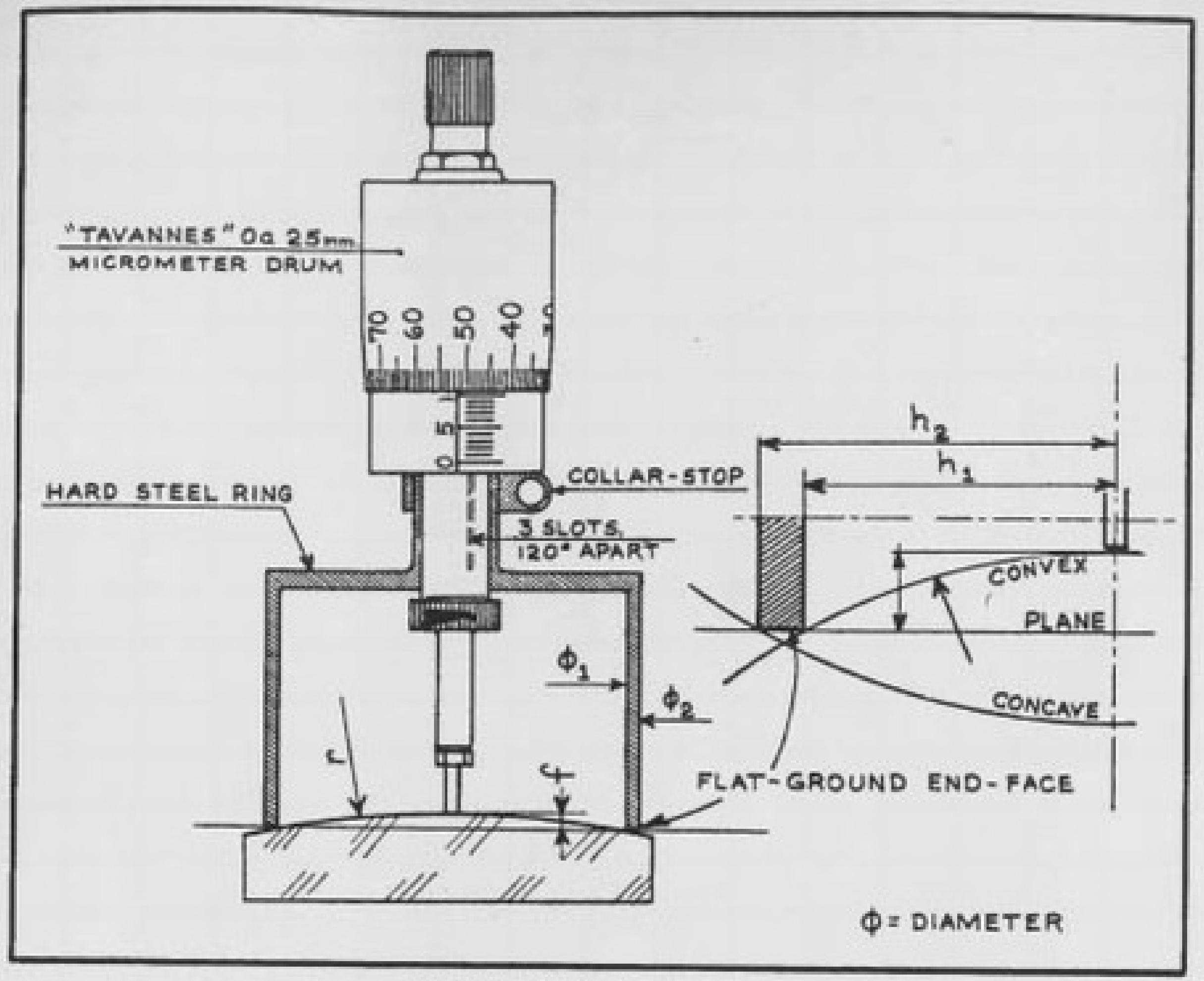


Fig. 80. Ring spherometer.

intervals for elasticity and fitted with an encircling clamp. This stem receives the modified sleeve (D = 0.39 inch) of a micrometer head of the modern watchmaker type. The micrometer unit *per se* is readily adapted to various types of mountings; for example, for testing thickness or parallelism of birefringent quartz filter plates, for telescope windows, Schmidt plates, objective lenses. We advise unhesitatingly the selection of the best possible micrometer for those who contemplate such work. Divisions of 0.01 mm are preferred. The graduated chrome-plated thimble should be large enough for easy interpolation to 1 μm. The diameter of the contact end of the micrometer spindle should be reduced to 2mm maximum. The tip may even be made convex by grinding and polishing to avoid any concern about error in the measurement constant when testing a concave surface of short radius. The complication of having a non-rotating contact tip is pointless, however, for this type of measurement. The micrometer should be of a quality that allows extremely gentle rotation of the thimble. If we avoid using the torque limiting rachet on the micrometer, which is invariably adjusted too high, then regardless of what the mechanics' license manuals say, we can define the point of contact within a micron simply by delicate handling and judging the feel of the thimble. A first reading of the spindle contact position is made with the

spherometer resting on a reference flat. The flat may be an available finished optical element, but it is better to prepare especially for the purpose a finely smoothed glass, its surface polished only 15 minutes on a pitch lap, so that it can be checked for flatness by interference. The second reading is taken with the spherometer on the element being tested. To insure reproducible contact pressure in taking the two readings, the micrometer thimble must be turned very slowly and a mental note made of the definite sensation of contact that corresponds to relieving a third or half of the weight of the spherometer against its contact ring. One may also note the feel at increasing micron intervals, while observing the lessened pressure on the ring that allows it to be more easily rotated on the smoothed surface. The difference between the two readings gives the depth of curvature f across the span of spherometer. The corresponding radius of curvature r is given by:

$$r = \frac{h^2}{2f} + \frac{f}{2} \qquad (73A)$$

It is convenient to inscribe the numerical value of the constants $h_1{}^2/2$ and $h_2{}^2/2$ on the spherometer, for convex and concave elements respectively. Since the term $f/2$ is often negligible for astronomical mirrors, where f is small compared with r, a single division will give r. As an example, taking all dimensions in millimeters:

Assume the inside diameter d_2 of the spherometer ring is 52. Then $h_1 = 26$, $h^2{}_1 = 676$ and $h^2{}_1/2 = 338$, the latter being the constant that will apply to convex elements.

Assume the reading on the flat gives the value 10.334 and the reading on the convex mirror 10.993. From this we deduce that a $f = 10.993 - 10.334 = 0.659$. The radius of the curved surface is therefore $r = 338/0.659 = 513$. For a more precise result that avoids approximations, the division could be calculated to an additional decimal place, giving 512.9, and we could add $f/2$, i.e. 0.3, giving 513.2 as a more exact radius. But remembering that the measurements are precise only to about 1 micron, the more exact final value has little physical meaning, since a spherometer error of one micron changes the calculated radius by $\pm$ 0.8 mm[9].

VIII-9. Smoothing

It is a good idea keep the radius of curvature close to the final value from the start of smoothing. This allows frequent switching of the mirror and tool positions, and leads more easily to perfectly conforming surfaces, i.e. two surfaces having exactly the same radius of curvature. For mirrors as small as these, two or three wets each with 20 and 40 min. emery or emeries BM 303 and BM 303½ are sufficient to remove the previous grain. Final testing of the radius of curvature should be made on the mirror *and on the tool*. We should

[10] The *flexure spherometer* designed by A Couder permits approximation to 1/10 micron, whereas dial comparators are generally accurate only to several microns unless very rigidly mounted.

be sure that the values f agree exactly (taking into account, of course, the two different spherometer constants). Thus, a difference of 2μ, or about 7 fringes, would already be too difficult to correct during polishing. If necessary, the disks could be made to conform more perfectly by using a finer emery: 60 min., BM 304 or even BM 305, the last refining wet being done partially with the tool on top and partially below.

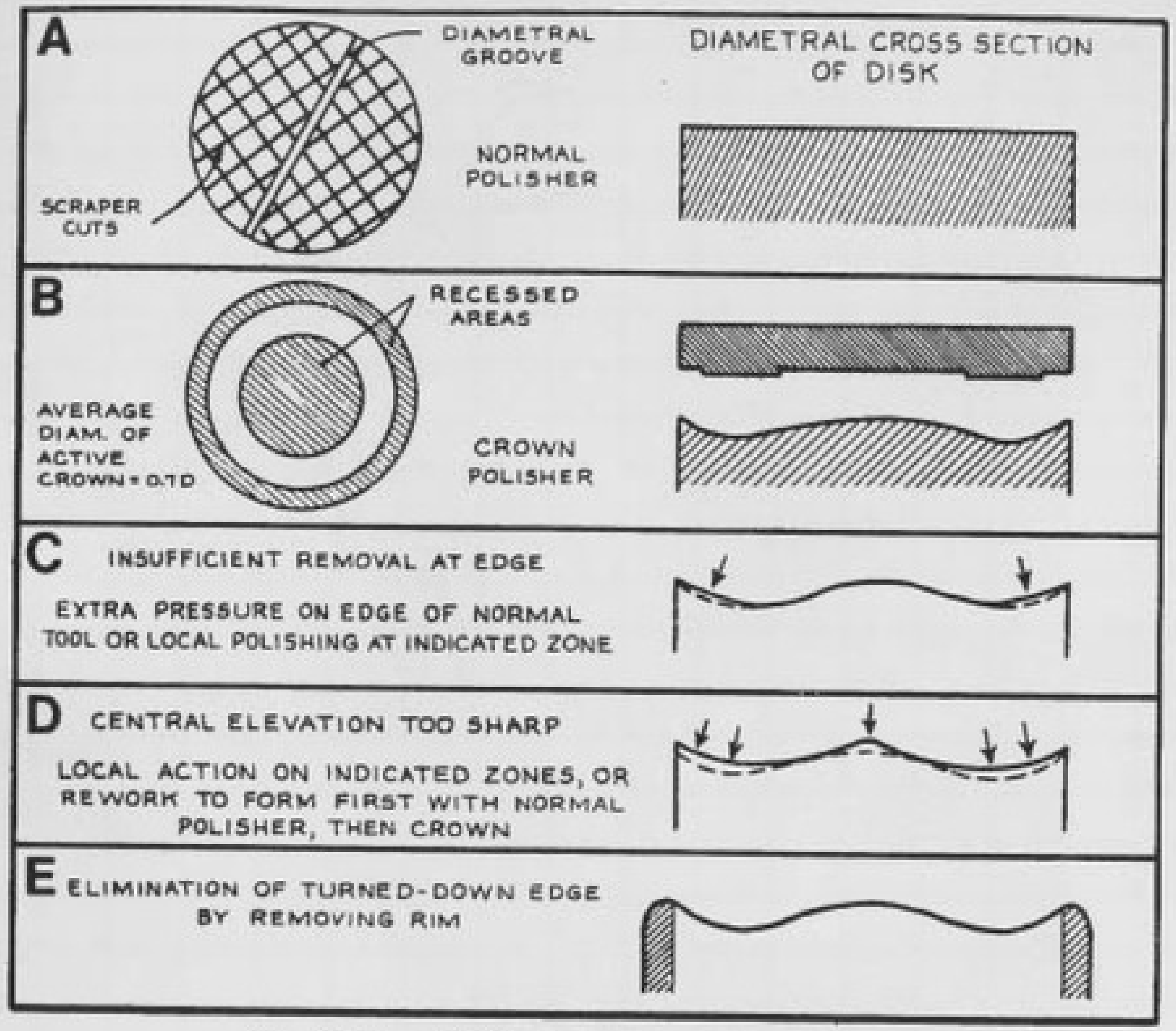


Fig. 81. Hyperbolizing the Cassegrainian secondary.

VIII-10. Polishing and Retouching

The two polishers may be made of wood, either plywood or solid, ⅝-inch thick. They are turned to the same radius of curvature as the corresponding disks, this being verifiable with sufficient accuracy by using a sheet metal template. The polishers are of the same diameter as the corresponding disks, to permit quick and easy interchange of tool and polisher. The two wood disks are paraffin-coated by total immersion. The polisher need not be made up of separate squares for our small mirrors. It is sufficient to secure a paper band around the rim as a retainer, and to pour a little hot pitch on the center of the tool to form a layer about ¼-inch thick. When the pitch is cool enough so that

the paper can be jerked free of the edge, we proceed to press the tool on the glass, first with heavy pressure and an inserted sheet of tracing paper, and finally with rouge. We may scrape out a groove along a diameter of the tool as well as a pattern of squares (Fig. 81-A), or a spiral may be cut with a sharp-edged scraper. These cuts are renewed regularly throughout polishing to maintain good contact.

Since our first concern is to verify that the glass surfaces are close enough in radius, we start by polishing the mirror and the reference surfaces only partially, though uniformly over their entire areas, by 15 minutes of polishing on each. This allows us to make a rough, preliminary interference check. If this shows a significant difference in curvature, greater than 8 or 10 fringes, it is best to return to smooth grinding so as to *match* the disk surfaces more closely. A concave difference of curvature, i.e. where the glasses touch at the edge, is more difficult to bring back to conformity than a relative convexity. It is even advisable to start with a convexity of three or four fringes, which will make the polishing easier. Since corrections of curvature are much more easily made when the glasses are not completely polished, it is best not to finish the reference all at once, but to advance the polishing of the mirror to about 75 percent of completion while approaching the curvature of the reference by the simple choice of the mirror and tool positions. If the mirror must be made more convex, it is of course positioned below, and *vice versa* to make it more concave. At the same time, we must be careful not to have the residual grey from fine grinding distributed too unevenly from the center to the edge. Polishing of the reference is resumed in a position relative to the polisher that will reduce the remaining difference of curvature with respect to the mirror. Longer strokes than normal (⅔ to ¾D) may help this correction if necessary, but with care to avoid deforming the surfaces! Naturally, complete polishing of the reference is superfluous; as soon as the disks differ by no more than 1 or 2 rings we should proceed to *shape the reference into spherical form*. Accomplishing this to the desired precision (0.1 fringe) is not as easy as the uninitiated may suppose.

The reference is easily tested by the Foucault method (Section II-22 and Fig. 33). If necessary, the apparatus can be modified slightly by mounting a small total-reflection prism adjacent to the light source, permitting the slit to be close to the knife-edge (Fig. 31). Deviation from the axis of a mirror of about 20 inches radius should be no more than 0.40 inch if we wish to neglect off-axis aberrations due to the test set-up. As with the large mirror, we should attempt to obtain the best possible form at the outset. Because of their importance, we repeat several admonitions. The work must be done in an environment where the temperature is between 68 and 75 degrees F. The polisher should be made of a good, pure pitch, rather on the hard side for our small disks (the fingernail making a faint impression under heavy pressure). Most important, the pitch must not be dried out by excessive or prolonged heating (Section II-5). Stretch out the working time with short, efficient wets, each pushed rather far, with strokes of ⅓ D. The lathe rotation should be low-speed, that is, the back-and-forth action of the hands should dominate. After three or four wets, the pitch should be uniformly covered with rouge and have a matte appearance. The characteristic pitch odor will be evident, much more so than when the pitch was cold. Renew the surface grooves (Fig. 81A) to maintain good contact. The polishing routine is governed by the amount of rouge or cerium oxide and water used in each wet, as well as by their relative proportions. It takes considerable experience to maintain efficient wets and a good pitch lap. The beginner often starts with too much rouge, or too much water; a mere brush-stroke of polishing agent should suffice for each wet. Many who believe they are following these precautions to the letter are astonished by the way they regularly generate seemingly irreducible zonal defects. A thermally inadequate regimen (too short a working time; insufficient wets) translates into a surface with a turned-down edge and a central elevation (Fig. 30D). Retouching the central elevation is not very difficult; the disk is positioned on top and overhangs the tool. As for the turned-down edge, we advise against retouching it on our small disk. This edge can be neglected if sufficient extra diameter is provided on the reference at the beginning. Otherwise one starts over again, hopefully working with improved technique.

Once the Foucault tests show that the reference is accurately spherical (Fig. 30C) throughout its useful diameter, or that it has the desired non-spherical form if one has chosen to see straight fringes against the secondary in the final figuring, all that remains is to complete the figuring of the convex mirror. The interference finges seen between the spherical reference and the mirror under test usually reveal a difference in curvature and deformation. The deformation can sometimes be used directly to start the hyperbolization. However, the normal and the most reliable method is first to correct the curvature and make the mirror spherical so as to obtain the straight fringes of Figure 75D. All that is then needed is to form the hyperboloid. This is really a small matter compared with the work which has gone before. When the deviation is no more than 0.1 or 0.2 fringe, local retouching with the thumb or with the index finger, if necessary, will suffice to complete the figuring (Section II-38). Generally, however it is better to trim the normal polisher to form a crown with an average radius of 0.7D (Fig. 81D), the tool then being used with rather short strokes, ¼ to ⅓D. Besides checking the maximum deviation value ϵ at the zone 0.7D (Fig. 75D), we must confirm that the surface contour has the desired shape. Those not familiar with this shape may cut a paper template to the desired contour of the central fringe, this being calculated from equation (59) and the incremental surface deviation per fringe spacing. Figure 81 illustrates some defective hyperbolas and appropriate retouching steps. In Figure 81C, where insufficient glass has been removed near the edge, a local polisher applied to this area can complete the action of the crown tool. Sometimes it is the central elevation which does not have exactly the right profile (Fig. 81D). Here local action may be tried, but often it

is better to restore the surface to a sphere before again undertaking final figuring. Some workers, regardless of what they do, are unable to avoid a turned-down edge. If this defect cannot be completely hidden by the mounting, there is still the recourse of making an oversized mirror, of the same diameter as the reference, using a finely annealed optical glass. After figuring the surface to a hyperbola across the useful diameter (Fig. 81E), the excess diameter can be removed.

MECHANICAL DESIGN OF THE CASSEGRAINIAN

Mounting the optics is very much a question of feasibility for the given amateur. We shall limit ourselves to some details that relate particularly to Cassegrainians of 8- to 12.5-inch aperture. One solution that can be realized with rather modest mechanical means is an adaptation of the standard tube concept (Fig. 56). A second solution uses castings, but their machining assumes access to a lathe and possibly a mill. Many of the design concepts which follow are not specific to Cassegrainians and are equally applicable to Newtonian and other types of telescopes.

IX-1. Adaptation of the Standard Telescope Tube

Square wood tubes are perhaps less appealing aesthetically than cylindrical tubes fitted with attractive end-rings, but they are much easier and less costly to make, and give excellent results. Only their stability against weather change leaves something to be desired, requiring that the alignment be checked from time to time. For an 8- to 12.5-inch telescope, it is best to choose a material more stable and durable than ordinary wood for the base of the mirror cell. Improved woods such as *Permaly* or *Durisol*[1] provide such assurance and are conveniently workable material. Sheets of these materials are flat enough to make further surface finishing unnecessary, and permit parts and accessories to be attached directly.

The large mirror must be mounted with particular care. We commented earlier (Section II-3) on the mirror sizes, such as the standard 20cm that can simply be supported on three marginal contacts. In practice, the value of R^4/e^2 may be as high as 1600 without serious concern, since the effects of flexure diminish as the cosine of the telescope angle from the zenith and in practice are almost never detected at this calculated value. However if, for reasons of economy, we stick with the Saint-Gobain plate glass, we have an upper limit

[1] These are usually made of beechwood ply, fully impregnated with a phenol-formaldehyde resin and highly compressed. They approach metals in mechanical properties but have a density of only 1.4. Cutting and finishing are the same as for hard wood and they can accept metal screws, for which holes may be threaded with ordinary taps. *Permaly*: Société Le Bois Bakelisé, 39 rue Washington, Paris 8^e *Durisol*: representative: M. J. Cadoux, rue de Chabriol, Paris 10^e. A similar material in the U.S. is manufactured by Westinghouse-Micarta®. This material is available with paper-, cloth-, or glass fabric-base materials. Available in sheets, tubing and other shapes.

for e of 4.5 cm and as a working value for the finished mirror $e = 4.2$ cm. This gives then $R^4/e^2 = 1385$ for a 25 cm disk ($R = 12.5$), so that three marginal contacts will suffice. For a 30 cm disk, the calculated value is 2870 and for a 40 cm disk the value is 9070, so that a more complicated mirror cell is unavoidable in these cases. Provided that R^4/e^2 remains less than about 3000, a simple, economical solution is still possible and often used. It consists in inserting a disk (or in the Cassegrainian, a ring) of thick flannel or heavy wool blanket material between the bottom of the cell and the back of the mirror, which should be quite flat. This distributes the pressure sufficiently uniformly, but frictional restraint against the walls of the cell could be a problem. Further, the optical axis of the mirror is not stable enough for photographic work, and with the back of the disk insulated by the pad, certain thermal effects may be aggravated.

A form of support which provides nine contacts points situated at the apexes of three isosceles triangles, the latter being themselves supported at their center of gravity, is effective up to $R^4/e^2 = 13000$ and is easily constructed. Nevertheless, the friction against the lateral supports may cause difficulty, i.e., astigmatism and loss of contact at some of the support points. Lateral friction should be minimized by supporting the mirror laterally against ball bearing cages (ringed by soft metal). The mirror will then rest positively on the nine contacts, even when the tube is only slightly inclined.

The best arrangement, however, is one using movable levers. This design is used on the large, modern telescopes, but it is not difficult to build despite its apparent complexity. Figure 82 shows a modification of the standard tube for a 30 cm (12-inch) mirror mounted at its margin on six support points. Three of these—the usual alignment screws—are fixed; the three intermediate contacts are load relief screws. The arrangement is valid for R^4/e^2 up to 9000 i.e., for a glass mirror not over 40 cm in diameter and 40mm thick. Counterweights acting through levers apply pressure load-relief contact equal to 1/6th of the axial component of the mirror weight. The center of gravity of each lever assembly, the lever axes, and the points of contact on the push rods should lie in the same plane, parallel to the back of the mirror. The arrangement in Figure 82 is not strictly correct in this regard since the "fixed" contacts also serve as mirror alignment screws, an arrangement that avoids the need for a double cell, but may incline the mirror slightly with respect to the back-plate if the latter is not quite square with the optical axis. In practice, an approximation is almost always satisfactory. Play provided in the adjusting screws that bear on the push-rods allows the levers and counterweights to be returned to operating position after retouching the mirror alignment. The lever axes should be as long as possible to minimize erratic action which could be especially noticeable at certain tube inclinations. Friction is minimized either by using small ball bearings, or shaping the ends of the lever axles to form 60-degree cones centered in the concave ends of adjustable screws in each mounting block (Fig. 82). The weight-relieving push-rods, which are tinned at the ends contacting the mirror, *must slide very freely* in their bushings

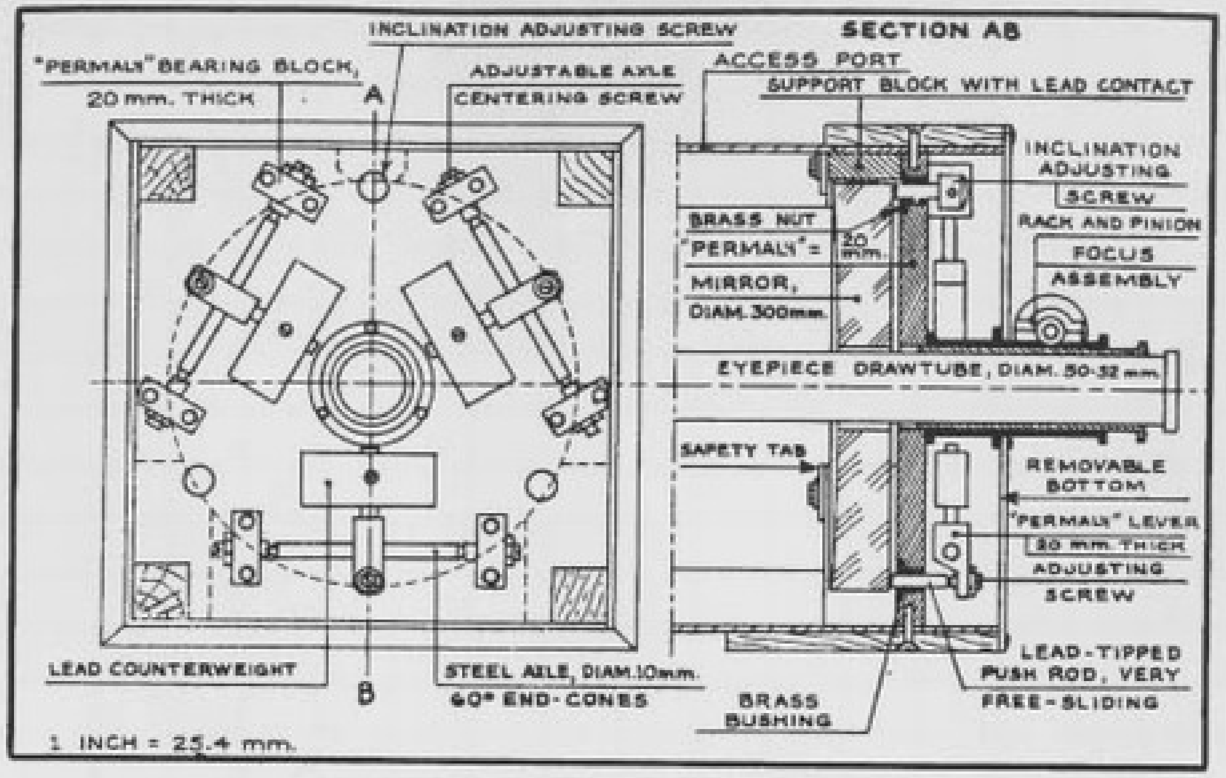


Fig. 82. Lower end of a square tube.

without lubricant. In sum, each support must be treated as a sensitive balance applying exactly the desired force at the intended point. Note that this force is independent of possible deformations in the cell, and that the axial component of the mirror weight is compensated for by an equal and opposite force regardless of the tube inclination. If we divide the weight of the mirror by six, then divide the result by the lever ratio of about 2 in the example illustrated in Figure 82, we obtain the required weight of each counterweight. The counterweights are usually rectangular in shape. Since the counterweight can slide along its axis, the pressure it exerts can be adjusted exactly. The most reliable way to do this is to observe the slightly defocused image of a star. *Luminous protuberances on the outer ring, seen in a plane inside the focus when pressure at the support points is excessive, correspond to the peripheral support points of the mirror.* The effect is easily observed in a Cassegrainian, where, one can tug on one of the levers to increase the pressure while continuing to observe the star image. For mirrors of modest size, this adjustment is neither difficult nor critical. The effects of flexure are quite small and even a rough adjustment makes them imperceptible. Figure 83 illustrates a cell of this type, made for a 10.24-inch mirror, in which the base is an aluminum alloy casting.

A final consideration in cell design relates to the contact points at the edge of the mirror. These should be aligned radially with the fixed points of support at the back and comprise thin pieces of lead secured slightly above the middle of the mirror thickness. Play in the mirror plane should be about 0.004 to 0.008-inch even for an equatorially mounted telescope. If the telescope crosses the meridian during a photographic exposure and the operator is

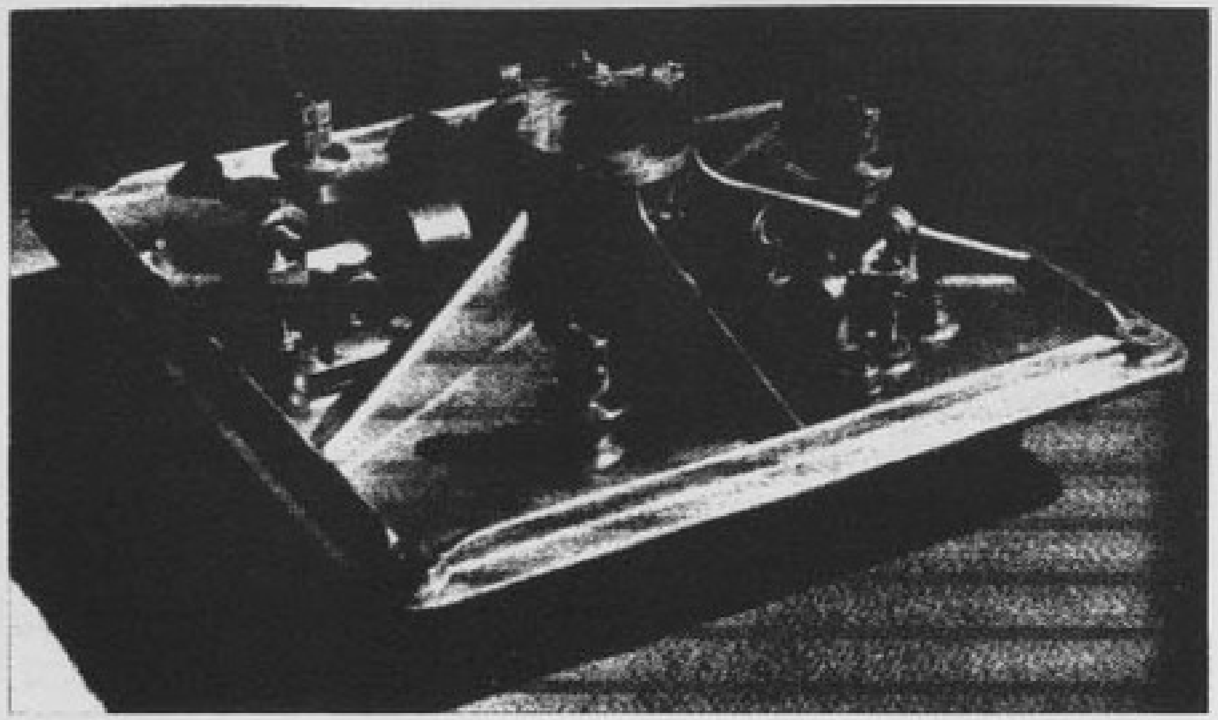


Fig. 83. Mirror cell with three fixed contacts and three astatic levers. (Design by Émery)

concerned about lateral slippage within the limits of play, he can interrupt the exposure, jar the tube while it is in a position to assure positive slippage of the mirror, then continue the exposure. The safety tabs on the front edge of the mirror should allow sufficient play, 0.04 to 0.08-inch, to permit adjusting the alignment screws without risk of forcing the mirror against this barrier. If the telescope is unintentionally tilted past the horizontal, the tube should be returned to the vertical, if necessary, to let the mirror fall back on the mirrors supports. Otherwise the mirror may remain tilted to one side, a condition which often baffles the beginner who is mystified by the sudden misalignment.

IX-2. Cylindrical Tubes

The mechanically inclined amateur may be strongly tempted to adopt a metal tube. Such tubes have a serious disadvantage, however, because heat exchange can occur rapidly along the metallic wall, leading to turbulence in the adjacent air. This can be especially disturbing if the tube diameter is too close to that of the optical beam. We recommend that the tube diameter be always at least 2 inches greater than the mirror diameter. The inner wall of the tube is sometimes insulated with cork sheeting about ⅛- to 5/16-inch thick. Other modern-day plastic insulating materials can be even more effective. These materials have millions of insulating air pockets molded internally. Hobby and handycraft stores are a good potential source for this type of material. The more finished appearance of metal tubes in the diameter range of interest to us is undeniable. If a soft steel is selected, a thickness of 0.125 inch will suffice for a 12-inch instrument fitted with machined end-castings. A

good craftsman must be found to roll the sheet metal and make an impeccable seam. The diameter does not have to be held to close tolerances. The use of aluminum poses additional fabrication and finishing problems. For these reasons we prefer tubes of insulating material. These are light, stable, easy to machine, of good appearance, delivered to exact dimensions, and generally less expensive than metal tubes. Modern composites of fiberglass and polyester are probably best. Water softener tanks and some hot water heaters are now made of these materials. ***Bakelized*** paper[2] which we have used for 30 years, has proved very practical. Its rigidity is excellent if, for a tube diameter of about 12 inches, the wall is about 7/32-inch thick. The resistance of the bare Bakelite to weathering is adequate, but it is best before using the tube to apply two layers of white enamel over a priming layer to assure good adhesion to the bakelite. The bakelized paper is dense and homogenous enough to allow tapping of holes for ordinary metal bolts.

IX-3. Construction of a 257 MM Cassegrainian

As a specific example, we present some details, often requested, on the author's personal instrument. It is a light telescope (44 pounds, without the equatorial head) of modest overall size, and very easily handled. However, we do not recommend the primary mirror ratio $f/D = 4.3$ for beginners. The principal optical dimensions in inches are:

$D_1 = 10.12$	$D_2 = 2.36$
$f_1 = 43.31$	$r_2 = 21.75$
$p' = 8.66$	$\gamma = 4.91$
$p = 42.52$	$e = 7.87$
$d = 34.65$	$\mathcal{F} = 212.6$

The dimensions, in inches, of the telescope tube, which is made of bakelized paper are: I.D. 11.8; O.D. 12.2; length 38.6

The tube can be attached to the equatorial mounting by a collar completely encircling the tube. The tube in this case is held by friction and easily shifted for balancing on the declination axis. Figure 87 illustrates another solution: an aluminum alloy cradle machined over a wide area, 10.0 by 7.5 inches, to fit the curvature of the tube and reinforced on the outside with a 1.57 inch-thick rib that permits mounting of accessories. In the present case these include an 80 mm by 420 mm finder and a wide-field astrograph camera of $f = 210$ mm. The tube is secured to the cradle by three inside plywood members, each drawn down by three ⅜-inch bolts. The large mirror, 1.65 inch thick, simply rests against three marginal inclination-adjusting screws. As we anticipated, since $R^4/e^2 = 1570$ there is perceptible flexing of the mirror in the vertical tube position, as evidenced by three-fold splitting of the first diffraction ring, but this is hardly disturbing. The cell for the large mirror (Fig. 84) is an aluminum alloy casting. The unit is designed to minimize the proximity of heat-exchanging metal surfaces to the mirror, and at the same

[2] See footnote 1.

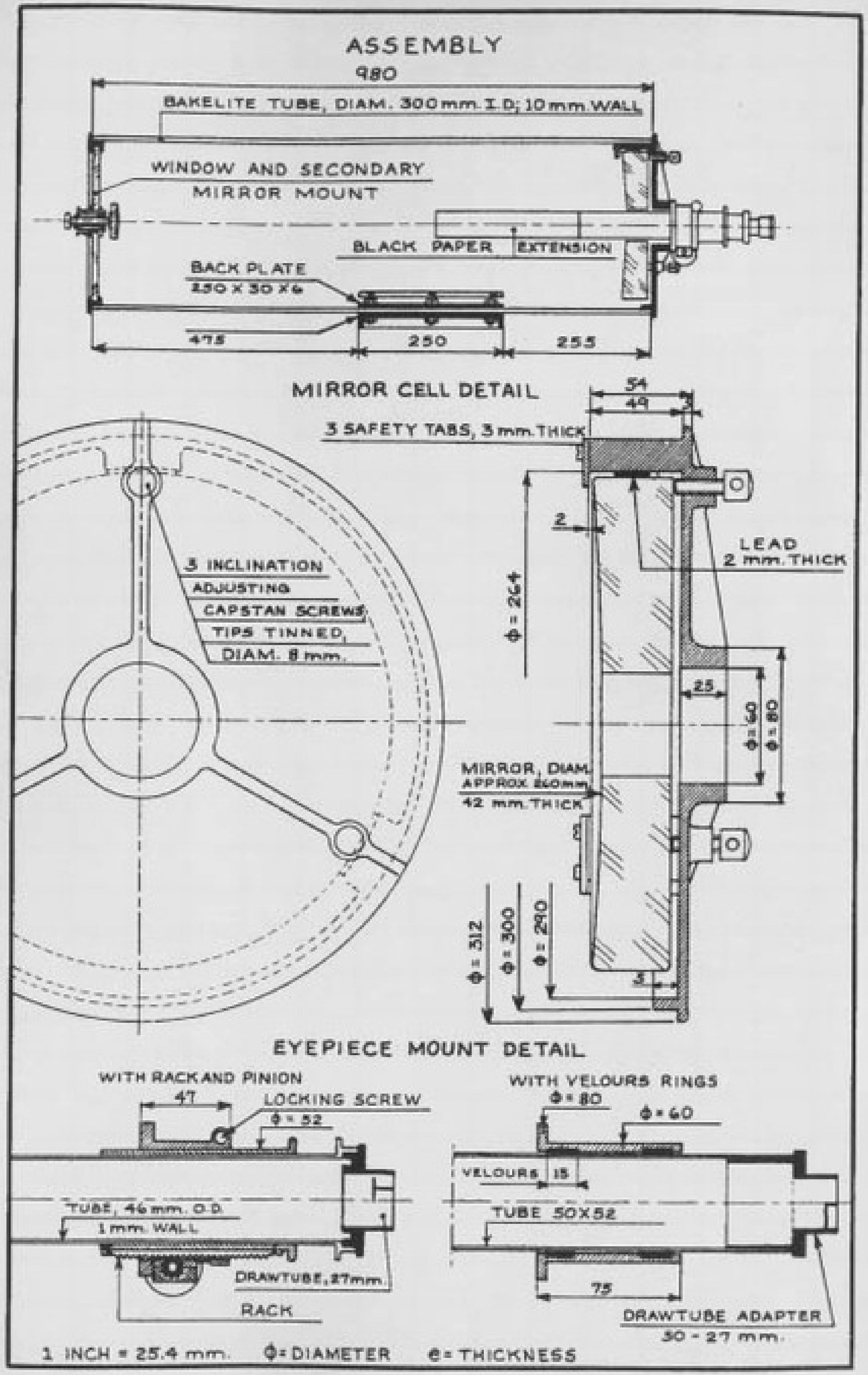


Fig. 84. Design of a cylindrical-tube Cassegrainian.

time has been simplified in that the cell is not, properly speaking, supported from a collar on the tube. Three sturdy projections at the rim of the cell, machined to a diameter 0.16 inch larger than the mirror, are fitted with mirror contact plates made of lead, leaving 0.008 inch play for the mirror. The assembly slips freely into the tube and is fastened by three screws that thread into the cell projections. The mirror is very easily removed for aluminizing.

The design of the eyepiece mount for an $f/20$, 200-inch focal length instrument should permit rapid exploration of the image along several inches of the beam. Turbulence continually shifts the focal position by several hundredths of an inch, plus or minus, so that constant *pumping* is necessary when making a planetary drawing, for example. This precludes focusing with a threaded mount even if the thread is rather coarse, and points to the classic rack and pinion as the most practical. The one shown in Figures 84 and 87 is of helical type, the pinion having a ratio of diameter to number of teeth equal to 0.5 The pinion bearing should be very sturdy and controlled by two large milled knobs. If a camera or heavy accessory has to be controlled by this same movement, provision should be made for clamping the rack and pinion, since the motion when unclamped should be very free. Travel of the rack and pinion in the present case is 2 inches, and that of the draw-tube 8 inches. This allows ample freedom for inserting accessories that have to be moved closer to the instrument's focal plane, for example photometer heads, photographic cameras, a spider thread micrometer, monochromatic birefringent filters, etc., without having to use special adapters. For future designs we recommend eyepiece mounts with 2 inch I.D. draw tubes that will accept the low power eyepieces of 40, 55 and 75 mm focal lengths (Fig. 84, lower right). Naturally, an adapter should be made for eyepieces of the normal barrel diameters, i.e. 27 mm or 1.25 inch (American standard). If the amateur does not wish to build a complete eyepiece mount with rack and pinion, he might consider an old Petzval or rectilinear camera lens mount, which can be easily found on the second-hand market. The tube should be checked for ease of movement with the pinion removed; otherwise there is the danger of rapidly destroying the rack or the pinion bearing. One must stand up firmly to machinists who invariably deliver tight-fitting draw tubes. A precison fit to 0.0004 inch is actually harmful. The telescope is not a machine tool, and focusing at high magnifications is possible only with very delicate manipulation that avoids the least shaking of the instrument. For friction between the sliding metal surfaces to be acceptable, it is essential that the draw tube be bored 0.004 inch oversize and that it be slotted. The tongues formed by the slots are pushed in just enough to stop unwanted movement when fitted with the heaviest eyepiece.

A more economical focusing arrangement can be made that is at least as satisfactory and easy to use as a free-working rack and pinion. It eliminates the metallic friction which usually leads to binding once the brass oxidizes on exposure to humid air. The bushing (Fig. 84, lower right) is bored 0.008 inch

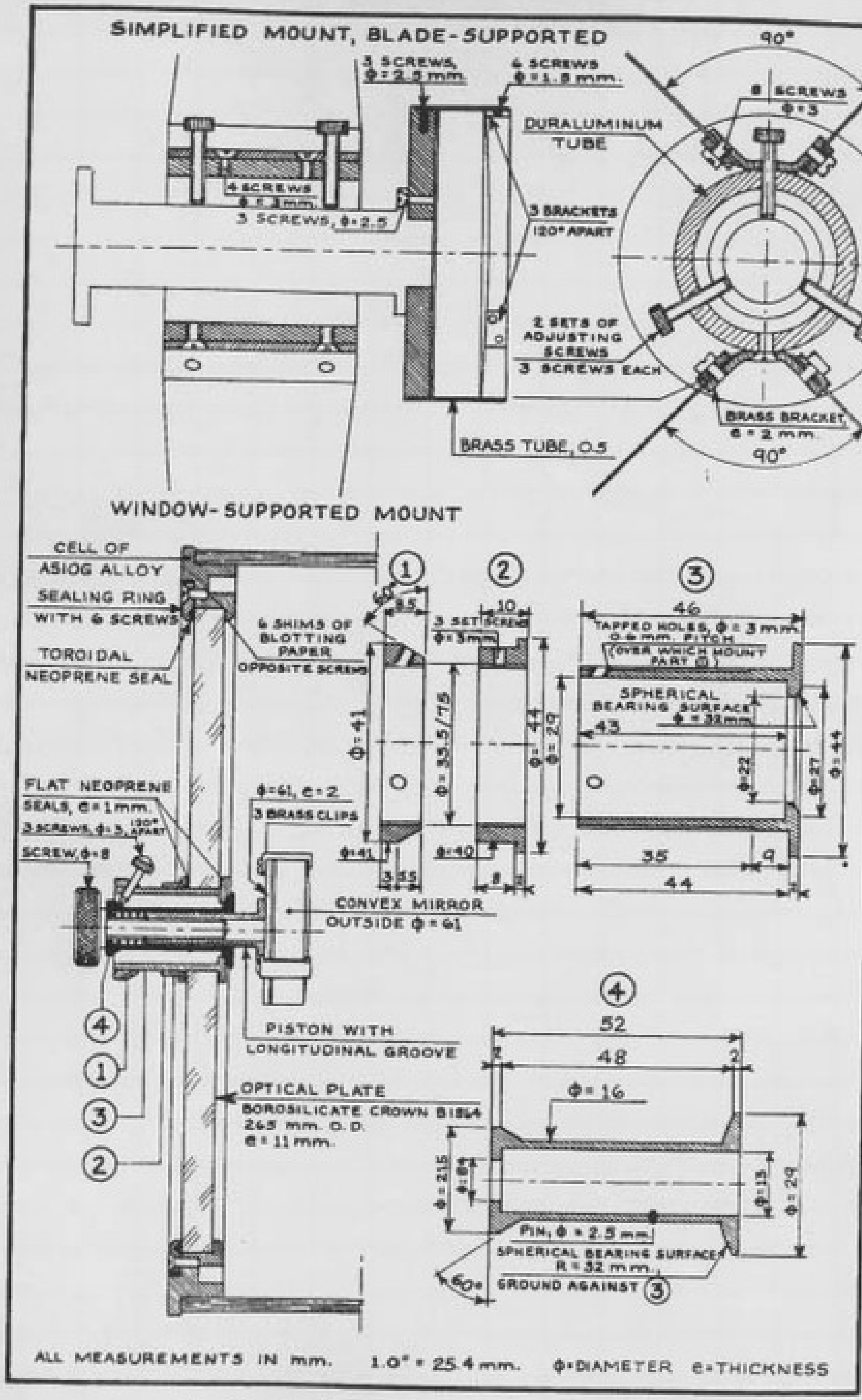


Fig. 85. Details of secondary mirror mountings.

oversize and provided with internal grooves near either end. Each of these is lined with a band of velour, the nap of which centers the drawtube and allows easy sliding action assisted by slight rotation with the hand. This arrangement, used by the old makers of telescoping spy glasses, is especially convenient for visual observation.

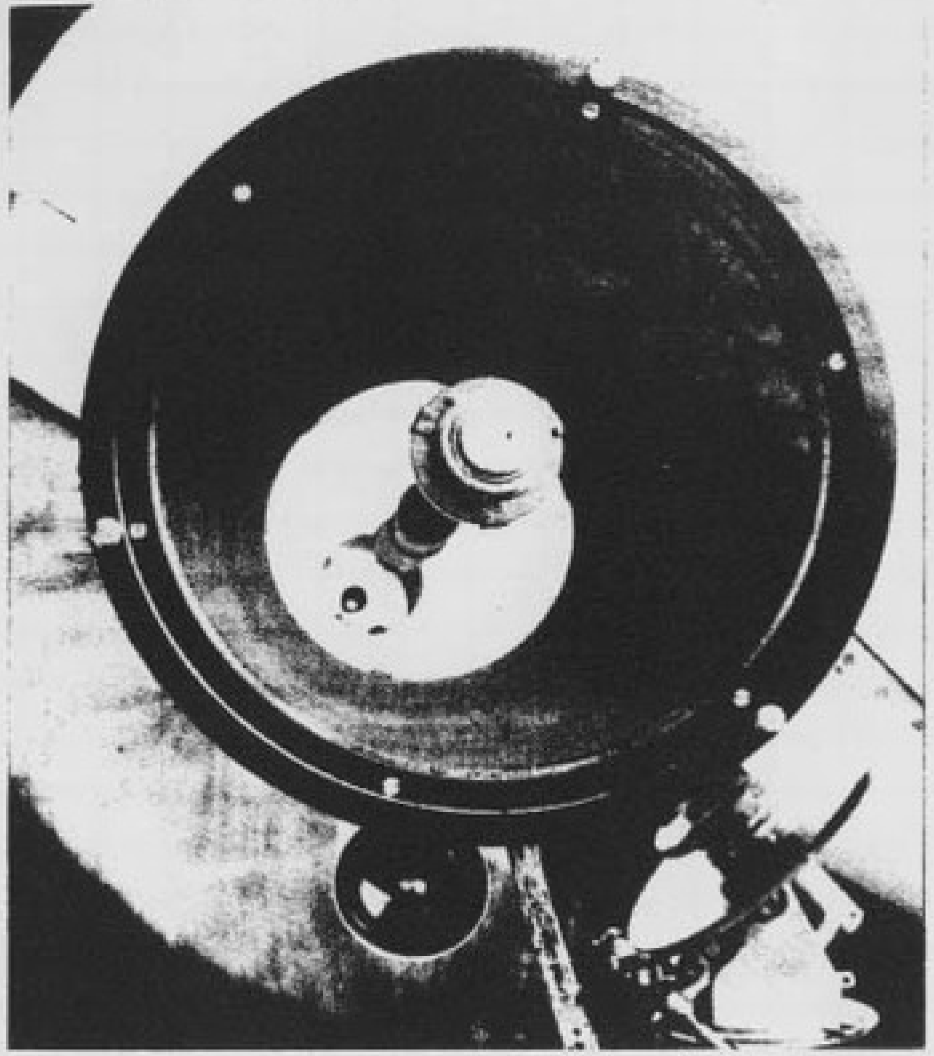


Fig. 86. Front view of the author's Cassegrainian.

We come now to the mounting of the secondary mirror. Figures 85 (lower half) and 86 show the design in the author's instrument. The telescope is fitted with a parallel-face optical window that hermetically seals the tube. As we shall see, this arrangement (described in detail in Chapter X) radically improves various aspects of internal thermal behavior, including turbulence. Further, the window directly supports the secondary, eliminating the spider mount and its detrimental effect on the diffraction pattern. Deformation of the window is much less harmful than it would be in a mirror, since only a change in thickness can cause phase shift in the wavefront. However, side play of about 0.008-inch should be allowed, and the retainer ring should apply only gentle pressure, against an O-ring type seal of very soft Neoprene rubber. Similarly, the secondary mirror mount is supported between flat seals of a very soft rubber.

The secondary mirror could also be supported by a spider mount of the classic type, or one made with curved arms. The top of Figure 85 shows another type of mounting. The convex secondary may be held by three prongs, that simultaneously provide three frontal resting points and center the mirror laterally (always with side-play of 0.004 inch). A tube providing three bearing points may also be used. In either case, mechanical strain on the mirror must be avoided, whether on the back face or on the rim. If we shake the mount sharply we should detect the slight knocking of the glass in its mount against the limits of its play.

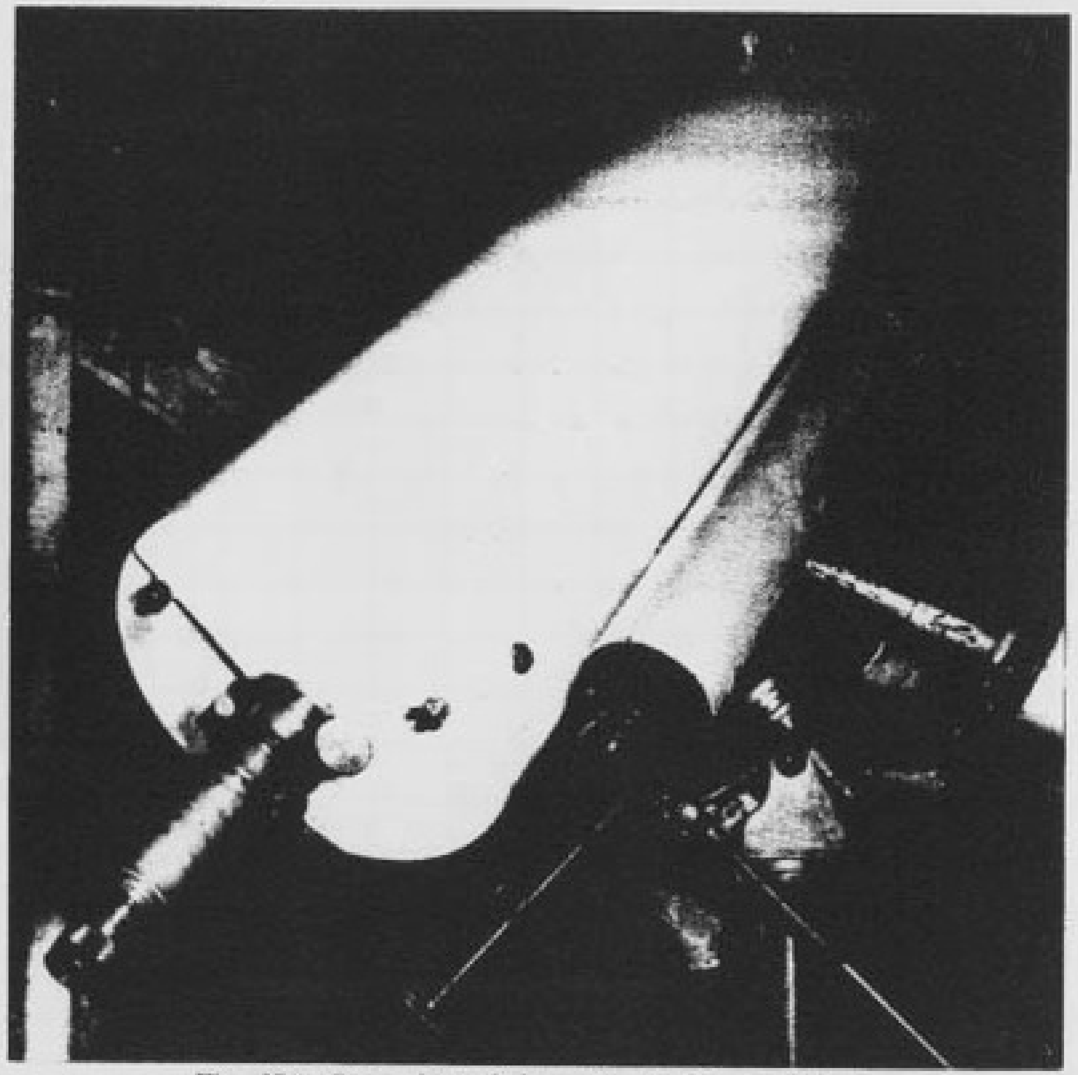


Fig. 87A. Rear view of the author's Cassegrainian.

In the mounting shown in the lower part of Figure 85 the mirror axis is centered by rotation on a spherical bearing. The center of the bearing is near the mirror apex, so that lateral displacement is reduced. The adjusting screws, when clamped in position, draw the bearing surfaces into contact. The alternative, more rudimentary solution shown at the top of Figure 85, makes use of two sets of screws, each consisting of three screws. It is advisable to provide for axial adjustments of the final focal position. In the design of Figure 85 lower left, the adjustment is external and controlled by a thumb screw. On the other, simpler mounting, it is done by temporarily loosening

and resetting the two sets of screws. On rather large telescopes, of 24-inch aperture, for example, the secondary is often translated axially from the eyepiece position either manually by drive rods and pinions, or electrically by a manual control with reversing buttons operating a small bidirectional motor. Focusing with the eyepiece is sometimes dispensed with altogether. Needless to say, the slightest heat from the motor, lying in the middle of the beam, will hardly improve the image, even if the arrangement is convenient for certain kinds of work.

X

THE TELESCOPE WINDOW

X-1. Advantages of a Telescope Window

Reviewing our general discussion in Section I-5 and our study of turbulence in Chapter XV, it appears that the main disadvantage of the reflector, compared with the refractor, is greater sensitivity to instrumental thermal effects due to the upper opening of the tube. Two types of disturbance may be distinguished:

1. The outside air, stirred up by wind and freely penetrating the telescope tube, undergoes rapid heat exchange with the tube walls, particularly if they are metallic. This creates veins of air of slightly different temperature and index of refraction, and changing local phase shifts. Slow spirals of air rise continuously from all the more massive telescope parts, including the main mirror. Wind cutting across the open end of the instrument generates whirlpools of disturbed air.

2. Assume that ambient conditions are stable enough to allow good thermal equilibration despite the large thermal inertia of the telescope. Gross heat exchange by conduction then disappears, but an unavoidable and persistent effect is that of *radiation* from the surfaces. In particular, the mirror itself radiates toward the sky, as well as the tube and the secondary mirror together with its supporting blades. All these components are surrounded by sheaths of air in which the refractive gradient may correspond (fortunately, rather locally) to phase shifts of as much as a half-wave. These sheaths of air are *perfectly stable.* Turbulence cannot be seen, but it causes very noticeable reinforcement of the first ring in the diffraction pattern, a defect that may be further enhanced by the central obstruction, as considered in Section VI-2. In addition, a mirror radiating toward the sky generally shows considerable spherical aberration, particularly if it is a large and rather thick disk which often has some residual strain.

Many suggestions have been proposed and tried for the improvement of telescope tubes. However, writers on the subject are far from agreeing on the best solution, underlining the fact that perfection has yet to be attained. American workers have shown a preference for tubes in the form of an open metal frame as a way to eliminate the chimney convection effect. For amateurs, this is something of a fad and an attempt to copy the giant telescopes in respect to thermal effects that otherwise could be almost totally ignored. Actually, the open frame can perform well in a hot, dry semi-desert environment, and even in temperate climates it is superior to a metal tube if the walls are too close to the mirror. Nevertheless, an open frame exposing the light path to every movement of outside air, and in particular to heated air caused by the observer, cannot be an ideal solution. Therefore, we have to consider the advantages and disadvantages of each form of construction. The more rapid thermal equilibration of the mirror in a open mirror cell and telescope frame is of secondary advantage. We should be ready to sacrifice this, given the impossibility of controlling the homogeneity of the air in such an environment. *The expectation of thermal equilibration of an open instrument, to any useful approximation, is only a delusion.* The square wood tube of the standard telescope is a good solution for an 8-inch instrument; only in a cold wind would one observe disturbances in the tube, and the stable air sheath around components within the beam's path is really of little consequence. Above 10 or 12 inches, the widely dimensioned tube with walls of good insulating material becomes only *a palliative*, and is increasingly inadequate.

Another approach, that of ventilating the tube, has also been given much attention, yet hardly qualifies as a cure. It is impossible to displace the inside air either by blowing or suction without introducing further disturbance. The conductivity of air is too poor for a vein created by expansion of an air current, or by adiabatic compression due to shock against an obstacle, to be erased simply by stirring, natural or otherwise. All the ventilating arrangements that we were able to test, some of them quite elaborate, gave results that were either negative or nil. An exception is the elimination of the air sheath due to radiation, if the ventilation is carefully controlled, but there is little advantage in this, since there is even greater degradation of the image by the turbulence that is introduced.

Finally, we can minimize thermal exchange at the walls adjacent to the light beam by hermetically sealing all tube openings, and particularly by sealing the upper end of the tube with a glass porthole, i.e., *an optical plate with plane, parallel faces.* Further, if the walls are of a poorly conducting material, heat exchange will be slowed enough so that optically heterogeneous veins do not form despite the low thermal conductivity of the air. At the same time, the stable air sheaths due to radiation become inobservable. In effect, the glass plate readily transmits visible radiation, but is almost totally opaque to the far infrared radiated by the structures close to the beam. The action is the same as that of a glass window in a building which admits the red and the near-infrared solar rays to heat the inside of the structure. Yet the building remains warm during the night because its own longer wavelength radiation is not transmitted back through the glass. However, actual use of a window-enclosed reflector telescope settles any possible doubt. For one thing, a Foucault test on a bright star shows only the effects of the outside air, not the

spiralling air that is characteristic of open tubes. For another, the first ring in the diffraction pattern is restored to normal brightness, appearing the same as in a refractor, if the central obstruction is less than 0.2 of the mirror diameter. *In fact, the reflector modified in this way becomes clearly superior to a refractor of the same diameter because of the total absence of secondary spectrum.* Naturally, we now take advantage of the possibility of supporting the secondary mirror, whether Newtonian or Cassegrainian, on the window plate to eliminate the spider support blades and the diffraction flares they produce. A third advantage is that the aluminum coatings on both mirrors are fully protected against soiling. Oxidation becomes undetectable, and concern about telescope maintenance completely disappears.

Let us now consider the disadvantages. If we select a borosilicate crown that is very transparent in that part of the spectrum visible to the eye, we can neglect absorption loss in the window of an amateur telescope of 10 to 12 inches in diameter, the thickness of which is not over 0.80 inch. On the other hand, each passage of the beam across a polished face involves a loss of about 4 percent. The effective transmission of the plate is therefore about $0.96^2 = 0.92$, representing a loss of 0.1 magnitude. This is a minor disadvantage in view of the image improvement. Nevertheless, light reflection from the window faces may be objectionable if the plate is perfectly normal to the optic axis. It may then behave like a well-adjusted autocollimating flat: a bright light reflecting back from a glass surface in the eyepiece, for example, acts as a light source. The light rays from such a source are reflected back through the system to the window, which then re-reflects it, resulting in the appearance of a point of light in the external field. The simple remedy, of course, is to incline the plate relative to the axis by an angle equal to the half-field of the weakest ocular, for example, by about 15 minutes, an amount that introduces no noticeable aberration. Modern anti-reflective coatings can now eliminate most or even all the reflection. Specifically, a layer of anti-reflective material a quarter-wave thick with a refractive index of $n_1 = \sqrt{n}$ is deposited and baked in a vacuum. For borosilicate crown, this unfortunately requires a substance of index $n_1 = 1.23$, but the lowest index available in practice is 1.38. Normal, single layer coating is therefore not completely effective. Multi-layer deposits use two well-chosen $\lambda/4$ layers, but the plate has to be heated to at least 250°C. This high heat, for such a large, high-precision plate, will almost certainly cause distortions and should be avoided. Large plates that are produced and coated in quantity make use of special fixtures to overcome this problem. An amateur's single window cannot justify the cost of such fixtures.

Other disadvantages are of a practical type: the cost of the window is comparable to that of an objective lens, requiring a finely annealed glass of prime quality that is much more expensive than a mirror blank. Further, the work of surface-finishing the plate is twice that required on a mirror.

On balance, is the effort justified? The answer is *no* if the telescope is not otherwise optically perfect in the sense already explained, and if the worker is not accustomed to judging stellar diffraction images in a 10-inch or larger instrument. More specifically, *beginners or users of a simple 8-inch standard instrument have little reason to stray into this laborious project.* Need we stress the sheer folly of capping the telescope with a commonplace slab of glass such as a Saint-Gobain porthole plate, in the hope of improving the image? Finally, the enterprise is not really of value except for an amateur elite who are at the same time good opticians, good observers, and owners of rather large telescopes. Such an elite do, of course, exist.

The Henry brothers, about 1890, were perhaps the first to cap a telescope with an optical plate. This plate, 8 inches in diameter and 0.67 inch thick, still exists in the collections of the Observatory of Paris. We are not sure they were trying to suppress thermal effects. Is it possible that their slightly biconcave plate, which shows a certain chromatism, was deliberately designed as a compensator for use with a special corrective eyepiece? Be that as it may, the plate is badly strained and it has not been possible to test it conclusively.

Bernard Lyot and André Couder once planned for the Observatory of Pic du Midi a telescope of 59-inch aperture closed with a glass plate. This project was mentioned in *l' Astronomie*[1]. Lyot had even envisioned a radical solution—that of filling the tube with helium. Compared with air, the helium would provide a double advantage: the refractive index varies less with temperature, and more important, helium is a far better thermal conductor, so that convective striae would be immediately suppressed. Unfortunately, it is difficult if not impossible to prevent escape of a monatomic gas such as helium from an enclosure as large and complex as that of a large telescope tube. Also, helium is not readily obtainable in most of the world, being a strategic substance produced almost exclusively in the United States. With the death of Bernard Lyot, further work on the project was abandoned.

We should note that photographic telescopes, either the Schmidt with its corrective plate, or the Maksutov with its meniscus, are also incidentally closed telescopes. Suppression of instrumental turbulence in a photographic telescope is not a significant advantage except in large instruments such as the 48-inch Schmidt at Mount Palomar. The excellent performance of that instrument is perhaps not unrelated to this fact.

In the late 1950's and early 1960's American amateurs became interested in visual Maksutov Cassegrainians of long focal length, i.e., $f/15$ to $f/23$. Standardization of design in several different diameters made possible the limited production of rough meniscus castings. This application of the Maksutov does not appear very convincing; the field of these instruments is not wide enough to take advantage of correction for off-axis aberrations. Sometimes great emphasis is placed on the fact that all surfaces are spherical and hence easier to fabricate. This is in fact true where a commercial firm can invest in high-precision test plates, but the tolerances are so tight that the amateur usually has to resort to asphericizing either the primary or the meniscus. Considering the extra work in preparing the meniscus and the almost certain need to correct one of the surfaces, one should not consider this a simple project! The best justification for the visual Maksutov is perhaps the

elimination of thermal effects in the tube. The only minor advantage compared with a classic Cassegrainian closed off with a plane-parallel plate would be that the curvature of the meniscus destroys the focus of unwanted reflections. On the other hand, the chromatism rapidly becomes significant. In any case, there is little interest in closing a small diameter telescope in which thermal effects are quite small. For those who nevertheless persist on this design we recommend careful study of the references.[1]

X-2. Choice of Glass

Borosilicate crown glasses are currently used very extensively, particularly for binocular prisms. Large optical glass companies such as Parra-Mantois and Schott produce hundreds of tons of these glasses each year. The horn-shaped melting pots hold about a ton of glass. This mass of glass is allowed to solidify, then broken or cut up into smaller, more manageable pieces. The glass may then be directly cut and shaped if the dimensions are appropriate, or it may be re-heated and molded to the approximate final shape. Such reforming is typical for a large flat blank. Glass is not homogeneous; if it were, most of our problems would disappear! We must search to find an absolutely faultless piece of the proper volume. Grains and bubbles are easily detected, but it takes an expert to detect *striae*, which we cannot allow in a piece of premium quality. Striae corresponds to rapid but very local variations in refractive index. If the piece is illuminated only by an intense *point source* several yards away, one can see the more pronounced striae by projecting the resulting shadow on a white sheet about 20 inches beyond the piece under test. Once the very rare piece of *premium quality* and volume is found, it must be shaped into a disk using a refractory ceramic mold. After molding, and when the disk has cooled somewhat, it is placed in the middle of a large electrically heated container filled with a refractory powder. For an extended period, sometimes weeks or even months, the temperature is very closely controlled and varied according to a predetermined curve peculiar to each type of glass. This curve always includes a wide plateau in the region of 650°C where the glass undergoes transition from β to α. *Astronomic quality annealing* has been so perfected in the last few years by the best glass producers that testing for annealing as described in Section VII-1 becomes superfluous. Needless to say, such fastidious annealing results in rather long delays in delivery. Here are some details that will facilitate your order: In France: Sovirel, Optical Department, 90–92 rue Baudin, 92306 Levallos Perret. In the United States: Schott, Durea, PA.

[1] *Sky and Telescope Bulletin C*, "Maksutov Articles from Gleanings for ATM's", Sky Publishing Corp., 1963, and *Construction of a Maksutov Telescope* by Warren Fillmore, Sky Publishing Corporation, 1961.

Type of Glass. The borosilicate crowns now most widely used bear the catalog numbers B 1664 and B 1864. The indices of refraction for the sodium D lines are respectively 1.51650 and 1.51800. For our purposes these may be considered equivalent, and doing so may facilitate delivery and reduce costs.

Diameter. If the optical diameter of the plate is just equal to that of the mirror, there will be a slight vignetting at the edge of the field, though barely observable visually. The width of the shoulder supporting the plate is about ¼ inch. The outside diameter will therefore be about ½" greater than the optical diameter. To this we add another ⅛" to arrive at the rough disc diameter, since edging at the factory is only approximate unless otherwise specified. To completely avoid vignetting at the edge of the field, we must further increase the disk size to allow for the effective width of the field measured at the window plane. Example: given a mirror of 10-inch optical diameter, a window 43 inches from the mirror, and the requirement of a fully illuminated 30′ field, the vignetting measured at the window is:[5]

$$43 \times 0.0002909^{*} \times 30 = .38 \text{ inch} \tag{76}$$

This gives, for the optical diameter of the window,

$$10.0 + .38 = 10.38 \text{ inches} \tag{77}$$

Adding the supporting surfaces of ½" gives a diameter of 10.89" to which we add an allowance for edging (⅛"), thus the diameter of the ordered raw disk will be 11 inches.

Thickness. The weight of a window determines the price of the raw disk, and the mass that must unavoidably be supported at the end of the telescope. Mechanical flexure of the window plate is little cause for concern, as we shall see later. More important is the difficulty of shaping and figuring a plate that is too thin. That sets a lower limit on thickness. It is possible to figure a good 10-inch diameter plate no more than 0.375 inch thick, but the difficulties involved are better avoided. Instead, we adopt a 0.625-inch thickness for a 10-inch disk, 0.750-inch for a 12-inch and 1.00-inch for a 16-inch. To this you can add about 1/16" per face for rough grinding and smoothing. However, to protect yourself you should stipulate in your *written instructions* to your glass supplier that you will need this amount (1/16-inch) on *both* sides of the disk to bring it to the desired smoothness and parallelism. Specifically, advise them *in your written instruction* that you expect them to inspect the blank to insure that there are no deep mold marks or folds that will extend farther into the glass than this amount.

* The value 0.0002909 is the equivalent in radians of 1 minute of arc.

[5] This assumes the mirror is the aperture stop, *which might not generally be the case.* For a fixed mirror diameter which is also the aperture stop, the window would have to be reduced in diameter by the extent of the field (in radians) times the window-to-mirror separation, to have no vignetting. Of course, what makes more sense is to make both the mirror and window the same aperture and accept the slight vignetting.

Premium Quality, Astronomic Grade Annealing. We have discussed the significance of these specifications. They are essential in ordering a glass plate that will be used as a light-transmitting element.

X-3. Cutting the Central Hole and Edging

It is sometimes possible, by special arrangement, to have these operations done at the factory. Cutting a hole in the plate gives us a useful way to mount the secondary mirror. (See the examples shown in Figure 85.) The hole diameter in this 10.43-inch plate is 1.34-inches. We can use the directions given in Section VII-2 for perforating a Cassegrainian primary mirror. For the window, the Ritchey method is best; that is, the hole is cut all the way through and the core is then cemented back into the hole with plaster. Since the biscuit-cutter passes completely through the window, we must guard against chipping on the back side of the disk. To prevent this, we must cement, with rosin, a wide, thick glass plate to the back of the window. Obviously you will have to heat both pieces of glass. Care must be exercised not to heat or cool the blanks too rapidly or they will crack. The safest method is to place the blanks (not touching) in a common baking oven with a small piece of rosin on one of them. Gradually, over the period of several hours increase the temperature, until the rosin melts. Remove the blanks from the oven and place them on a ¼" layer of newspapers (this provides insulation and a resilient surface to work upon). If there is not sufficient rosin melted on the glass, rub more on it until you have it completely covered, then carefully place the other glass onto the rosined surface and center it. In a few minutes the rosin will have cooled to the point that the blanks will not easily move apart. Place another ¼" of newspapers on top of the cemented pair and let cool overnight. After the hole has been cut you can separate the blanks by placing them in the freezer section of a refrigerator (the disks must be at room temperature—not when they are hot) and letting them freeze. Usually they will slide apart with little effort. You may also separate them by soaking the blanks in paint thinner or by reheating them slowly in the oven. If you choose the latter course, remember to cool the window blank very slowly; most breakage occurs during too-rapid cooling. After the blank has been separated from its glass backer and cleaned up, bevel the inner edges of the perforation and the edges of the plug on both sides. Cement the plug in place with a thin mixture of plaster, and when this is dry, coat with several layers of shellac to seal against moisture.

Edging the window plate, which must be well centered on the central hole, is recommended but not absolutely necessary: the plate is of zero optical power, and translation within its plane is without effect. Let us describe briefly a method, long used in the optical laboratory of the Observatory of Paris, which requires no special machinery. As shown in Figure 87, we mount a large ball bearing race on the table of an ordinary drill press and center it with respect to the spindle. The window is positioned on the bearings with three interposed cardboard inserts. On top of the window, aligned with the cardboard inserts, are placed three rubber erasers that transmit the rotation of the drill presses' spindle via a drive plate. A weight is attached to the operating lever, heavy enough to assure transmission of rotation without risking slippage of the glass. For a 10-inch window, the speed should be no more than 100 rpm. All we now require is to bring against the edge of the disk a lever carrying an iron plate as shown in Figure 87. If the irregularities left on the disk at the factory are no deeper than 1/32-inch, a 2 min. emery will suffice. Edging is then finished with a 5 min. or 320 emery. To improve the appearance and to protect the edges against chipping, a regular practice at the Observatory of Paris is to bevel the edges using the same grit sequence, so that a quarter-round circle of about 1/16" radius is formed.

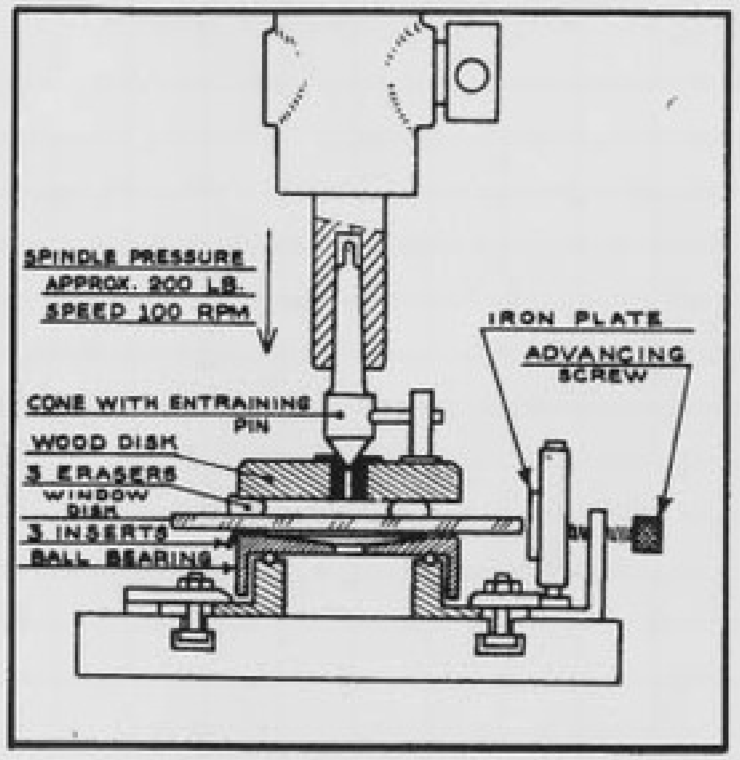


Fig. 87. Edging a window plate on a drill press.

X-4. Smoothing Tolerances and Parallelism

A plate with imperfectly parallel flat faces acts like an objective prism of very small angle; the star image becomes a small spectrum, the violet being on the side of the thick edge of the plate, the red on the thin side. If the magnitude of the defect is at about the tolerable limit, the normal image is merely bordered on one side with a red fringe; the blue-violet on the opposite side is less noticeable. What maximum prism angle may we tolerate to assure that chromatism is not detectable in the image? We can arbitrarily set very tight tolerances because, as we shall see, this involves no special difficulty either in execution or testing. Assume that the angular width of the spectrum, measured from the blue (say the F or Hβ line of hydrogen, 4,861 angstroms) to the red (say the C or Hα line of hydrogen, 6,563 angstroms) is no greater than a

tenth of the angular radius ρ of the diffraction spot. We designate the prism angle of the disk as A. From the equation for small-angle prisms, we obtain the dispersion, ΔD:

$$\Delta D = (n_F - n_C)A \qquad (78)$$

The indices n_F and n_C, and their difference or *mean dispersion*, are shown in glass catalogs. For the borosilicate crown B 1664 we have $n_F - n_C = 0.00807$.

Calculating the maximum acceptable value for A, then, if $\Delta D \leq \rho/10$,

$$A = \leq 12.4\rho \qquad (79)$$

Example: Consider a telescope of aperture = 30 cm, and $\lambda = 0.56$ mm. The angular radius ρ of the diffraction spot is

$$\rho = \frac{14.1}{30} = 0.47 \text{ arc second} \qquad (80)$$

Thus, from equations (78) and (79), the borosilicate plate may have a prism angle of

$$A = 0.47 \times 12.4 = 5.8 \text{ arc seconds} \qquad (81)$$

Note that with a good micrometer and an experienced user, differences in plate thickness can be measured to about 1 or 2 μ, or say 3μ if the micrometer is not the best and the user is less adept. The ratio of 3μ to 12" (300mm) corresponds to an angle of 1×10^{-5} rad or about 2 arc seconds. It is therefore easily within our abilities to do better than the stringent tolerances we established above, which would correspond to a thickness difference of 8.4μ!

Curvature of the faces: The two window faces need not be perfectly flat; all that matters is that they transmit a good plane wave. If either or both faces have a slight curvature, the window becomes a long focus lens. The aberrations of a telescope looking through a lens with a focal length of the order of a mile are obviously not changed in any appreciable degree. The significant tolerances in this lens will be determined instead by its *aberrations*. First of all, if the curvatures are of the same sign, we have a meniscus whose geometric aberrations are indistinguishable from those of a plate with flat surfaces. If the curvatures are opposite in sign, we have a biconvex or biconcave lens. We need not bother about spherical aberration in such lenses, since this is extremely small and in any event is masked by defects inherent in the optical fabrication process. When curvature becomes a problem it is chromatism that we see first. A simple lens has two different foci for the C and F wavelengths; between these lies the circle of least aberration, of diameter equal to:

$$d = \frac{D}{2\nu} \qquad (82)$$

D is the diameter of the plate, and ν is the *dispersion constant* of the glass, the value of which is also given in the Parra-Montois catalog:

$$\nu = \frac{n_D - 1}{n_F - n_C} \qquad (83)$$

Here, n_D is the refractive index of the glass for the sodium D lines. For the borosilicate crown B 1664 we find $\nu = 64$, giving as the diameter of the circle of least aberration with this glass $d = D/128$.

Assume as a very exacting tolerance that d shall remain less than the diameter 2ρ of the diffraction spot. We therefore increase the focal length F of the lens sufficiently for the diffraction spot to be as large as d. If we make these calculations and express D in millimeters, we have:

$$F \geq 5.73D^2 \qquad (84)$$

Example: a 260 mm diameter plate of borosilicate crown B 1664 should have a minimum focal length of $5.73 \times 260^2 = 387{,}348$ mm or 387 yards. Assuming the plate to be biconvex or biconcave, the radius of the faces to a first approximation is likewise 387 meters. A spherometer bearing on a small circle of 75mm radius (Figures 80 and 90) will detect a difference of 7.3μ (0.00028 inch) with respect to the plane, a value comfortably large compared with the possible measurement error of about 1 micron (0.000039 inch).

We can conclude that simple mechanical testing of the plate during smoothing is enough to eliminate any risk of geometric aberration. When polishing is completed, it will suffice to re-examine and retouch the zonal aberrations the same as in dealing with a spherical mirror, in order to obtain a plate that is perfect in the practical sense.

X-5. Rough Grinding, Fine Grinding and Smoothing

The molds that form the glass into a disk usually leave the faces slightly convex. Further, because a mold release powder is used, the surface texture is coarse, though usually not very deep*. We will use the (approximately flat) back of the tool, employed earlier to shape the main mirror, and with 120 corundum or 1 min. emery make this surface conform with the two faces of the window plate. The plate faces will arbitrarily be designated 1 and 2, these numbers being marked on the rim of the disk. The wets are applied alternately to face 1 and face 2, so as to maintain continuous contact with the tool. As a rule, the positions tool-above and tool-below are alternated regularly, except at the beginning of the operation when the plates' convex faces logically indicate working with the plate on top. Or, more generally, we interrupt the sequence when the spherometer shows the plate is developing a measurable curvature and correction is needed. With the plate on top, it can be adequately gripped with the hands even though it is not very thick. Attaching a handle is

* Some suppliers grind the disks on large turntables that leave them slightly convex. The surface is also coarse since sand is often used as the abrasive. It is a good idea to determine how your supplier intends to process your blank—will it be ground, and if so with whet abrasive or if molded the depth of any inclusions that must be removed for a clear plano-plano surfaces?

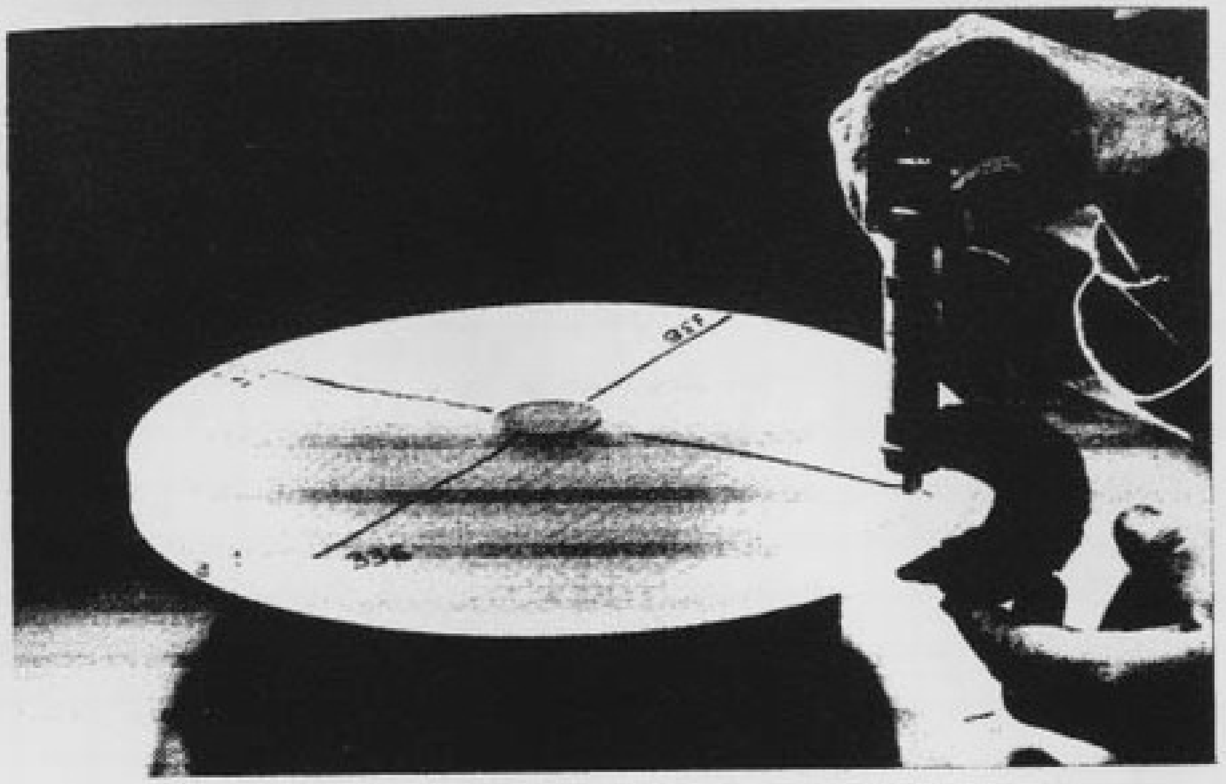


Fig. 88. Verifying parallelism with a micrometer.

not necessary. If the tool has a convex face formed in an earlier rough grinding operation, and this surface rests on the work post, a wide ring cut from a thick wool blanket will keep the tool from rocking. With the window plate in the lower position, we must be careful from the start to avoid straining it, since it is extremely flexible. Flatness of the post should be checked, and a disk of thick wool blanket always inserted between the plate and the post. The retaining cleats are made thin enough to allow free passage of the tool with good clearance. The cleats are positioned to allow lateral movement of 0.02 to 0.04 inch, thus permitting systematic (and indispensable) rotation by a quarter turn with each wet. After ten wets on each face, made with normal strokes of ⅓ D (Figures 21 and 21A), the surfaces are generally in good enough contact to allow making the first tests for parallelism and flatness. As we have seen, a well-made micrometer caliper will serve for testing parallelism. The micrometer screw is not used in this case to measure absolute values. However, approximating differences to about 1 μ requires a micrometer that has been well cared for, and is properly used and lubricated with special instrument grease. For convenient measurement of the plate, given its weight and bulk, it may be laid flat on a wood disk of sufficient thickness, say 0.750-inch and of diameter smaller than the plate. Two lines, mutually perpendicular, are drawn across the diameter of the plate with a soft lead pencil. We will measure the plate thickness where these lines meet the edge. Before making the measurements, make sure that the plate is dry and free of stray abrasive grains. The micrometer contact faces should also be checked very carefully for cleanliness.

Adjust the micrometer so that the two faces are separated approximately two or three turns wider than the thickness of the window. Now carefully insert the window between the two micrometer faces. Do not let the micrometer drag on the window; support its weight with your hand. Failure to do this will eventually abrade the faces of the micrometer and possibly scratch or chip the window. Now, gently turn the micrometer screw without using the ratchet. The ratchet does not provide the degree of sensitivity which you will need to develop. If the micrometer does not *feel* flat when you make your measurement, or repeated measurements in the same spot results in readings that vary by several microns, carefully inspect the area for fine abrasive, or even lint. Don't neglect to re-inspect the micrometer faces which might have picked up some contamination. It is advisable to repeat the measurements at each position 2 or 3 times. It is possible that these will show a reduced thickness by a micron or less, indicating a thinning of the lubricant on the flanks of the micrometer's threads. Multiple averaged readings provide a truer picture of the actual relative thickness.

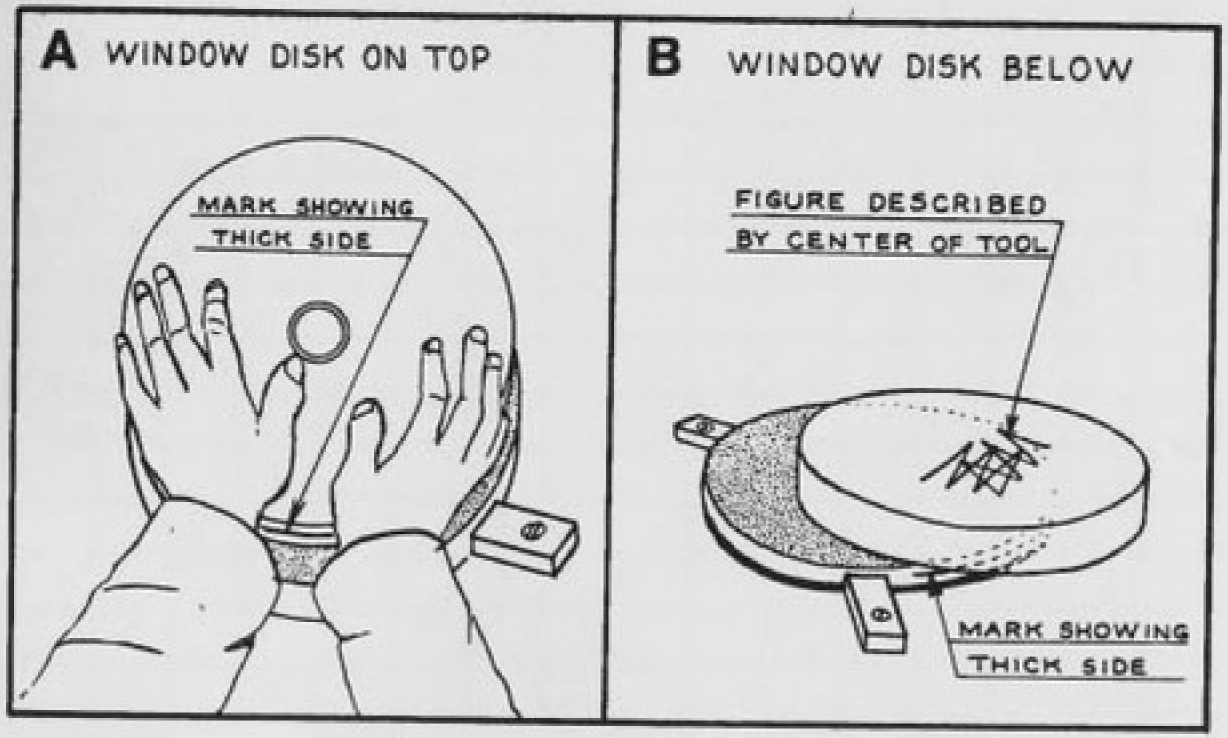


Fig. 89. Retouching a defect in parallelism.

Typically, the blanks will initially depart from parallelism by about 4 or 5 thousandths. The first readings may be limited to a precision of .001 inch. After you have determined, by your measurements, the location of the thick edge of the disk, mark its location on the rim with a dark, soft-lead pencil. Correction for parallelism can be done with the window in either the upper or lower position. When the plate is on top, one applies pressure through the palms which are positioned on the thick edge. The plate is not rotated, but the operator continues turning around the post (Fig. 89A). If retouching is done with the plate below, the tool should overhang the thick edge of the glass plate

by a wide margin, with all the strokes being off-center at this location (Fig. 89B). This strong corrective action will remove a half to one or more thousandths of an inch per wet of 120 corundum; it is possible that, left uncorrected, we could create a facet at this point of maximum effort. To avoid this, each corrective wet should be followed by several wets with the disk alternately above and below, using only normal strokes of ⅓D. As you proceed with this process it is quite possible that you will observe that the thick edge seems to move, from wet to wet, around the edge of the disk. This is a normal process and is a good sign that you are not in fact creating a facet. There is little point in trying to get the faces parallel to better than .001 inch with 120 corundum. Rather than trying to improve on this figure at this point it is wise to also work on general curvature. By checking the surface with a spherometer every five or six wets we can decide which position the window should be in to hold the curvature near a plane. For this we need a spherometer whose diameter does not exceed half the diameter of the disk. This permits us to move the instrument around the disk to determine the departures from planarity at many points. This multi-point method allows us to detect such deformations as a hyperbola due to excessively long strokes. The spherometer described in Section VIII-8 would have too small a span; however, one could mount its measuring head in a wide tripod cut from a 0.40 inch thick aluminum plate (Fig. 90). Three hardened steel points are mounted at the corners of an equilateral triangle within a tolerance set by drill-position error. The three sides of this triangle are measured with a good steel rule to about 0.004 inch. Taking the average of these, we divide by $\sqrt{3}$, i.e., 1.732 to find the radius h of the circumscribed circle. Since the departures f from surface flatness are very small compared with the radius R, the following simplified formulas suffice:

$$R = \frac{h^2}{2f} \tag{85}$$

$$f = \frac{h^2}{2R} \tag{86}$$

The working constant $h^2/2$ is inscribed on the spherometer mounting. This is merely divided by R or by f to obtain, respectively, f or R.

Figure 91 illustrates the use of a spherometer of classic construction. The one seen in the photograph is an historic instrument that belonged to Foucault and was built by the tool craftsman Froment. The thread has a pitch of 0.5mm and the barrel is divided into 500 parts. The tripod and barrel are made of aluminum cast by H. Sainte-Claire Deville (in 1857—a time when aluminum was a very scarce metal). Today, astronomical opticians use spherometers based on digital logic and costing thousands of dollars. However, it is quite possible to make an instrument that is nearly as good, and more than meets our requirements; all that we sacrifice is some convenience.

Differential measurements are made to determine the contour of the plate. The spherometer is zeroed on a reference flat of known accuracy, then

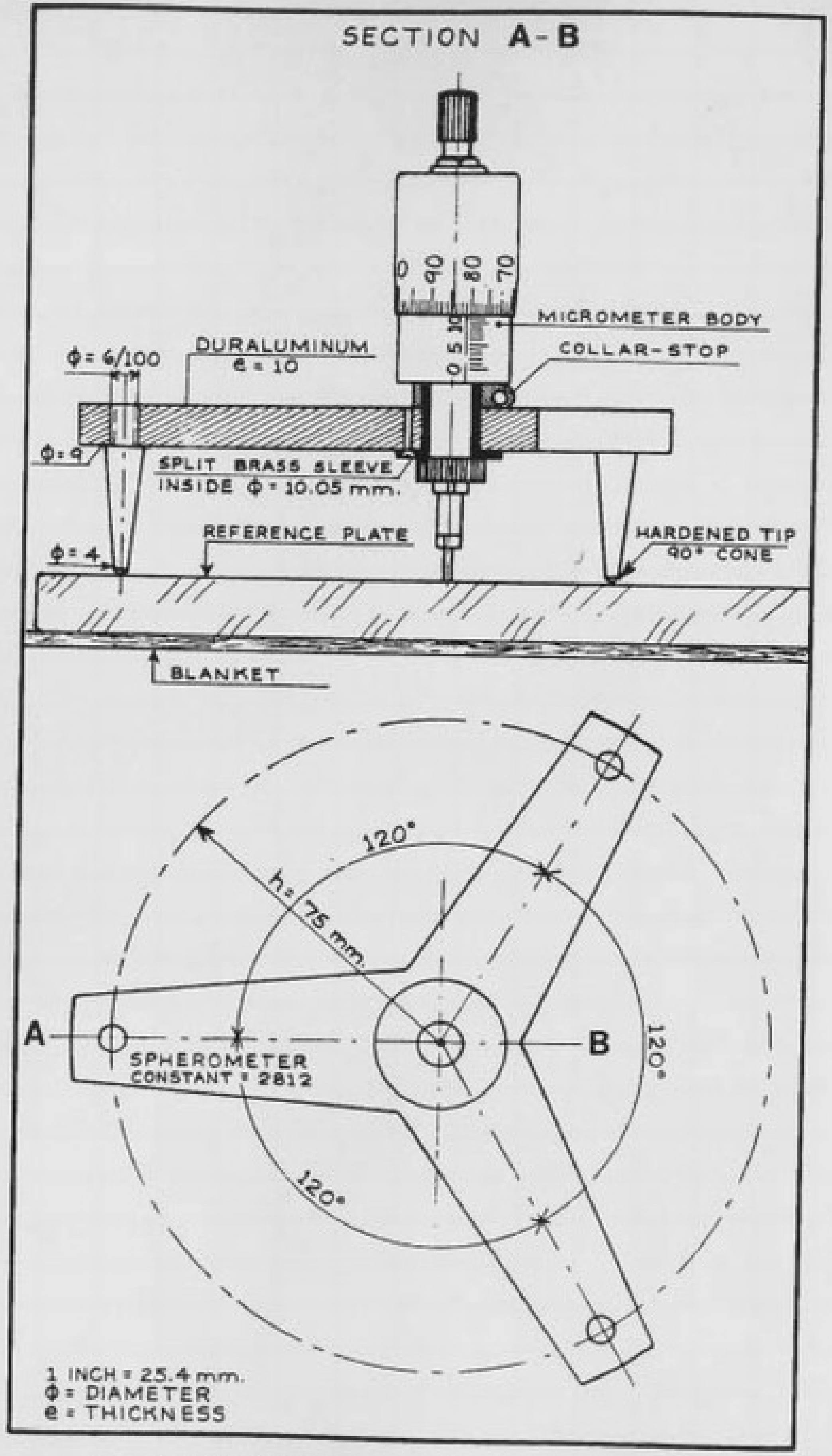


Fig. 90. Triangular spherometer using a micrometer head.

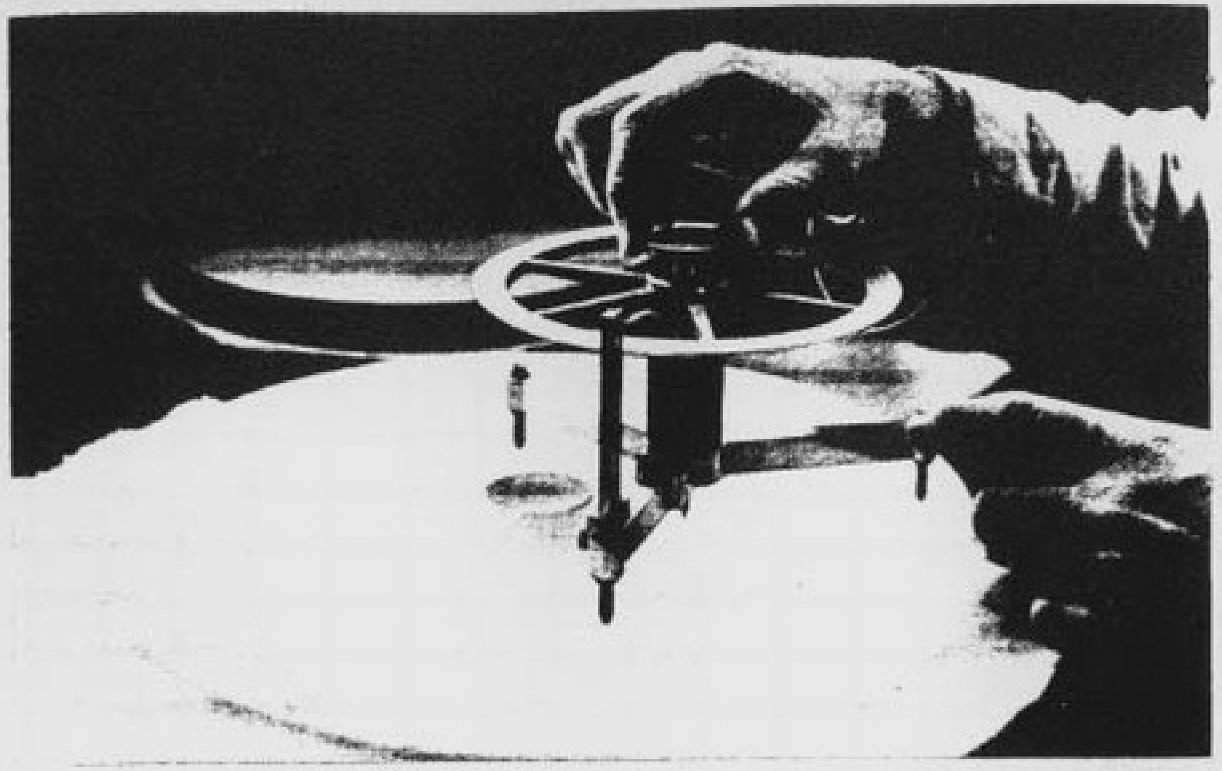


Fig. 91. The spherometer used by Léon Foucault resting on a 300 mm optical window

measurements are made of the test surface. A suitable reference surface can be made by fine grinding three common glass blanks in the sequence: A/B, B/C, C/A. . . . If one continues this sequence using finer and finer abrasives the surfaces commonly produced are flat within a half-wave. For our purposes it is not necessary to polish out the reference plates made in this manner. Returning to the spherometer, its thread must be good, not so much for *absolute* measurements but so that we can duplicate the same *relative* measurements repeatedly. For the highest possible accuracy the operator must develop a technique which we now describe. Starting with the micrometer spindle almost in contact with the reference flat, very slowly advance the spindle until it just begins to contact the flat. Now try to back off and then advance in increments of 1 μm to determine the point of first contact. Once the point of first contact is found with a *lightweight* spherometer as shown in Figure 90, a slight tangential touch by the finger causes a more or less easy rotation which, on a polished glass, is accompanied by a sharp squeak, the frequency of which varies critically with the applied pressure. One should not attempt this with a heavier instrument which can easily scratch the test plate. When an average point of contact has been found, read the micrometer scale and record the value. Now move the instrument onto the plate to be tested, taking care not to move the screw or heat the tripod by direct hand contact. If the surface is concave, the micrometer face will not contact the surface. If the surface is convex the micrometer face will contact the surface and the entire instrument will *rock*. Determine and record the average point of contact as on the reference. Using this technique a difference of 1μ between the depth of curvature on the flat and the glass under test shows up as a striking difference.

At this stage do not try to achieve very precise measurements. The rough ground surface of the glass is quite abrasive to the fine surfaces of the spherometer tripod points and the micrometer. Work to achieve a flatness of about 5μ (0.0002 inch) at this stage. It will probably take many wets to achieve an acceptable parallelism and curvature with 120 corundum. Before moving to a finer abrasive make sure that any large pits, particularly near the edge, have been removed as well as any surface imperfections left by the casting of the plate. Following the same sequence as we do for mirrors, we proceed to fine grind and smooth the plate. It is good practice to use many wets; it will pay off with a better surface later. After the 180 or 2 min. emery followed by the 5 min., or BM 302, the parallelism and curvature should be within 1 or 2μ. By the time one moves on to 10 minute emery or BM 302½, correction for parallelism should have been completed. Attempting to correct for parallelism at a later stage than this can result in a local zone (facet) that is difficult to completely eliminate with the much slower-acting, finer abrasives. At the 20 min. or BM 303 stage onward, the objective should be to smooth the surface and maintain the already achieved near-zero curvature and parallelism, using normal wets and alteration of tool and plate positions.

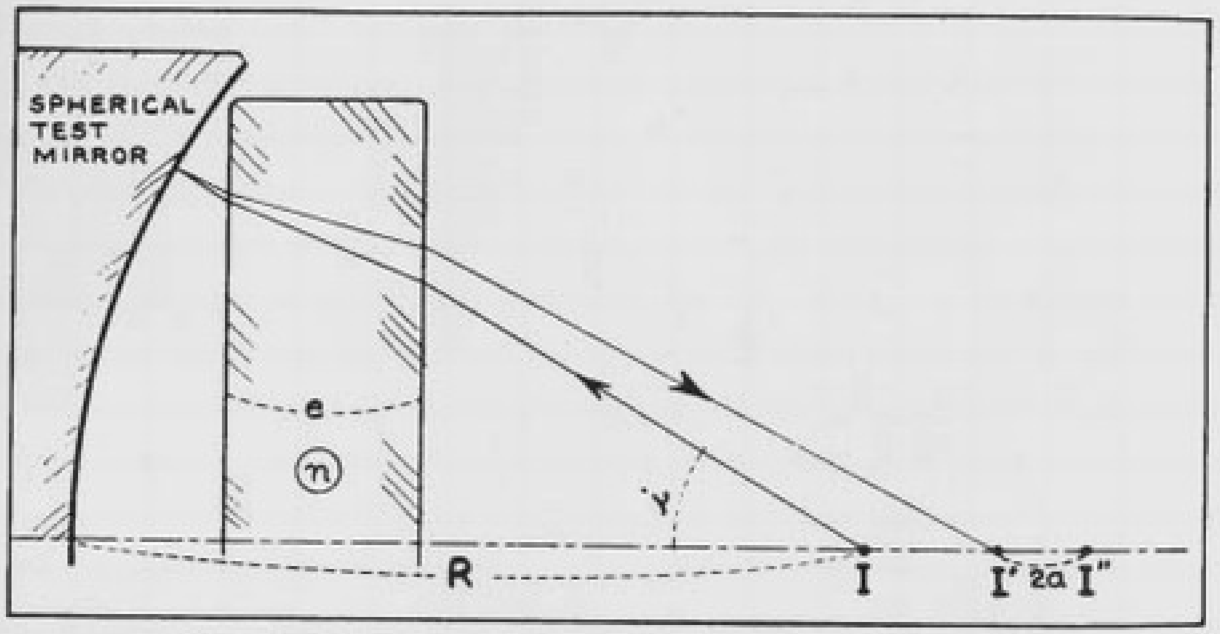


Fig. 92. Testing a parallel-face disk in front of a spherical mirror.

X-6. Optical Testing of the Window

In the workshop, the easiest way to test the plate is to place it against a spherical mirror of radius R and to examine the figure at the center of the mirror's curvature. In Figure 92, for clarity, the thickness *e* of the plate has been highly exaggerated, and the radius R of the mirror greatly reduced. If we do a normal Foucault test of the mirror (without the window in place) we will find the center of curvature of the mirror (smooth cut-off). If we now insert a hypothetically perfect plane-parallel window plate in front of the mirror, we

Workshop spherical mirrors used to test flats are usually made with a long focus (see Fig. 52). With such a mirror at our disposal we can take advantage of the fact that the incident angle *i* is reduced. For example, we may have R = 236.2 inches for D = 11.8 inches; thus $\sin i = 5.9/236.2$ and $\sin^2 i = 0.000625$. A plate 0.79 inches thick thus exhibits a longitudinal aberration of:

$$\Lambda = 0.3726 \times e \times 0.000625 = 0.00018 \text{ inch or } 4.6\mu \qquad (92)$$

Therefore, we can completely ignore longitudinal aberration. Even if we have a mirror of only 10 feet radius, thereby quadrupling the aberration, it is still less than the positioning error with the knife edge used with the utmost care!

The defects observed when we interposed the plate are therefore caused only by the plate itself. Since they are caused by refraction, *we must reverse the conventionally assumed lighting direction in interpreting the mirror shadows.* With the knife moving from right to left, we must imagine the evenly grey surface is also illuminated from the right. Since most opticians are accustomed to the knife edge moving from right to left, and visualize the surface as if it were illuminated from the left, we should modify our Foucault tester slightly to avoid confusion. The knife should be reversed and mounted in a special frame which allows the image to be cut from the left. With this arrangement the optician testing a refractive optical element does not have to make special mental allowances to interpret the shadows.

X-7. Polishing and Retouching

The instructions given in Sections II-15 and II-18 are also applicable to the polishing of a plate with parallel faces. Polishing tools greater than 10 inches in diameter may be prepared with 1-inch squares instead of ¾-inch. As in the case of the perforated Cassegrainian primary mirror, the slight swelling in the pitch produced by pressure against the edge of the central hole should be scraped away before beginning each polishing session. The strokes are of normal amplitude, ⅕D. Polishing of the two faces should, from the beginning, proceed in parallel in order to liberate on both sides of the plate the compression forces (first observed by and named after Twyman) induced during the grinding and smoothing stages. For example, face 1 could be worked for one hour, then face 2 for one hour, in both cases with the plate on top. Polishing would then continue for one hour on each face with the plate below for uniformity of smoothing. When the plate is on top, we must be sure that our hands are clean and free of polishing compound, so that they do not become unintended local polishers of the upper surface. Also, we must avoid localizing hand pressure steadily on the same zone. Since the plate is very flexible, a central cavity could result from a hand constantly positioned at the center. With the plate in the lower position, we must observe the familiar precautions for preventing astigmatism: flatness of the work post; use of a thick resilient material (blanket or foam rubber) for padding; and systematic rotation by quarter-turns at least every 15 minutes.

A polishing spell of two hours on each face permits us to make the first test in front of a spherical mirror. For safety of the disk, it is wise to mount it centrally in a plywood frame. The circular opening in this frame is 0.04 inch larger in diameter than the window plate and is fitted with pivotable brass clips (Figure 93). The plate is not very sensitive to flexing when mounted vertically, but it is always best to avoid strain caused by a tight fit.

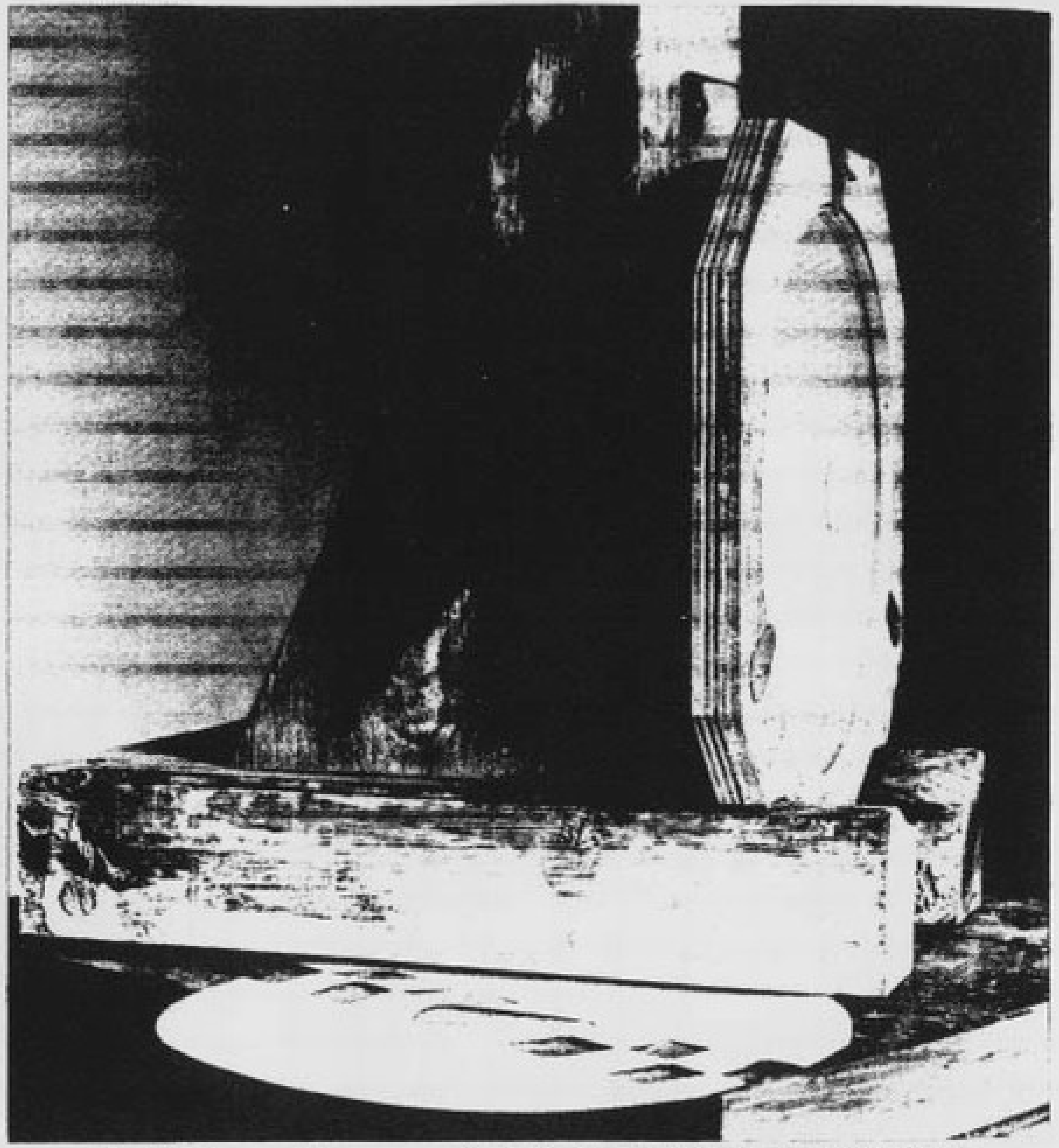


Fig. 93. Setup used to test a optical window in front of a spherical mirror.

The difference in knife position with and without the window inserted indicates whether or not the optical power is acceptable. But at the same time one almost always sees zonal defects or significant spherical aberration corresponding to differences in optical thickness of the glass. To interpret these defects, we must remember not only that the convention for lighting direction is reversed (if we have not modified the knife edge as above), but that

observe a shift of the image I to position I′ (Figure 92). This shift in position, ΔR′, is caused by refraction of the non-parallel beam as it twice traverses the window (to and from the mirror). We can calculate what this shift should be for rays of small inclination:

$$\Delta R' = 2e\left(1 - \frac{1}{n}\right) \qquad (87)$$

Using the borosilicate crown B 1664, we have $n = 1.51650$; therefore $\Delta R' = 0.681\ e$. With our actual window rather than the hypothetically perfect disk in the beam, we find that we arrive at a knife position I″. *If this observed shift,* $\Delta R''$ is greater than $\Delta R'$, it indicates that the plate is a concave lens; if smaller, then it is, of course, convex. The difference is:

$$\Delta R'' - \Delta R' = 2a \qquad (88)$$

To calculate the focal length F of the lens:

$$F = \frac{R(R + a)}{a} \qquad (89)$$

If, for example, the spherical test mirror has a radius of 236.2 inches and the difference $\Delta R'' - \Delta R' = 0.79$ inches, the plate is a concave lens of 2.24 miles focal length. This value has to be compared with the tolerance on lens effect defined by equation (84), in connection with mechanical testing for curvature during smoothing.

The geometric aberrations of a plate with parallel faces are by definition very small since the plate in practice has no optical effect. There is no lateral chromatic aberration; however there is a slight longitudinal chromatic aberration which, for a single traverse (which will be the case when used as a window) is:

$$\delta R = \frac{n_F - n_C}{n^2}\, e \qquad (90)$$

For our borosilicate glass, $\delta R = 0.00351\ e$, an effect too small to detect in the plates we are concerned with. We must, however, calculate the spherical aberration because, strictly speaking, our work shop test set-up is not precisely the correct one for measurig this aberration. In normal use, the light traverses the telescope window only once, the rays being at perpendicular incidence and *parallel.* In our test set-up, however, the window is traversed twice, and by a beam that is *significantly convergent.* Equation (87) is not precise except for rays of zero inclination. Convergent rays of incidence angle i undergo an additional translation Λ which is the longitudinal aberration caused by the test set-up. For two traverses we have as an approximation to the fourth order:

$$\Lambda = e\ \frac{n^2 - 1}{n^3}\ \sin^2 i \qquad (91)$$

a defect caused by refraction corresponds to a thickness of glass that is four times greater than for an element such as a mirror tested only by reflection (see Fig. 6B). For a plate that is traversed *twice*, twice as much glass must be removed as on a mirror showing the same defect on the wave surface. If there is a large departure from sphericity, for example, a wide, deep central cavity (showing more than 2 inches longitudinal aberration for a double traversal and with $f/20$ beam) faulty smoothing should be suspected: the strokes may have been too long, or the hands may have been exerting systematic pressure at the center. In effect, the great flexibility of the disk makes it sensitive to this kind of error. If we suspect this is happening, we can check the shadow pattern which would show a net retardation if there is a hollow zone on one or both sides of the disk. Usually, it is unnecessary to return to fine grinding to correct this defect. The defects usually diminish gradually as normal polishing proceeds. However, we should not just blindly start polishing and bring each surface to a near-finished state before beginning testing. It is best to make several rough measurements as soon as the surface will pass light and to continue these tests on a regular schedule. If the defects noted in these tests do not gradually diminish appreciably after three or four hours of polishing, positive correction becomes necessary. It goes without saying that during this time you have inverted the tool and plate each hour and have kept the lap carefully trimmed to insure that your technique itself is not perpetuating the problem. Initially, one should always work to modify the surface by changes in pressure and stroke amplitude or by extra pressure at the edge of the lap. Alternatives such as deforming the surface of the lap by localized trimming or scraping, or localized retouching with a small polisher, are not good ways to correct large defects. For example, a large central hill is at first simply treated by increasing the strokes to ¾ D. For a wide cavity, the boundary between the two zones is reduced by extra pressure where the edge of the tool passes over this position, the tool being in the upper position. To distribute the correction and blend the action, the lap and window should be reversed after each wet and a ½D stroke used when the window is on top. Our testing method does not tell us which face of the plate is responsible for the overall observed defect. In retouching a large defect, the action may be applied to both surfaces. However, at the end of polishing, the defects as a rule are small, and retouching would not be applied to more than one arbitrarily chosen face. Overall, the work of correcting a optical window is much like that done to achieve a good spherical mirror. The instructions in Section II-35 and in all the figures dealing with mirror retouching are valid here, the only exceptions being that (a) the knife has to be reversed, i.e., it now enters from the left with the surface under test being visualized as though illuminated from the left, and (b) the thickness of glass to be removed is doubled.

Aside from the above, we must now begin to look for defects of homogeneity, which are often present in even the most carefully selected optical glass. We have commented on the selection process applied at the factory for precision quality glass, but more subtle variations of index, e.g., weak striae, unfortunately are recognized only when precision polishing is well advanced. Careful control exercised during high-quality annealing is not in itself a guarantee of perfect homogeneity of index.

Fig. 94. Foucault shadowgram showing various types of material detects in a 16-inch plate. Knife edge entering from left.

The Foucault pattern in Figure 94 illustrates most of the defects that may occur. Some explanation is necessary. First, as in all the Foucault pictures reproduced in this book, the sensitivity of the technique used was many times greater than will be seen in visual testing with a simple Foucault tester. Second, Figure 94 was made on an experimental molding of barium crown glass intended for a large objective prism (diameter 15.75 inches; thickness 3.94 inches). You are not likely to find defects as pronounced as these in the more easily produced borosilicate crown glass plate of 0.80 inch thickness. At A, the enormous concavity on the wavefront (knife and imagined lighting at left) is produced by a nodule of glass of higher index. Nothing can be done about this; the defect cannot readily be compensated for by altering the optical faces. Defects such as these are gross and you should expect the supplier to replace the disk. At B we see a concave anomaly of index that is partially retouchable by smoothing its edges with a local polisher passed over these areas. C is another example of an easily retouchable slow variation of index. The large striae D, E and F are unacceptable in a premium quality glass. Note, however, that they are curved and that the light diffracted by these defects would not be detectable or really objectionable except in the course of subtle observations on faint celestial objects near a brilliant source. G is a wide band of very faint striae that would escape notice in a projection test, and would be troublesome only in a coronagraph lens. Finally, we see at H a large faint stria of curious structure, the effect of which is again almost negligible despite a long, nearly straight portion. Often, slow variations of index cannot be distinguished from a surface defect. What matters in practice is that, where local refractive defects are correctable, it is always clear what the corrective action should be. On the other hand, one would not be overly concerned with the individual topography of the surfaces, since regular working of the faces will always restore their stigmatism. To attempt to make both faces precisely flat, for example by interferometric testing against a reference, would be a waste of time since phase shift due to internal defects would still persist to spoil the image.

Because checking of wavefront sphericity at the center of curvature by the Foucault test is so easy, we can push retouching quite far without even measuring or calculating the actual surface(s) of the window. However, if we rely solely on such visual evaluation of the surface, we might misjudge what appears to be a slight but in fact significant aberration, or on the other hand fuss unnecessarily over a trifling local elevation and in so doing create more significant deviations. We must constantly remind ourselves that our test is very sensitive, since the light doubly traverses the window, and that the test mirror is of long focus. In sum, measurements with the perforated masks and calculation of the refracted wave are just as important as when we deal with a deformed mirror. They enable us both to know precisely the kind of surface errors we are observing, and the effect of our correcting technique. Finally, they present to us an unambiguous statement of the quality of our finished window.

X-8. Quantitative Testing and Data Reduction*

The apertured mirror masks (Figures 38 and 74) can be used here without modification. If, for corresponding zones on the mirror and telescope window, we algebraically add the departures from an ideal wave contributed by each, we easily obtain the defects of the combination. A concrete example (Fig. 95) shows how a test data sheet on the window is compiled.

Below the basic data identifying the window disc we find on lines 1, 2 and 3 the numbers of the zones, the outside radii h_x and the customary

*See Appendix B-2 for data reduction program in BASIC

TEST DATA SHEET: WINDOW DISK (DIMENSIONS IN INCHES)
OUTSIDE DIAM: 10.26; OPTICAL DIAM.: 10.20; THICKNESS: 0.626;
HOLE DIAM: 1.33   BLANK: PARRA MANTOIS M12, TYPE B1864;
$n_D = 1.51955$; $\nu = 64.5$ SPHERICAL TEST MIRROR: R = 217.5; DATA
REDUCED TO TELESCOPE FOCAL PLANE WHERE DIAM. = 9.71 $\mathcal{F}$ = 51.18; $\rho = 1.42 \times 10^{-4}$
FOCAL ELONGATION: 0.215; $2e(1-\frac{1}{n}) = 0.428$; WINDOW LENS EFFECT: F = 6.96 MILES CONVEX

1	ZONES	1	2	3	4	5
2	h_x	(0.78) 1.811	2.756	3.622	4.409	5.079
3	h_m	1.299	2.283	3.189	4.016	4.744
4	$(h_m 3/R^3) \times 10^6$	141	246	345	434	513
5	M_{SPHERE}	1.206	1.211	1.192	1.198	1.199
6	M'_{D1}	1.307	1.363	1.337	1.346	1.370
7	$(M'_{D1}-M_{SPH})/2$	0.0505	0.0760	0.0725	0.0740	0.0855
8	Λ_{RD1}	- .0275	- .0020	- .0055	- .0040	+ .0076
9	$\Lambda_{3D1} \times 10^3$	-3.88	-0.492	-1.90	-1.74	+3.90
10	λ_3/ρ	-0.27	-0.03	-0.13	-0.12	+0.27
11	$u \times 10^6$	+0.75	+0.10	+0.37	+0.34	-0.75
12	M'_{D2}	1.367	1.390	1.371	1.371	1.394
13	$(M'_{D2}-M_{SPH})/2$	0.0805	0.0895	0.0895	0.0865	0.0975
14	Λ_{RD2}	- .0120	- .0030	- .0030	- .0060	+ 0.0050
15	$\Lambda_{3D2} \times 10^3$	- 1.69	- 0.74	- 1.04	- 2.60	+2.57
16	λ_3/ρ	- 0.12	- 0.05	- 0.07	- 0.18	+0.18
17	$u \times 10^6$	+0.33	+0.14	+ 0.20	+0.51	-0.51

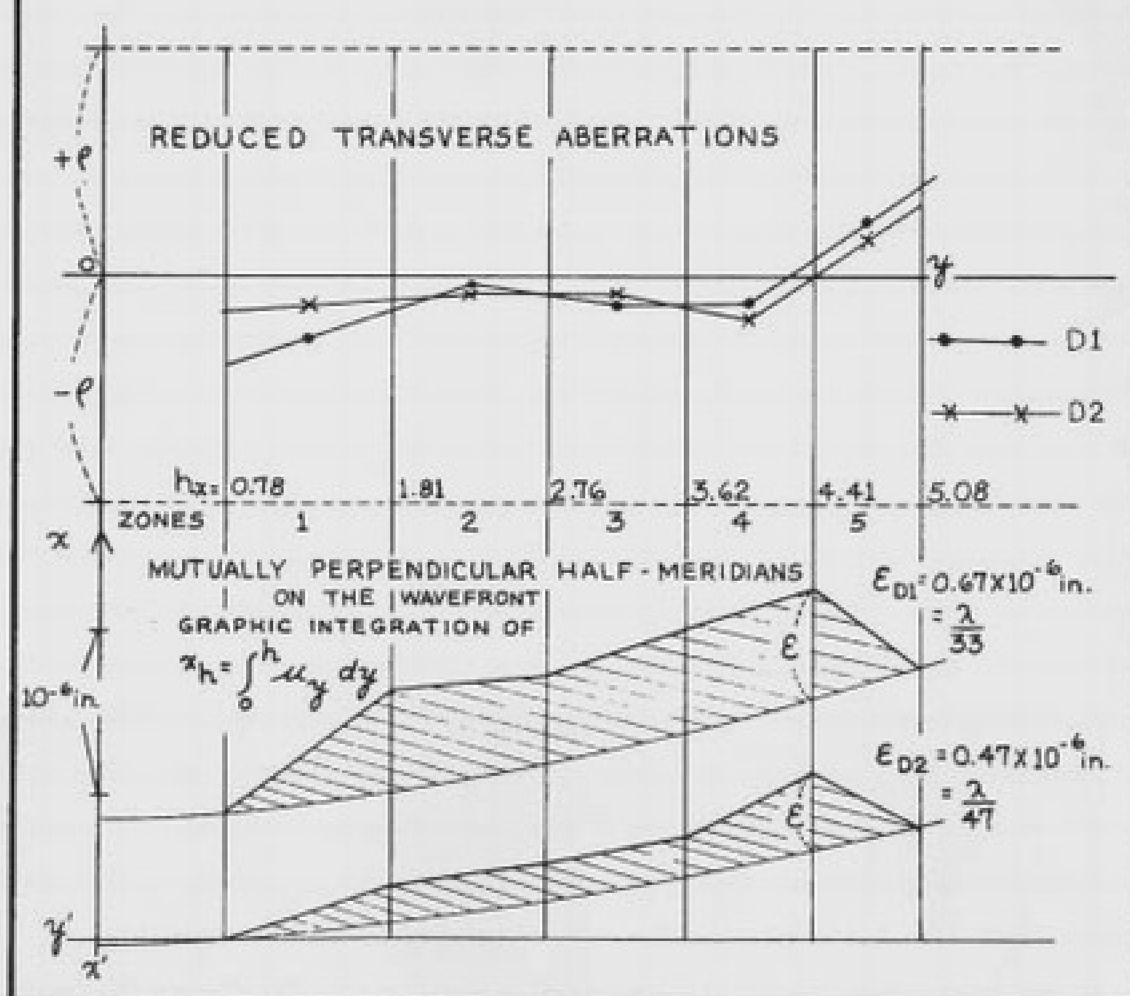


Fig. 95. Test data sheet for a telescope window.

average radii h_m. Line 4 shows the special factors, as a function of the radius of incidence, that will be applied to reduce the aberrations to the focal plane of the window-equipped telescope.

In this example, we are dealing with a Newtonian of 51.18-inch focal length. Our knife position measurements made with and without the interposed window will reveal the longitudinal aberration Λ_R, attributable to the window *per se*, as seen at the center of curvature of the workshop spherical test mirror of radius R. The corresponding longitudinal aberrations $\Lambda_{\mathcal{F}}$ contributed by the window *at the focal plane of the telescope (of focal length $\mathcal{F}$), fitted with this window* will be:

$$\Lambda_{\mathcal{F}} = \Lambda_R \frac{\mathcal{F}^2}{R^2} \qquad (93)$$

The corresponding transverse aberrations $\lambda_{\mathcal{F}}$ at the focal plane of the telescope will be

$$\lambda_{\mathcal{F}} = \Lambda_R \cdot h_m \frac{\mathcal{F}}{R^2} \qquad (94)$$

It is this factor $h_m \mathcal{F}/R^2$, multiplied by 10^5, which is given for each zone on line 4. These numbers, multiplied by Λ_R expressed in inches, will give the values of $\lambda_{\mathcal{F}}$ (in units of 10^{-5} inch) to be compared with the radius ρ of the diffraction spot.

Line 5 gives the average longitudinal knife position values found for the spherical mirror alone. Despite the high quality of this mirror, we note that the five readings are not identical, as they would be in a perfect mirror. These defects of the test apparatus *per se* must evidently be subtracted out. We note incidentally that the parabolic telescope mirror can be used if a spherical mirror is not available; the observed aberrations would simply be greater. Retouching the window would then consist in reestablishing the same parabolic correction on the wave front, but this would of course be somewhat more difficult than working toward the quasi-uniform field of brightness presented by the sphere.

On line 6, we enter the average raw knife position data obtained after interposing the window, with the perforated mask exposing a first (horizontal) diameter D_1 across the surface of the disk. Line 7 presents the differences between the values on line 6 and line 5, *divided by two*. From this point on, then, we deal with simple defect magnitudes, and not the double of these values.

On line 8, the values of line 7 are adjusted upward or downward by a constant amount so as to measure the aberration in the plane of the circle of least aberration. In the example, we find by trial and error that subtracting 0.0787 from the values in line 7 gives us longitudinal aberration values of Λ_R which, multiplied by the factors on line 4, give values of transverse aberration λ_F on line 9 in which the maximum numerical values are equal and opposite in sign. Although line 9 shows values to a tenth-microinch to allow

good approximation to the circle of least aberration, such precision is obviously not meaningful physically. Lines 10 and 11 need little comment: the former shows the transverse aberration as a fraction of the diffraction disk radius, and the latter shows the slopes μ of the individual zones calculated as in mirror testing (see Section II-40).

Lines 12 through 17 reproduce the same calculations along a mirror diameter D_2 on the window's surface(s) perpendicular to D_1. The mirror has not moved, nor have its defects changed; the disc has merely been rotated by a quarter turn. The advantage of two independent data reductions is that we can better judge possible astigmatic defects and random errors in knife position readings.

The graphs at the bottom of the data sheet are similar to the one seen at the bottom of Figure 46 and described in Section II-40. These are graphic integrations of the wave slope along the two disk diameters, exaggerated a million-fold. The hatched profiles show the cumulative wave front error. The defects on the glass are the inverse of these errors, and are about twice their amplitude. See appendix B for a computer program written in BASIC for the reduction of window test data.

THE EYEPIECE

XI-1. Role of the Eyepiece and Its Selection

Compared with the objective, the eyepiece of a telescope plays a relatively modest role. Its commercial manufacture offers no difficulty comparable with that of the objective. On the basis of availability then, the main reason for the amateur to make the eyepiece himself disappears. The amateur will be none the less discomforted, therefore, to learn that a good set of eyepieces may represent by far the largest single cost in the making of his telescope. The question of eyepieces must therefore be investigated carefully.

The eyepiece is a form of magnifier that helps the observer make the best possible use of the detail present in the primary image produced by the objective. However, our ordinary notion of a magnifier used to examine nonluminous objects must be refined in certain important respects. Remember that the diffraction spot formed by an $f/6$ objective is only 4 microns in radius (Sections I-3 and II-40), and that in our Test Data Sheet we took into account transverse aberrations of the order of 1 micron. To be consistent, then, we must expect our "magnifying glass" to reveal clearly details of this magnitude. Note also a fact that is familiar to every microscopist: very bright objects on a dark field are particularly revealing of defects in the optical system.

Assume the instrument with its eyepiece in place is focused at infinity and pointed in daylight at a uniform, bright background. Looking at the eyepiece from a distance of about 8 inches, we see a small white circle. This is the exit pupil of the instrument, which in a reflector is limited by the diameter of the main mirror, and is formed by the eyepiece which acts here as a small objective. This small circle is the *exit pupil*, or *eye ring*. In principle, it should appear behind the eyepiece, where the eye can center its own pupil and collect all the light received by mirror. The diameter P of the eye ring is equal to the free diameter of the mirror divided by the magnification, this providing a convenient experimental way to measure the magnification $M=D/P$.

Measuring D is easy; measurement of P is more exacting because the pupil may be only several tenths of a millimeter if the eyepiece is a strong one. If interpolation to a tenth-millimeter with a rule divided into millimeter divisions is insufficient, it is best to use a *dynameter*. This is a small instrument originally devised by Ramsden, consisting of a scale on glass divided into millimeters (which can be purchased as a microscope micrometer eyepiece) and by a positive eyepiece, i.e., one whose object plane is accessible for viewing this scale. The eyepiece is first focused on the scale, then the combination is focused on the eye ring and the reading is estimated to a tenth-millimeter. Naturally, if the eye ring exceeds the diameter of the pupil of the eye, the latter will diaphragm the mirror. In total darkness, the pupil of the eye may have a diameter as large as 8 mm, but one should not count on a useful diameter above 7, and even this may be reduced for older observers. An $f/6$ telescope should not be used with eyepieces of focal length greater 6×7 or 42mm. Though the study of very faint objects such as nebulae or comets may justify such low magnifications, we must not forget that defects of the cornea are enormous, and that the eye cannot be considered a perfect instrument at pupil diameters above 0.6 mm or say, at the most, 1 mm.

To evaluate any eyepiece, not only must we have available a perfect objective and a normal eye, but we must specify that the off-axis properties of the objective do not play a part. And not least important, we must specify the *focal ratio of the beam* and the *exit pupil diameter*. Depending on the magnitude of these variables, the relative influence on image quality of any of the three optical elements involved—objective, eyepiece, and eye—may be greater or less. For example, if we couple with a $f/15$ objective an eyepiece strong enough to give an exit pupil less than 0.6 millimeter, we find that the image is an index primarily of the quality of the objective, and that neither defects of the eye nor those of the eyepiece contribute a significant effect. With an $f/6$ objective and an exit pupil less than 0.6 millimeter, defects of the eye are not often troublesome, but those of the eyepiece may be. The eyepiece should therefore be well corrected.

In considering the quality of image seen in our standard $f/6$ telescope, using a low-power eyepiece that gives an exit pupil of about 6 millimeters, we must not only consider defects of the eyepiece but we must also remember always the defects of the eye itself. The eye here affects the image more, for example, than small, residual aberrations of the objective on the axis. Finally, in this case also ($f/6$ beam and 6-millimeter pupil), we find that to speak of image quality at the edge of the field is, in a sense, meaningless; the defects of the eye enter here in a variable, almost unpredictable way. For best viewing, the pupil of the eye normally adjusts itself to coincide with the exit pupil. But in turning to an object at the edge of the field, the eye rotates about a center positioned a considerable distance behind the pupil. Effectively, therefore, the pupil is diaphragmed like a cat's eye, and vision is no longer centered near the axis of the cornea, where alone the eye has sufficient optical quality.

The evaluation we give below of various eyepieces is of a conditional nature only. The observations were made on many eyepieces obtained from various manufacturers, and often undoubtedly did not exploit fully the possibilities of a given design because of imperfect fabrication.

The question of eyepiece, then, is an important, but difficult one. A satisfactory answer is not available to meet every situation.

XI-2. Principal Types of Eyepieces

Figure 96 shows the construction of various eyepieces. Except for the wide-angle types, which are not drawn to scale, all are shown approximately full size as they would appear if designed for 17 millimeters focal length. The direction of the light rays is from left to right. Two optical planes of interest are indicated. The one farther from the eye, shown by dotted lines, is the plane of the real image (the primary focus) and the field stop. The other is the plane of the exit pupil, which is made, if possible, to coincide with the pupil of the eye. Ideally, the eye-cap coincides with the exit pupil, but in practice, except for certain low-power eyepieces, it is an additional 7 or 8 millimeters outside the eye lens, in order to improve eye comfort.

1. Huygens eyepiece. In one form this is designated the "4-3-2" (the Huygens design); in another as the "3-2-1" (the Dollond). The numbers indicate the respective ratios or relative magnitudes, of the focal length of the field lens, the lens separation, and the focal length of the eye lens. The resulting total focal length of the eyepiece is 8/3 in the first case, 3/2 in the second. When made to these proportions the eyepiece is free of lateral chromatic aberration. The field stop usually has an angular width of 45°. Reflections in the eyepiece are broad and relatively weak and are therefore not objectionable. A serious shortcoming is the spherical aberration, which becomes enormous at the focal ratio of $f/6$ or $f/8$ of our standard telescope. At $f/6$, and an exit pupil of 3 millimeters, the results are frankly pathetic. The slightest shifting of the eye off the axis produces intolerable flaring of the image. Unfortunately, the Huygens is the design in most widespread use. Where economy forces the use of Huygenian eyepieces of this type already in the amateur's possession, it should be remembered that the least objectionable are those of highest power, corresponding to exit pupils of less than 1 millimeter.

2. Ramsden eyepiece. This is a "1-1-1" design, the relative focal length of which is likewise 1. The preferred practice actually is to set lenses somewhat closer than the formula indicates, to avoid focusing the eye lens on defects or dust particles at the field lens. The eyepiece does not fully correct for lateral chromatic aberration—a red fringe is visible at the inner edge of images that lie near the border of the field—and the field angle is often limited to 30°. This aberration is sometimes used to advantage: by suitably decentering the star under observation, the aberration can correct for atmospheric dispersion. Spherical aberration is barely ¼ that in the Huygens, and although this is not perfect, the results with a beam of $f/6$ focal ratio, or more especially with a $f/8$ ratio, are acceptable. It is not difficult for the amateur to make such an eyepiece. The lens dimensions are indicated in Fig. 96-2, and a simplified lens

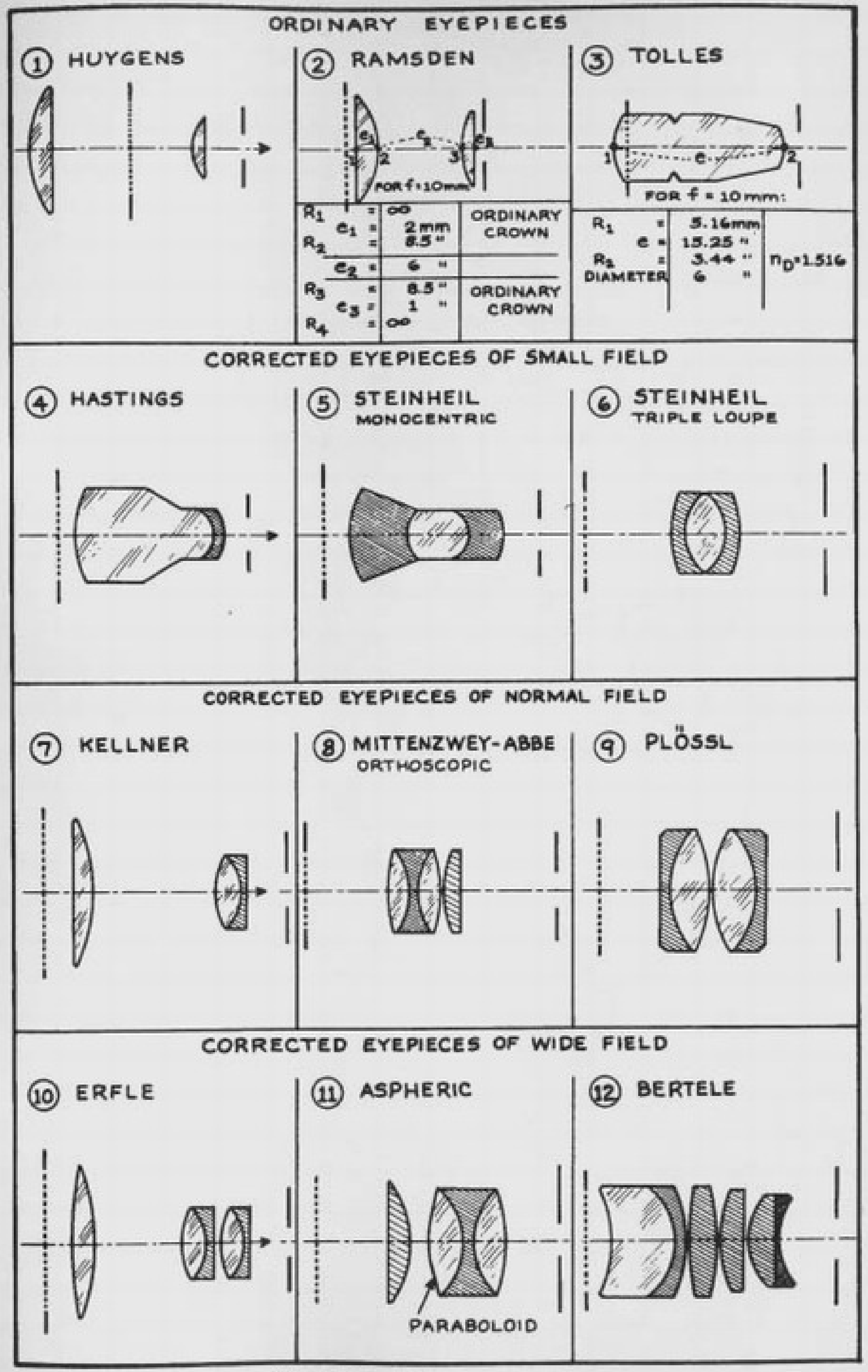


Fig. 96. Principal types of eyepieces.

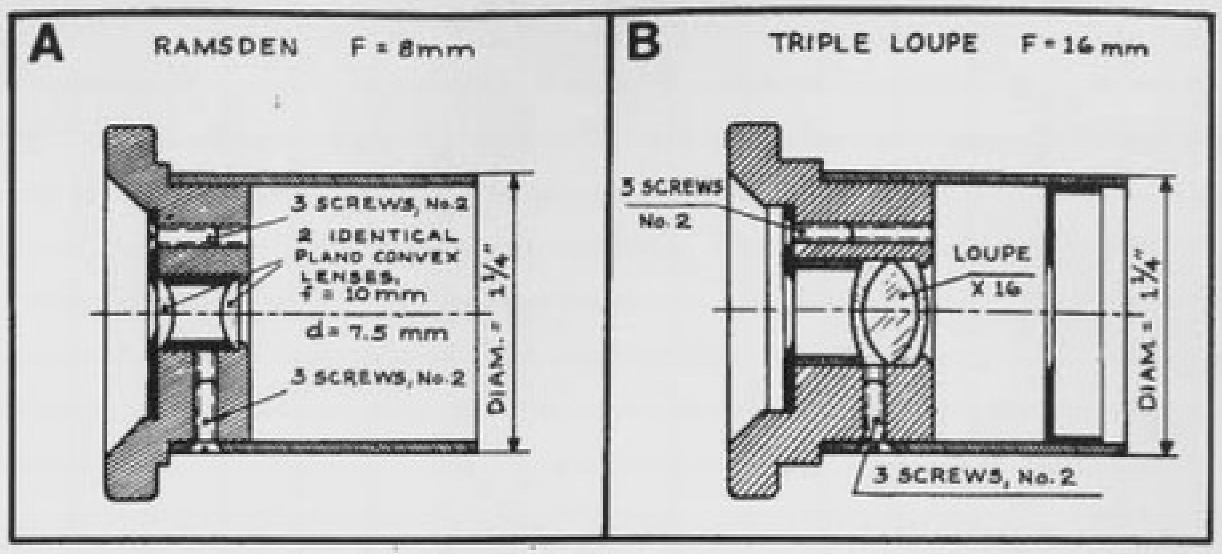


Fig. 97. Mountings for inexpensive eyepieces.

mount, that can be made even on a lathe without thread cutting provision, is shown in Fig. 97*A*. The Ramsden is definitely the economy eyepiece, but it is not recommended for beams of focal ratio as low as *f*/6 if the exit pupil exceeds 2 millimeters.

3. Tolles. This is a single thick lens. It is much better than the Huygens in respect to spherical aberration and in tolerance to decentering of the eye. It is easy to mount and free of troublesome reflections. The extreme curvature of the field limits the useful field angle in practice to about 12°—a strong argument against its use in an altazimuth-mounted telescope, where following of star motion would be difficult. The very short radius of the surface next to the eye (equal to one-third the focal length) makes fabrication of this eyepiece of an *f*/6 telescope difficult in the shorter focal lengths.

4. Hastings. A variation on the Tolles. Chromatic correction is good, but field curvature is appreciable, and distortion increases rapidly beyond the 25° included field angle.

5. Monocentric. Originated by Steinheil, to whom we owe several related designs. Chromatic correction is very good, but field curvature prevents effective use of a field much wider than 25°. An excellent eyepiece for planetary observation, but impractical unless the telescope is mounted equatorially.

6. Triple loupe. Also originated by Steinheil. Has excellent chromatic correction and very slight spherical aberration. With a beam of focal ratio *f*/6, the image is perfect on the axis even with a pupil as large as 4 millimeters. Astigmatism and curvature of field are not troublesome unless the field exceeds 30°. Reflections are unnoticeable. Field stop and exit pupil are both well separated from the lenses. Among the eyepieces that have but two air-glass interfaces, this is the best. The design is often used for high-quality eye-loupes described as "aplanatic" or "distortionless." These can be adapted to good advantage as eyepieces. The focal length of the loupe is theoretically equal to 250 millimeters divided by the magnification indicated on the mount. The lens should be checked, however, before buying; remove it from the mount and look for the cemented joining-line at the edge that is characteristic of the Steinheil loupe. Magnifiers of similar external appearance are often merely two separate, simple lenses. Figure 97*B* shows a suitable mounting for a triple loupe of approximately 16 millimeters focal length.

7. Kellner. Very good in respect to chromatic correction: images on the axis are perfect for beams of focal ratio *f*/6 and a pupil of 3 millimeters. Astigmatism and curvature of field are appreciable, but despite this field angles in excess of 40° are common. This is a widely used eyepiece in prism binoculars and field glasses, and is often available at low cost from vendors of optical surplus in focal lengths varying from 16 to 24 millimeters. Variations in design are many, but all suffer from a small, very bright, and often troublesome reflection.

8. Orthoscopic. One of the most important eyepieces for astronomical work, and one of the best corrected, at least theoretically. The author has examined the product of five different manufacturers, and found all well corrected on the axis, though displaying appreciable field curvature and astigmatism at the edge of the 40° to 45° field. These defects were as pronounced at *f*/20 as at *f*/6, and with pupil diameters ranging from 1 to 4 millimeters. The poorest of the eyepieces showed coma and an appreciable unevenness of chromatic correction that can be attributed only to defective construction. The eyepiece shows many reflections, but these are broad and pale and rarely objectionable. The primary focus and exit pupil are well spaced from the lenses.

The orthoscopic is the eyepiece we recommend for our *f*/6 and *f*/8 standard telescopes. It is available from certain manufacturers in a very extensive series of focal lengths. The author has also calculated a special series (see Section XI-4) for the standard telescope which are highly corrected for the chromatic nonuniformity mentioned earlier.

9. The Plössl Eyepiece. Since the first edition of this book we were able to interest a maker[1] in the commercial production of highly corrected eyepieces of this type, for which we calculated a very complete series (see section XI-4). A long comparative study of Plössl and orthoscopic eyepieces under conditions of special interest to us gave the following results.

Achromatism: Perfect in the Plössl, as in the orthoscopic when the latter is at its best. Edge of the field and star images are free of color. *Spherical correction on axis*; no aberration discernible by the eye in either case, even for the weakest eyepiece. *Astigmatism*: With the eyepiece of 25 mm focal length this becomes perceptible in the Plossl at 15 degrees from the center of the field, equivalent to that at the edge of the field in orthoscopics (19 degrees), but is still moderate at the edge of the field in the Plössl (26 degrees). Visual

[1] From the firm Clavé, 9 rue Olivier Métra, Paris XX. This brand of eyepieces has become very popular since the first edition of this book.

evaluation of this defect is very subjective; minute corneal defects (not detected by present opthalmological methods) play at least as large a role as residual eyepiece errors *per se* when the pupil's diameter is over 3 mm. *Curvature of field*: well corrected in the Plössl. *Reflections*: In the Plossel, an off-axis bright star gives a small, fairly bright reflection. For planetary observation, we recommend that the object not be exactly centered; this avoids the superimposed reflection which can degrade low-contrast detail. The reflection is less serious than in the Kellner but more troublesome than in the orthoscopic. The problem can be eliminated with hard anti-reflection coatings that are feasible on small optics. *Relief distances of the principle planes*: The object focus and the eye point are at 0.73 of the focal length relative to the external lens faces, an advantage in viewing a real object (when using a reticle) and in positioning the eye effectively at the eye circle of the strongest eyepieces. The orthoscopic gives similar eye relief distances.

In summary, compared with the orthoscopics, the Plössls have the advantage of a wider field and the disadvantage of a more disturbing reflection if uncoated. On the other hand, Plössls are more easily produced commercially than orthoscopics. The curvatures are a little less pronounced for a given focal length; but more importantly, the Plössl avoids the more difficult double cementing of the triplet. Finally, the dense flint and barium crown glasses of the Plössls are less hygroscopic than those used in the orthoscopic, which need frequent wiping.

Wide-Angle Eyepieces. We must give at least passing mention to wide-angle eyepieces, though we do not anticipate using them in the standard telescope. Only for certain studies with a so-called *richest field telescope*, which uses a maximum exit pupil (6 to 7 millimeters) and usually a beam of very low *f* ratio (*f*/4 or *f*/5) does one need a highly corrected wide-angle eyepiece. For any other work, eyepieces of this complexity are unjustified. On the question of the maximum field angle that will be of interest to amateurs, opinion is divided. If the field exceeds 60°, it is in the nature of a physical feat to fix the eye on a detail at the margin. But this is a matter each observer must decide for himself. If he is searching for a comet, it is sufficient actually to perceive merely a faint nebulosity, even if imperfectly and indirectly, to be able thereafter to bring it to the center of the field. The following are some wide-angle eyepieces.

10. Erfle. A derivative of the Kellner. Here the eye lens has become two cemented lens-pairs. Astigmatism is considerable, even in the best designs, when the field angle attains 65°.

11. Aspheric-lens type. The nonspherical figure given to one of the surfaces opens up extraordinary possibilities for correction of distortion and astigmatism. For example, in an apparently enormous field of 90°, these defects may be no greater than in an Erfle at 60°. Because of the highly distorted aspherical surface, however, commercial manufacture is very difficult and has not yet resulted in a satisfactory product.

TABLE VIII
EYEPIECE COMBINATIONS WITH FOUR TYPICAL AMATEUR TELESCOPES

	Plossl Eyepieces Focal Length- Field of View	Magnification—Pupil diameter in mm—Field in minute of Arc			
		Standard 8-inch Newtonian		Cassegranian	
		$f/6$	$f/8$	8-inch $f/15$	10-inch $f/20$
50 mm draw tube	75 mm - 36°	N/A	N/A	40- 5 mm - 54′	67–3.8 mm - 32′
	55 mm - 44°	N/A	29–6.9 mm - 91′	55–3.6 mm - 48′	91–2.7 mm - 29′
	40 mm - 48°	30–6.7 mm - 96′	40–5 mm - 72′	75–2.7 mm - 38°	125–2 mm - 23′
27 mm draw tube	25 mm - 45°	48–4.2 mm - 56′	64–3.1 mm - 42′	120–1.7 mm - 23′	200–1.3 mm - 14′
	20 mm - 45°	60–3.3 mm - 45′	80–2.5 mm - 34′	150–1.3 mm - 18′	250–1 mm - 11′
	16 mm - 45°	75–2.7 mm - 36′	100–2 - 27′	188–1.1 mm - 14′	313–0.8 mm - 9′
	12 mm - 45°	100–2 mm - 27′	133–1.5 mm - 20′	250–0.8 mm - 11′	417–0.6 mm - 6′
	10 mm - 43°	120–1.77 mm - 22′	160–1.3 mm - 16′	300–0.7 mm - 9′	500–0.5 mm - 5′
	8 mm - 43°	150–1.3 mm - 17′	200–1 mm - 13′	375–0.5 mm - 7′	626–0.4 mm - 4′
	6 mm - 43°	200–1 mm - 13′	267–0.7 mm - 10′	500–0.4 mm - 5′	833–0.3 mm - 3′
	5 mm - 41°	240–0.8 mm - 10′	320–0.6 mm - 8′	600–0.3 mm - 4′	N/A
	4 mm - 41°	300–0.7 mm - 8′	400–0.5 mm - 6′	N/A	N/A
	3 mm - 41°	400–0.5 mm - 6′	534–0.4 mm - 5′	N/A	N/A

12. Bertele. This gives a field up to 80° wide, though using only spherical surfaces. But the thickness of the field lens is almost as great as the total focal length, and the eight air-glass interfaces make a good antireflection coaing obligatory for any astronomical work. Maurice Paul, in bringing this eyepiece to our attention, mentions the interesting possibility it offers for correcting coma in wide-aperture mirrors ($f/4$) as far as 1° off the axis, where the aberration normally becomes quite serious.

XI-3. The Barlow Lens

This is a *concave lens* which is inserted at an appropriate distance D from the focal plane F from the objective (Fig. 98). As a result, the emerging beam

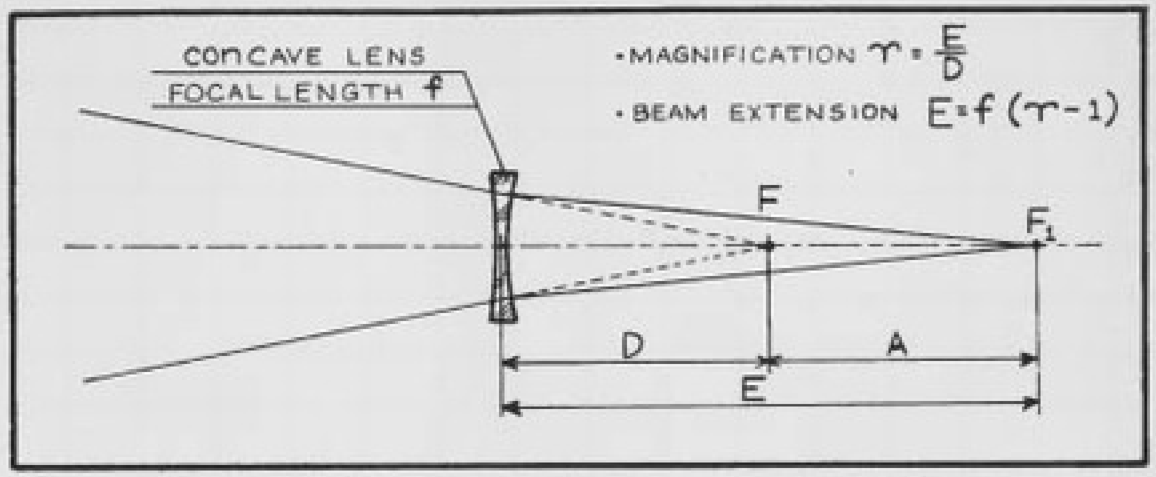


Fig. 98. Insertion of a concave lens in a converging light beam.

converges at F_1, and its relative aperture is less than that of the primary beam. Let E be the distance between the lens and the resulting image at F_1. The magnification γ of the image due to the lens, which has the same effect as the convex secondary in the Cassegrainian, is given by $\gamma = E/D$. If the focal length of our Barlow is f this magnification corresponds to an image projection distance $E = f(\gamma - 1)$.

We can use a Barlow lens that is small in diameter and of short focal length f without sacrificing the field of ordinary eyepieces. This greatly increases the focal length of an instrument with only a slight change in the eyepiece section and with practically no increase in overall telescope length. An extendable eyepiece tube could even allow continuously variable magnification with a single eyepiece; however, we must be mindful of aberrations. Chromatic aberration introduced by a single-element lens would be tolerable when associated with an under-corrected refractor objective. However, for use in a reflector, it is essential that the lens be achromatic and corrected for spherical aberration. Maurice Paul has given a formula[2] for a lens which also corrects for mirror coma, for beam widths not exceeding $F/D = 5$. This is a

[2] Systémes correcteurs pour Réflecteurs Astronomiques, "Revue d'optique, Vol 14, No. 5, May 1935.

Clairaut cemented aplanatic doublet which has been manufactured and made available commercially at our request by the firm Clavé since 1955. This 25 mm diameter lens, with a clear aperture of 23 mm, is mounted to slide into an drawtube of 29 mm O.D. and 27 mm I.D., slightly longer than the standard (Figure 99). The distance E is equal to the 113 mm focal length of the lens. The fixed magnification γ is therefore essentially 2 for any of the associated eyepieces. The focusing action is exactly the same as with a classic drawtube using a simple eyepiece. To preserve the perfect spherical correction of the lens,the prescribed distance E and the magnification of 2 must be adhered to, but experience shows that especially in photographic applications the value of γ may extend to about 4 without serious detriment.

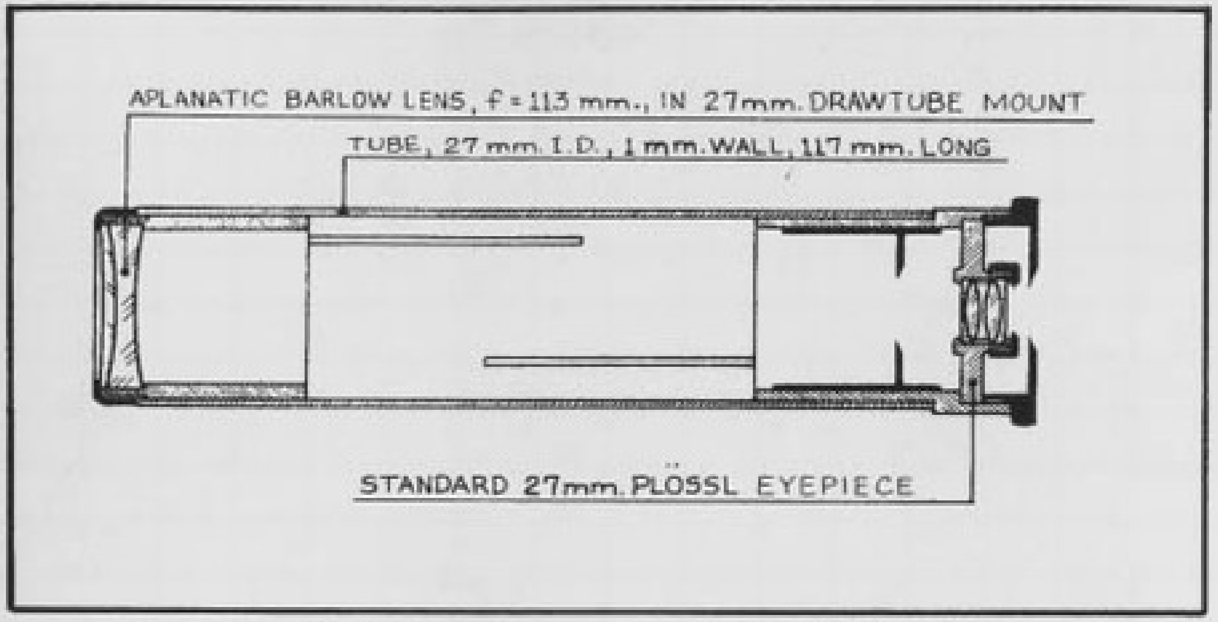


Fig. 99. Mounting for the standard Barlow lens.

The Barlow lens is especially useful with Newtonian telescopes of relative aperture F/D between 5 and 8. Here is why: first, the eyepiece receives a beam whose relative aperture has been reduced by a factor of two and therefore operates under much more favorable conditions. The excellent correction of the Plössl or the orthoscopic eyepiece is of course still preferable, but a simple Ramsden becomes quite acceptable on a telescope of $f/7$ when extended to $f/14$ by the Barlow. The correction for off-axis coma of the paraboloid is equally beneficial for images viewed in the field of relatively weak eyepieces.

Secondly, a given enlargement is obtained with an eyepiece of twice the focal length. This is distinctly an advantage for high magnifications, since very strong eyepieces ($f = 3$ to 5 mm) that would otherwise be needed must not only be of high optical quality, but they are rather disagreeable to use because of the precautions they require. The eye must be well-centered and very close to the eye lens in order to see the entire field. But then the eyelashes soil this very small lens, which must be kept meticulously clean.

Thirdly, the Barlow immediately puts two telescopes at our disposal: without the Barlow we have the classic Newtonian, which is still best for low

magnifications and the large pupil needed to observe nebulae and comets. Used with the Barlow, the Newtonian is comparable to the Cassegrainian, which is ideal for planetary observation and the resolution of close double starts.

Fourth, the cost of a Barlow is only about half that of a Plössl eyepiece and doubles the number of magnifications available with any given series of eyepieces. Useful families of eyepieces used with a Barlow are examined in Table VIII.

The disadvantages of the Barlow are minimal. The hard anti-reflection coating applied to the two surfaces in commercial production makes light losses practically negligible. Aberration due to possible decentering of the

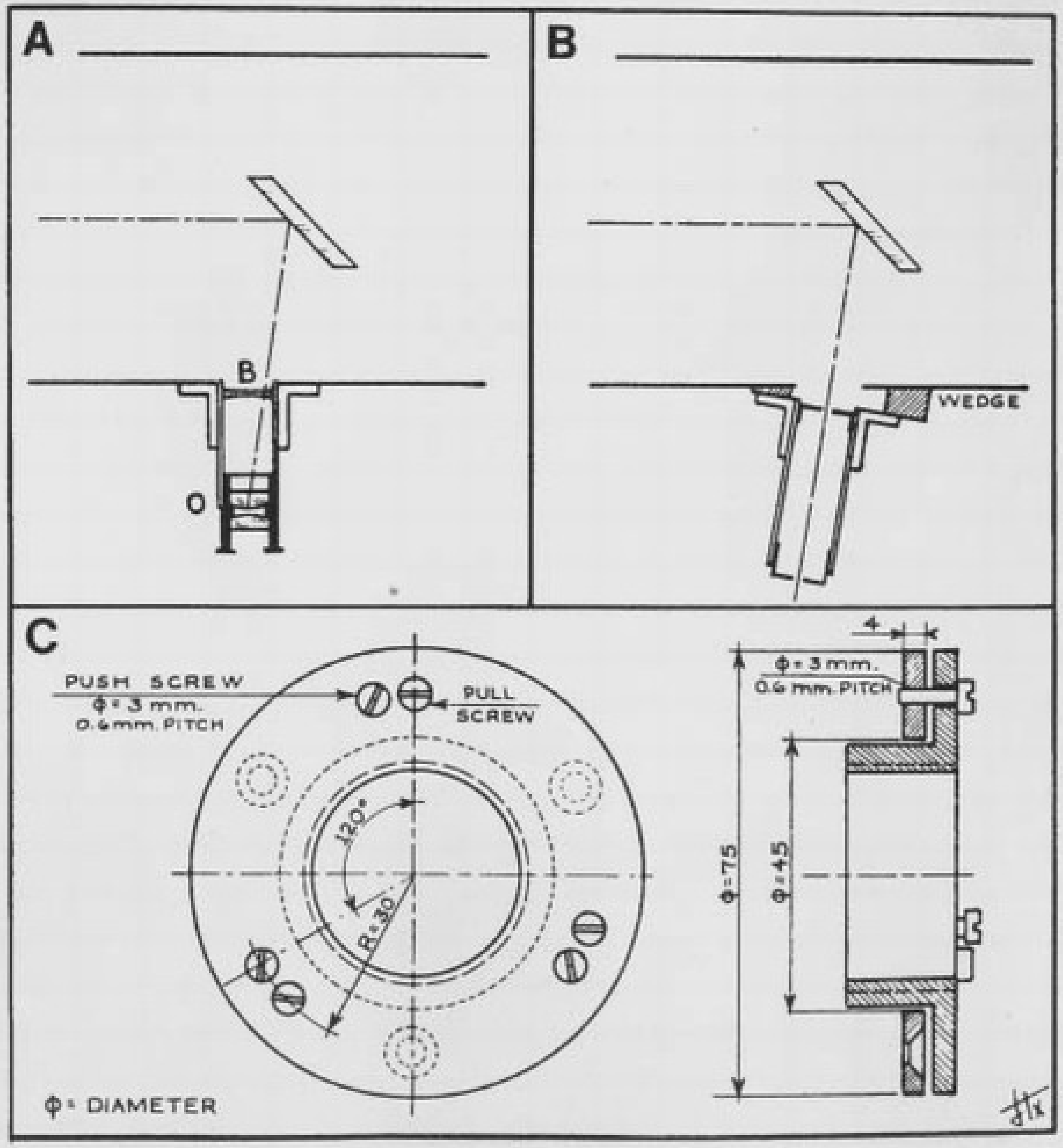


Fig. 100. Aligning a Barlow lens eyepiece mount.

Barlow must be avoided by very careful adjustment of the eyepiece mounting. Figure 100*A* is a very exaggerated illustration of faulty positioning of the support flange. Although the telescope can still be aligned if the eyepiece O alone, is corrected, and only slightly inclined with respect to the optical axis, the defect would not go undetected with an appreciably decentered Barlow.

In Figure 100*B* the fault is corrected by inclining the mounting, this being much easier than trial-and-error determination of the correct flange position accompanied by constant readjustments of the diagonal mirror angle.

The inclination adjustments can be with an arrangement of 6 push-pull screws coupled to a collar mounted on the tube (Fig. 100*C*), or more simply by inserting a wedge under the conventional mounting (Fig. 100*B*). Parallelism of the eyepiece tube with the axis can easily be checked by removing the eyepiece optics and temporarily replacing them with two holes 1/16 to 1/8 inch diameter positioned at the two ends of the Barlow tube (Fig. 100*B*). Starting with the telescope normally aligned (Section XIV-1), the eye is positioned at the eyehole. If the diaphram opening at the far end is of the right diameter, it frames the image of the diagonal's silhouette when the drawtube is parallel to the axis; otherwise an adjustment must be made on the screws or the wedge angle. When the inclination is substantial, it may help to make a second adjustment on the inclination of the primary mirror. This adjustment is made while observing a star at high magnification, with the Barlow.

XI-4. Standard Series of Plössl Eyepieces.

The eyepieces of 3 to 25 mm focal length are dimensioned for a sliding fit in the standard of 1.25-inch I.D. mounting.

The mountings of these standard eyepieces are designed to minimize focal adjustment as much as possible when eyepieces are changed (Fig. 101). The shift in focal setting between the 3 and 25 mm eyepieces is not more than ½ inch.

For low magnifications on the Cassegrainian a second standard drawtube had to be created to maintain a useful field width. These large eyepieces of 40, 55 and 75 mm focal length are slip-fitted into a drawtube of 2-inches diameter I.D. (Fig. 102). Normally, these would not be used on a Newtonian; however, the firm of Clavé has produced a capstan focusing mount which accepts the two drawtubes, permitting observers specializing in very faint objects to use the Newtonian with the lowest possible magnification, assuming that the diagonal flat is properly dimensioned (See Section I-5). Where possible, preference should be given to Plössls with anti-reflective coatings on the four air-glass surfaces, which eliminates the only disadvantage of the design compared with the orthoscopic. Table VIII, gives the *magnifications, the diameters of the eye ring or exit pupils in mm, and the field in minutes of arc* obtained when these eyepieces are mounted on four different amateur instruments: a standard 8-inch $f/6$, $f = 1200$ mm; a standard 8-inch at $f/8$,

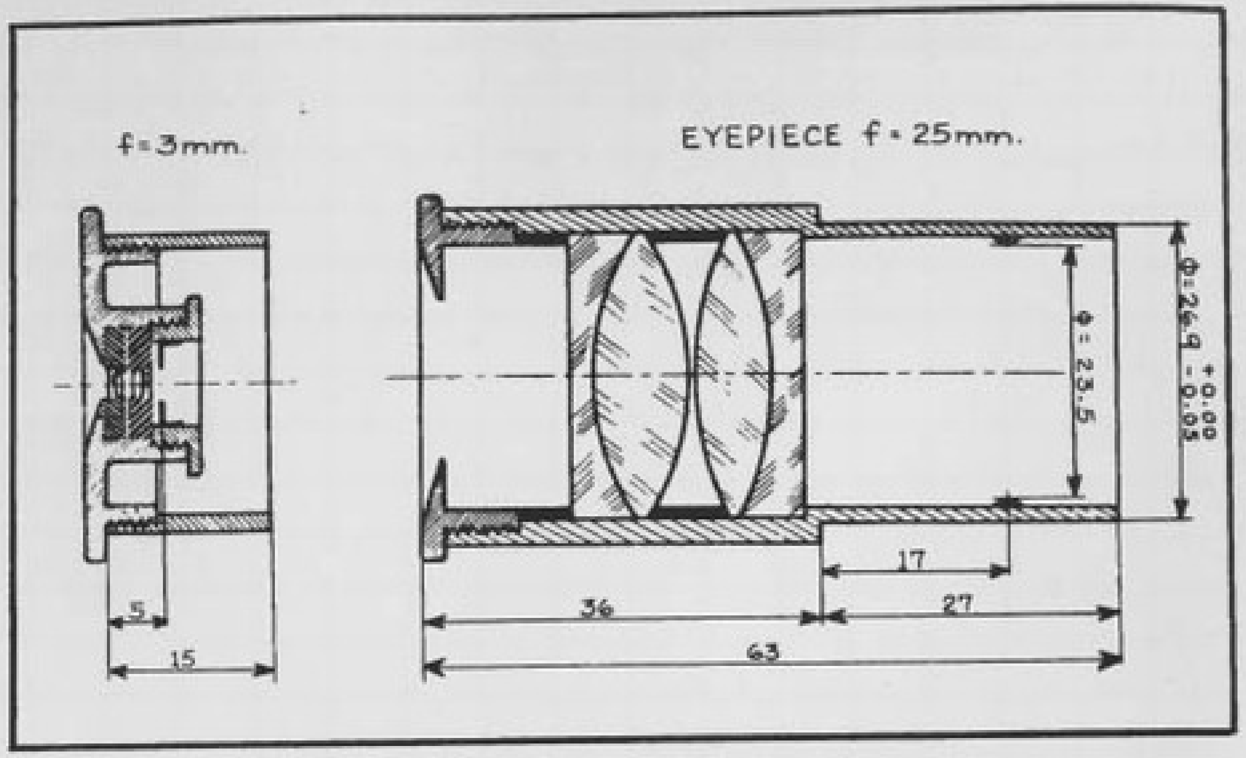


Fig. 101. Plössl eyepieces for the standard telescope.

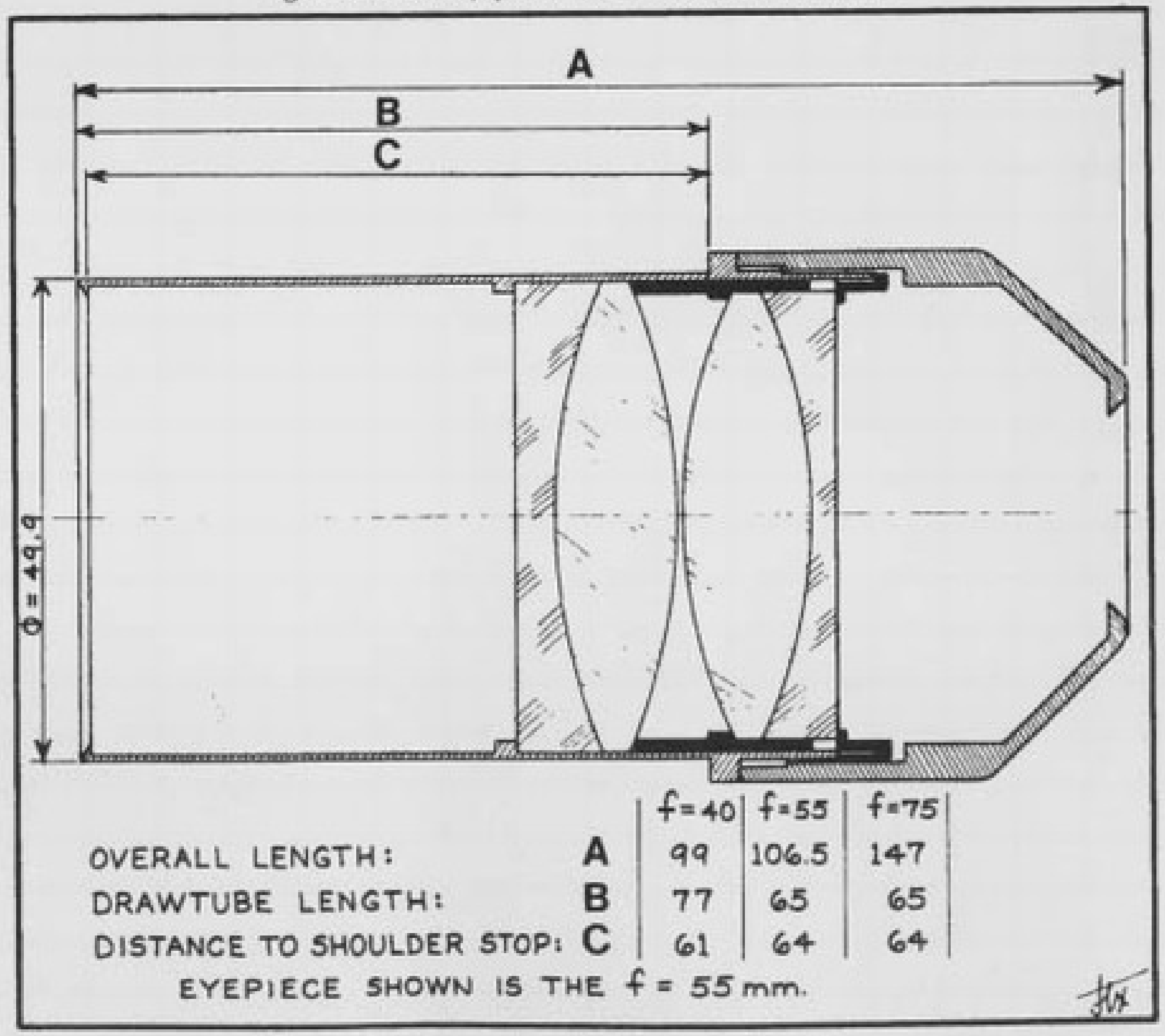


Fig. 102. Plössl eyepiece for Cassegrainian telescopes.

$f = 1600$ mm; a 8-inch Cassegrainian or refractor at $f/15$, $f = 3000$ mm; and a 10-inch Cassegrainian $f/20$, $f = 5000$ mm.

Naturally, it is unnecessary with a given instrument to have the complete series. Another error would be to select regularly spaced magnifications. Those magnifications should be selected which will be truly useful, remembering that the number of available magnifications is effectively doubled by the Barlow lens—an extremely important advantage for the standard telescopes. A practical assortment should always include the lowest magnification ocular that mounts in the available drawtube, i.e., the 1¼ for the standard. This eyepiece is needed because its wide field allows an object to be easily located and centered. It is also useful because the pupil will be large enough for studying faint objects: nebulae, comets and diffused luminous regions. One should then have a working eyepiece that allows effective visual exploitation of the instrument, i.e., having a pupil of somewhat less than 1 mm diameter and a magnification of about 250 on a 6-inch instrument. This eyepiece is suitable for study of planetary surfaces. Because the problem of turbulence is so variable, it is useful to have a more complete assortment bracketing this value in fairly close steps. Naturally, on a powerful instrument where, despite the problems involved, one expects a good image with a pupil of 0.8 and 0.6 mm, the assortment must include intermediate magnifications to cope with viewing conditions. In a long-focus telescope designed for planetary use, the choice of magnifications is limited. Often a value too high or too low by 30 or 40 in the range of about 250 or 300 translates into a noticeable loss when viewing low-contrast details.

Magnifications 70 to 150 are of limited interest on 6-inch telescopes except for variable star observers who want a wide field to see reference stars yet avoid large pupils which could create gross error in oblique vision. The large magnifications correspond to pupils of 0.5 mm or less. Pupils of less than 0.3 mm are not useful: the brightness is insufficient for viewing the middle tones of planets, and for a 6-inch or larger aperture, turbulence will often be a seriously limiting factor. These high magnifications are mainly useful for easy viewing of the star diffraction pattern, needed for careful centering (Section XIV-1) and for the separation and measurement of close double stars.

In summary our examples of rationally selected sets of eyepieces, subject to modfication for specialized interests, are the following:

1. *Standard 8-inch telescope*, $f/6$: a Barlow lens; a Plössl $f = 25$ (M = 48 and 96); and $f = 5$(M = 240 and 480); supplementary eyepieces: $f = 6$ (M = 200 and 400) and $f = 4$(M = 300 and 600).

2. *Standard 8-inch telescope*, $f/8$: a Barlow lens; a Plössl $f = 25$(M = 64 and 128); an $f = 6$(M = 267 and 534); an $f = 8$(M = 200 and 400).

3. *A 8-inch Cassegrainian or refractor* $f/15$: a Barlow lens; a Plössl, 50 mm draw tube, $f = 75$(M = 40); Plössl, 27 mm draw tube; $f = 16$(M = 188); $f = 12$(M = 250); $f = 10$(M = 300); $f = 8$(M = 375); $f = 6$(M = 500).

4. *A 10-inch Cassegrainian* $f/20$: a Plössl, 55 mm draw tube, $f = 75$(M = 67); Plössl, 27 mm draw tube: $f = 25$(M = 200), $f = 20$(M = 250), $f = 16$(M = 313), $f = 12$(M = 417), $f = 10$(M = 500), $f = 8$(M = 626).

5. *A 12-inch Cassegrainian*, $f/50$: A very specialized instrument with minimal obstruction for planetary observation: Plössl, 50 mm draw tube: $f = 75$(M = 200), $f = 55$(M = 273), $f = 40$(M = 375;), Plössl, 27 mm draw tube, $f = 25$(M = 600). For this last instrument the Plössl series is still inadequate; it should include in addition an $f = 62$(M = 242), a $f = 45$(M = 323), a $f = 35$(M = 429) and an $f = 30$(M = 500).

THE EQUATORIAL MOUNTING

XII-1. General Discussion

At the celestial equator the diurnal movement shifts the star positions by 15 minutes of arc in only a minute of time. Thus, even in a Plössl eyepiece with an apparent 45-degree field, the real field of view is reduced to 13 arc minutes when the magnification is 200X. After centering the object, focusing and

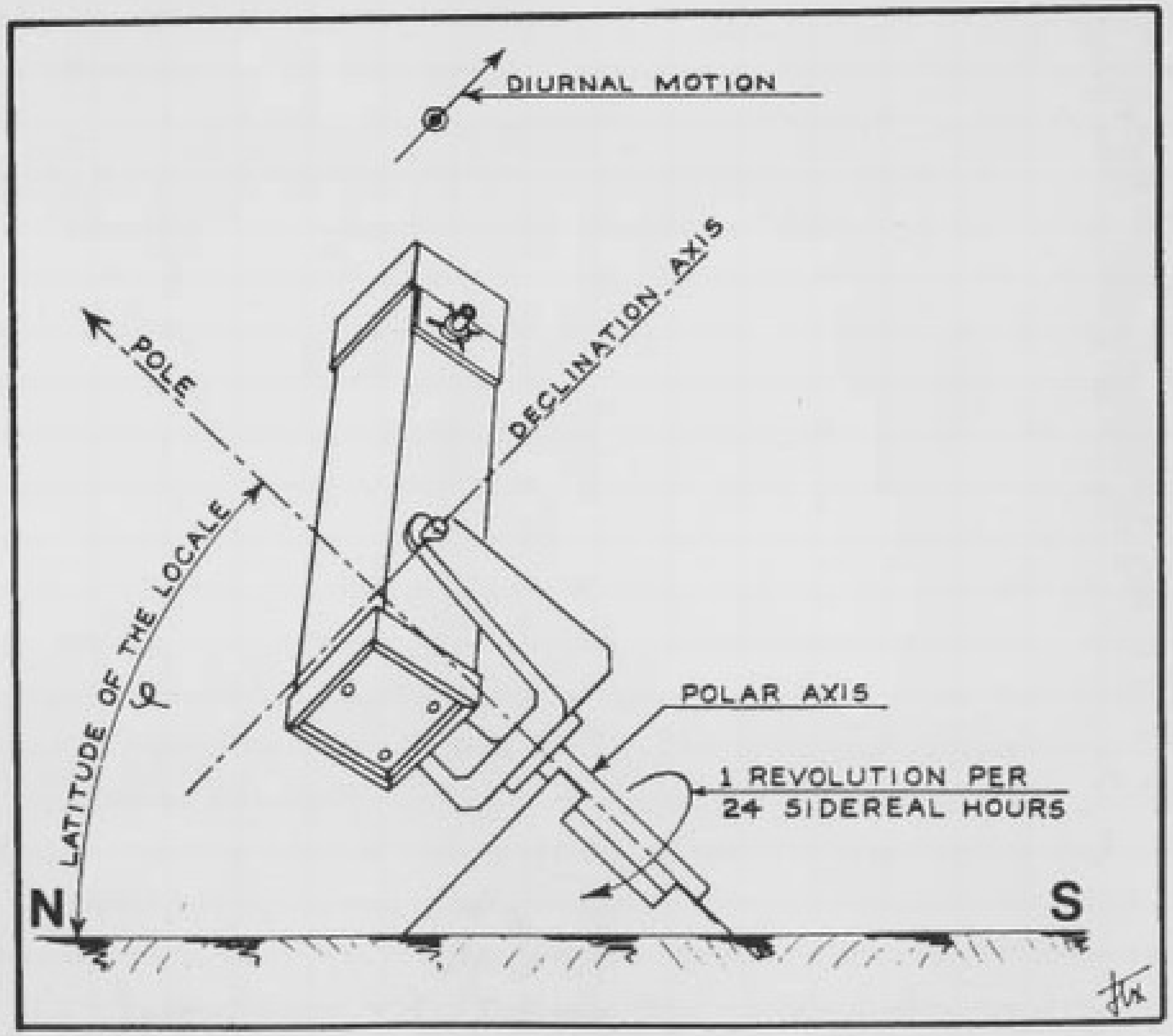


Fig. 103. Principle of the equatorial mounting.

waiting for damping of the vibration, *only a scant 15 seconds remain for actual observation*. It is a sorry observer who lets the object slip out of the field of the standard azimuthal telescope: he has to adjust *two* independent motions to re-aim the instrument, and recourse to the finder is therefore unavoidable. One would have to be very determined to build a long-focus planetary instrument under such circumstances. The Dobsonian altazimuth mounting which is held only by friction, is a more felicitous arrangement, the observer need only push the instrument in the direction of the objects motion. However, even simple photography at the focal plane, is limited to exposures of a fraction of a second. Understandably, the user of an 8-inch, even if not especially ambitious will in short order want to be free of this limitation, which become almost intolerable at magnifications of 400 or more. The justifications for the altazimuth mounted telescope are primarily practical namely ease and economy of construction, and transportability. We shall see that a host of problems confront us once we depart from this design.

Theoretically, an *equatorial mounting* is simple (Fig. 103); we need only to incline the ordinary altazimuth; the azimuthal axis, originally vertical, should be at an angle above the horizon equal to the latitude of the locale and oriented in the plane of the meridian, its upper end pointed north for those in the northern hemisphere. Briefly stated, this axis is pointed toward the celestial pole, hence its name *polar axis*. It is therefore parallel to the earth's rotational axis and we need only to counter-rotate the telescope around this axis at the rate of one revolution per sidereal day. This will immobilize the entire sky with respect to the instrument. The other axis of the mounting, perpendicular to the polar axis, is the *declination axis*. It is used only to aim at the object at the start of observation, and is not again adjusted during observation if the equatorial mount is properly aligned.

In practice the complications mount rapidly because the new instrumental capabilities bring on new requirements and new problems. A precise clock drive is shortly recognized as indispensable. Next, one must have setting circles for locating faint objects. Finally, there is long-exposure photography which immediately discloses a world of new problems which one fine day demands revision of the entire instrument. Almost invariably, the importance of a rigid mounting, and smoothness and precision of the clock drive, is at first underestimated. These difficulties in no way derive from the principle of the equatorial as such; they would apply in the same degree if we transported an azimuthal to the north or south pole so as to avoid any mechanical modification. There are some ingenious solutions for mechanical coordination of the azimuthal motions, to avoid the cost of the equatorial. Such fixes are of little more than passing interest: they are more complicated, fussier to adjust, harder to implement with the precision of an equatorial, and finally, unable to compensate for large rotations of the field during long exposures.

But this is not all; the equatorial, built with the precision appropriate for its capabilities becomes a heavy, nearly un-transportable object. There is then

the question of searching out a suitable location—corner of the garden, or a terrace, even a simple window opening in the right direction. The locale should permit good visibility in all directions, a concrete foundation should be poured, and a shelter built with a mobile roof, if not an actual cupola. Sometimes, for lack of alternatives, one is content to use a terrace or to adapt an attic; but finally, it seems a veritable observatory will be needed for the full enjoyment of the equatorial.

Many colleagues are undaunted by all this. Nevertheless, the questions raised, the second thoughts, and the errors committed that might be easily avoided show that it will help us to examine critically a number of the possible alternatives in equatorial design. We do not believe in a standard equatorial design that can be adopted by a large number of amateurs. The amateur's technical skills, habits, and available machine tools are simply too variable.

An office worker would rarely have access to a fully equipped workshop. He would adapt such machined parts as he can locate, and avail himself of outside help. The amateur who is a professional cabinetmaker or carpenter would prefer a design in wood, whereas a virtuoso welder might like a finely constructed assembly of welded sheet metal. A favored few will not shrink from the work of pattern making and machining necessary to make large castings, which alone can guarantee rigidity for certain types of mountings. Though we cannot offer a plan adapted to each amateur's means and ambitions, it is useful to discuss the principle types of equatorials and to note their various limitations. The varied styles of the many effective instrumetns built by our colleagues demonstrate how useful personal initiative can be.

XII-2. Principle Types of Equatorial Mountings

The following lettered sections A, B, C etc. refer to corresponding illustrations in Figure 104, the declination axis in each case is the *δ axis* and the polar axis as the *α axis*:

A. *Cradle, Yoke, or English Mounting*.—This design is attributed to Ramsden (1791). The instrument is supported in a closed frame or cradle. The load is therefore supported between the bearings of both the polar and the declination axes. *All off-axis loading is eliminated*, a decisive advantage for rigidity of the structure, which should be the primary concern in any mounting design. An incidental advantage is that the trunnions may be smaller in diameter, *thereby reducing friction*, and favoring a smooth, precise drive. To balance an equatorial, the center of gravity of the entire moving assembly must be positioned at the intersection of the axes. (Or, where this cannot be done, as in the case in an offset mounting (B), balance is obtained separately on two centers of gravity respectively on the two axes). The cradle mount is balanced *without a main counterweight*, therefore without the added weight that is always undesirable with regard to flexure and vibration.

Because it is inherently stable, the cradle equatorial can be built with various simple, conveniently available materials without serious disad-

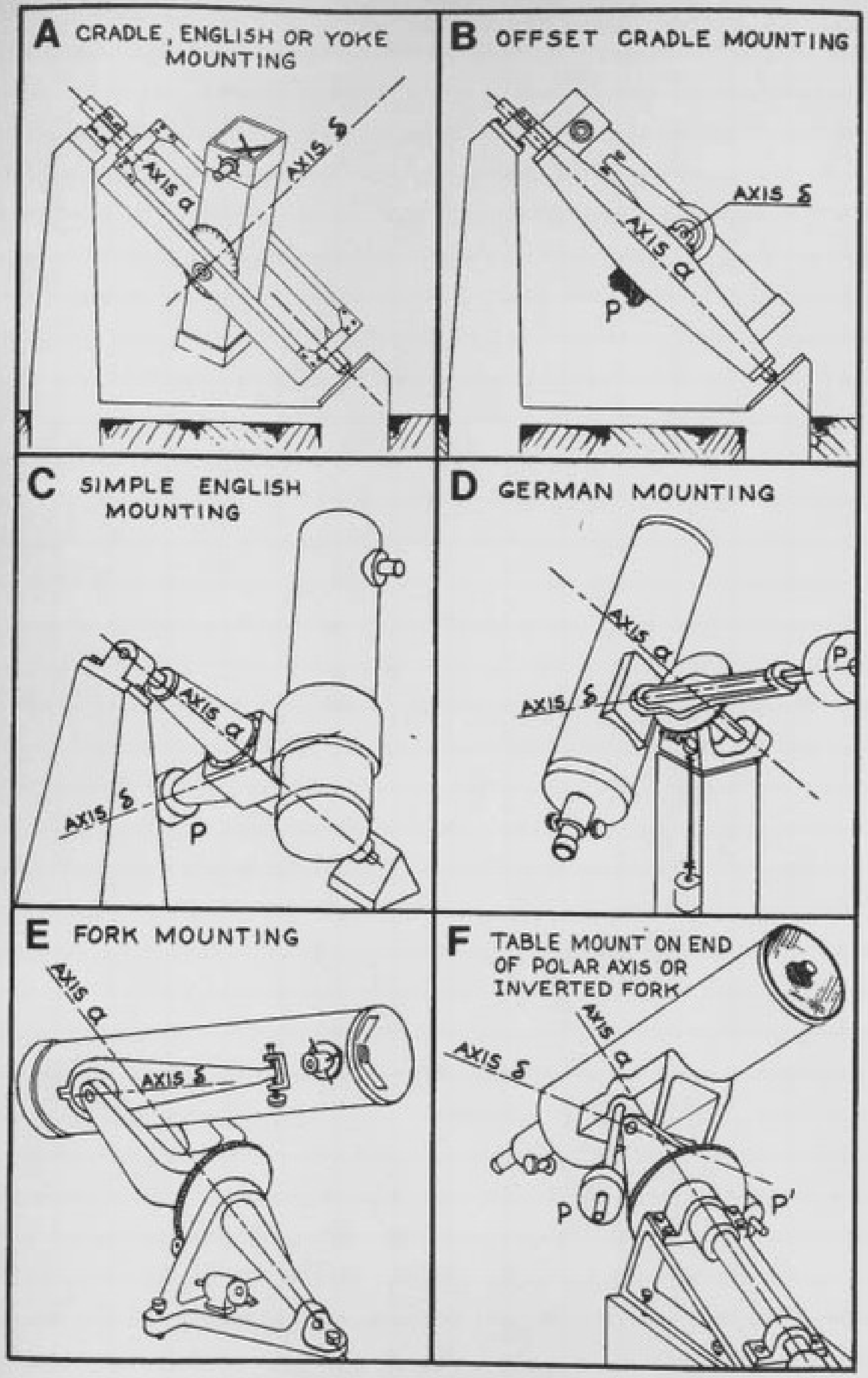


Fig. 104. Principal types of equatorial mountings.

vantages (Section XII-4). Large dimensional errors or poor mechanical detailing do not necessarily spell disaster as they would in a German or a fork mount, for example.

Consider now the disadvantages. First, the *considerably larger overall size,* which makes a fixed installation in an adequate setting almost obligatory. The north and south support pillars are sometimes made of metal, and can be erected in an attic, but masonry-reinforced concrete or brick is less expensive and more stable. Further, the cradle mount *does not permit viewing of the pole* and its vicinity because of interference by the north cross-beam and its support. This disadvantage is a minor consideration in the work of most amateurs. We wonder how many amateurs may have rejected the cradle mount for this reason and actually gone onto study the polar sequence or rare objects of some consequence at very high declination. Amateurs are all familiar with the very distinctive cradle mount of the Hale 200-inch on Mount Palomar, where the north cross beam is replaced by an enormous horseshoe to allow optical alignment of the instrument with the north celestial pole. At the time the Mount Wilson 100-inch, built with an ordinary cradle, was being used, there were complaints about the impossibility of viewing the polar sequence. We are not sure that the same argument would prevail today and justify the added expense of a horseshoe design.

B. *Offset Cradle Mount.*—The polar region is made accessible here by means of a special cradle with bearings sufficiently offset from the polar axis. The arrangement is not difficult to build and even mounting of the declination bearings is easier. The basic advantages of the closed cradle are retained, but a counterweight P is necessary for equilibrium with respect to the polar axis. This is no serious disadvantage because the cradle can be quite rigid despite the effectively doubled load. Figure 111 shows a variation on this design comprising two telescopes, balanced in this case with respect to a declination axis which intersects the cradle axis.

C. *Simple English Mounting.*—In this design by Sisson (1760), the polar axis is a beam whose two ends, in the form of trunnions, rest on the north and south bearings. The declination axis is supported by bearings mounted on the polar axis, generally not far from the center. The polar axis is not cantilevered, but the telescope is cantilevered on the declination axis. Because of this, *a well conceived and executed mechanical design is essential.* A counterweight P is needed on the declination axis. This will not excessively vibrate if it is supported on a sturdy conical extension arm instead of simply being threaded onto the end of the declination spindle. This form of equatorial, like the cradle mount, permits following any object near the meridian without difficulty. It is as suitable for a Newtonian as for a Cassegrainian or a refractor; all that may differ is the height of the support piers. In general, an object can be viewed with the telescope in either of two positons, i.e., on the east or the west side of the polar axis, after *rotation* by 180 degrees on both axes. This type of equatorial can easily be constructed by the modestly equipped amateur (Figures 112 and 113).

D. *German Mounting.*—This was conceived and built (about 1815) by Fraunhofer for use with heliometers, then for the 240 mm equatorial Dorpat (1824), made famous by the measurements of double stars by W. Struve. The upper end of the polar axis carries a tube which supports the declination bearings. The telescope is mounted at one end of the declination axis. *This double cantilever is very unfavorable for rigidity* and the counterweight P at the end of the declination axis is hardly a help in damping the vibration. To reduce the mass of the counterweight and flexure in the support for the declination bearings, it helps to position the telescope as close to the polar axis as possible. Unfortunately, this also reduces the diameter of the clock drive gear and therefore the precision of the polar movement. The German mounting, which was intended originally for visual refractors, has another irritating fault: for certain positive declinations *the instrument cannot cross the meridian* without bumping into the supporting pier. For visual work, this is not very serious; the polar axis is simply rotated around the pier and the object is then picked up again by adjusting the declination axis. This cannot be done, however, during a long photographic exposure because the plate itself would have to be rotated 180 degrees relative to the field. In practice, the cross-section of the pier cannot be made small enough to reduce this problem; one would have to devise an elbowed pier which would always be a source of vibrations that are very difficult to damp out. It is best to dismiss the German mounting for long-exposure photography. Despite all these deficiencies, this is probably the most popular of mountings, even among owners of Newtonian telescopes. This can be explained by a certain tendency to conform, and perhaps by the relative ease of improvising the mounting from existing machine parts, such as a lathe headstock that provides a base and polar axis (Figure 120). Such arrangements are almost always makeshifts that have to be compensated for by considerable skill and patience on the part of the user.

E. *Fork Mounting.*—This elegant solution has two points of obvious weaknesses: the extremely cantilevered end of the polar axis, which requires a very large cross-section for the north bearing, and the fork itself, which cannot be made rigid enough except by an expensive design. On the other hand, there is *no counterweight and no need for rotation,* and further, *the overall size is reduced,* this being particularly valuable in a semi-fixed installation (Figures 117 and 121). The most favorable application is the mounting of a Newtonian of modest size, such as a 8- or 10-inch, where the center of gravity is rather close to the end of the tube weighted by the main mirror. In this case, when the instrument crosses the pole the eyepiece is not too high for comfortable viewing, and the fork is not overly cantilevered. In any event, it is best to base the construction on carefully designed castings and a large polar axle rather than on the assembly of iron beams supported on too weak an axle.

F. *Mount With Table Atop The Polar Axis or Inverted Fork.*—The equatorial fork mount described in the preceding section would not be practical with a Cassegrainian where the eyepiece would often need a right-angle prism for accessibility. A short fork can be built to support a table offset from the declination axis. This arrangement is fairly practical for the observer except in the vicinity of the poles. *Unfortunately, it requires counterweights* P and P′ which act as vibrators. The designer Meyer of Carl Zeiss had many mountings of this type made. They had a complicated axial load relief arrangement that was a source of vibrations. The design has fallen into disuse. The Belgium Astronomical Society published an article in 1943 giving a detailed design for an equatorial of this general type made with welded tubing and iron beams.[1] Our colleague J. S. Dubois mounted his 260 mm Newtonian on the prototype of this mounting (Fig. 123). Despite this rather successful example, and the great convenience of ready-made detailed drawings we know of no other instrument made to this design.

XII-3. Designs to be Avoided

Access to the eyepiece of a 10-inch or larger Newtonian equatorial is often awkward, and prolonged observation soon becomes stressful, particularly for long photographic exposures in cold weather, because the operator is rather poorly protected. The search for a more comfortable design is, in itself, entirely justified. There is always the tendency to consider using flat mirrors at an oblique angle of incidence. In practice, we advise against all such systems, but this opinion requires an explanation. The amateur instrument, say of 8- to 12-inch aperture, still has a theoretical resolving power that can truly be fully exploited in practice. Despite the effects of turbulence (Chapter XV), it pays to equip it with *perfect optics,* but perfect optics as we understand them are hardly obtainable, according to A. Danjon and A. Couder (Section II-41), except for *very simple* instruments: Newtonians, Cassegrainians, or $f/15$ refractors. We still consider the complication of adding a telescope window worthwhile, but do not accept the intervention of a large oblique mirror, though the flat is theoretically even more *neutral* optically than the window. It is the physical properties of such mirrors which cause difficulties. In use, the mirror is never, to a useful approximation, in good thermal equilibrium with its surroundings. It cannot maintain the perfect correction that was presumably obtained in the workshop. If the residual strain is regular, i.e., centered on the contour, and increases from the center to the edge without anomalies, then at any point on the cross-section a distance h from the axis the thermally induced change of optical path length Δ may be represented by the expression:

$$\Delta = ah^2 + bh^4 \qquad (95)$$

[1] André, Le Télescope S.B.A., "Ciel et Terre," LIX, Nos 1-2 Jan.-Feb 1943.

The *a* term corresponds to a change in radius of curvature, which the observer, absorbed in adjusting the focus as he awaits the fleeting moment of abated turbulence, will not even notice. The term *b* introduces spherical aberration, but this is usually of no consequence in a small telescope. But on a plane mirror obliquely reflecting the beam, it is the *a* term which quickly becomes detrimental. The mirror is no longer flat and *the resulting beam is astigmatic* (Section III-5). This is not a small matter for only the paranoid to fret about: thermal drift of the order of 1°C per hour is enough to cause a disturbing degree of astigmatism in an 8-inch beam reflected at 45 degrees from a 12-inch flat. Disks made of fused silica or the more recent special ceramics will of course reduce this effect considerably. But aside from their very high cost, we must remember that defects of surface figure show up as quadrupled defects in the wavefront compared with the same defects on a window or lens. Very careful surface figuring is necessary if appreciable aberration is not to be added to the system. Even then, the ensemble will be *much more vulnerable* in general to optical perturbation than a straightforward Newtonian pointed high in the sky. Based on experience, we would formulate the following conclusion: *It is always better to stay with a small, simple instrument (for example, a standard 8-inch) than to devote enormous effort building a stationary instrument (for example, a 16-inch coelostat design) from which it would be very difficult in practice to extract performance equaling that of an 8-inch.* We concede, of course, that coelostats and coudé telescopes are interesting and even indispensable *for other astronomical purposes,* where attaining theoretical resolution is no longer the primary concern, such as when using large spectrographs. Our only concern here is to dissuade amateurs from blindly copying professional installations in which the design objectives were very different from their own. Let us, however, look at several arrangements that improve convenience or comfort for the observer at the cost of various disadvantages:

The coudé Cassegrainian, already examined in section VI-3, is very practical and entirely acceptable. The auxiliary flat is too small and too close to the focus to cause problems such as those just discussed. The only annoyance in the system is the non-conforming image, this being reversed with respect to the object because of the odd number of reflections. To avoid this reversal we cannot replace the flat with a roof prism perfect enough to avoid any doubling.

The double coudé Cassegrainian, also examined in Section VI-3 and illustrated schematically in Figure 67, is likewise not a risky design for dimensions of the usual amateur instrument. The image conforms to the object but turns in front of the observer both with rotation around the polar axis and around the declination axis. An inclined seat fitted with a head-rest is needed to take advantage of the fixed eyepiece at medium latitudes. The principle disadvantage of the system is the *need to project the focal plane much farther behind the main mirror* than in a ordinary Cassegrainian. This

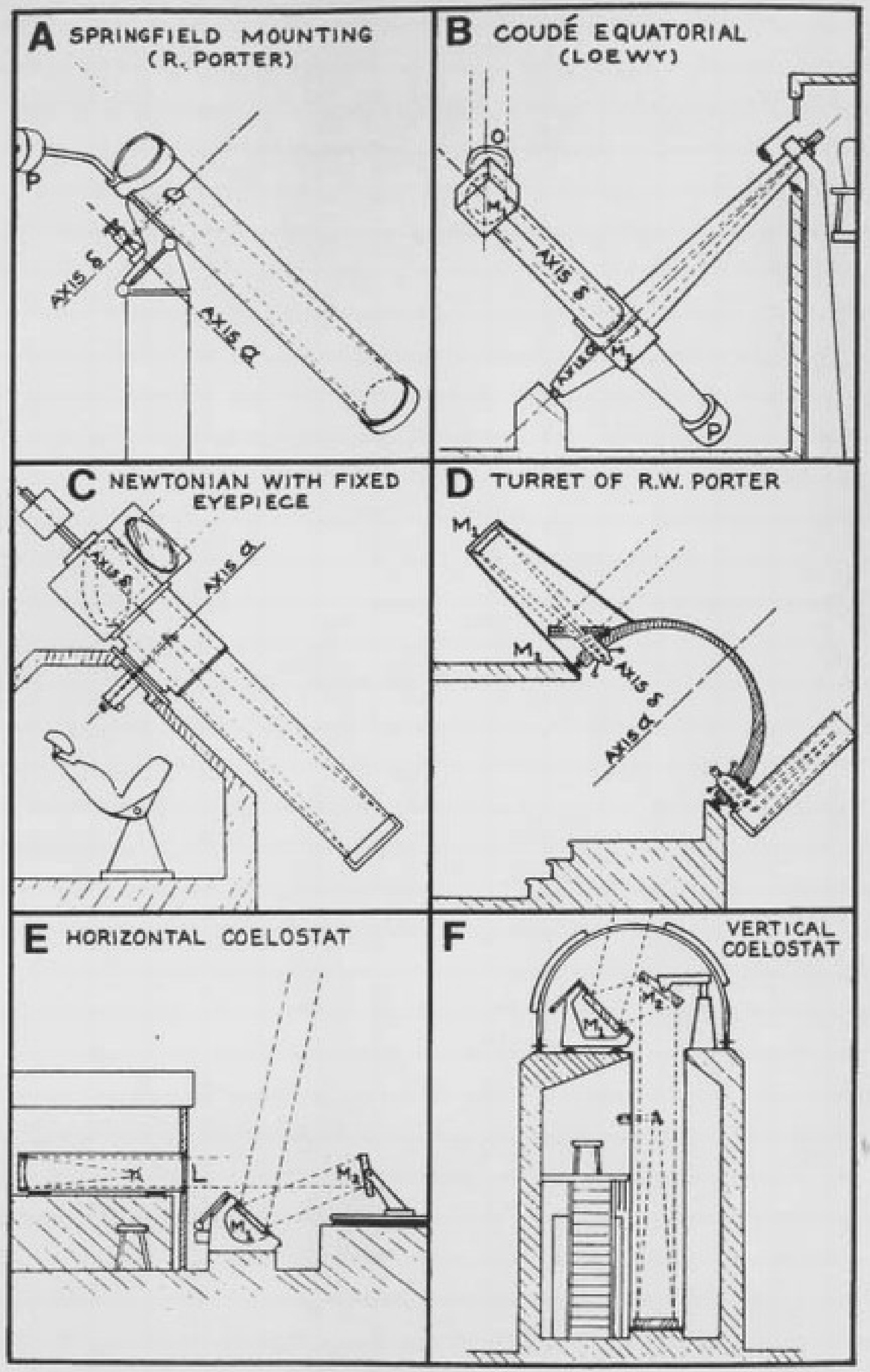


Fig. 105. Designs to be more or less avoided.

means that we must either enlarge the obstructing diagonal or increase the effective focal length.

Figure 105 illustrates other designs that are at least unusual:

A. *Springfield Mounting.*—This design by the late R. W. Porter has been used rather widely among American amateurs, and is a very acceptable design if well constructed. The Newtonian telescope is far off-center with respect to the declination axis, the latter coinciding with the axis of the beam reflected by the classic diagonal. A second flat or a prism, very close to the eyepiece, reflects the beam a second time at right angles, making it coincident with the polar axis. The observer is stationed at a *fixed and convenient position* as though before a microscope. The *increase in obstruction* by the larger flat, needed for the extended, elbowed beam, is considerable. *The image is reversed* so that the novice has to make copies of his reference charts and view them in reverse on a light box. In addition the image rotates both with declination and right ascension. The extremely cantilevered tube requires an *elbowed counterweight* P, which is a disconcerting presence behind the observer's head and is difficult to adjust because it compensates simultaneously for both axes. Overall, the instrument is mechanically *less stable* than a classic equatorial. American amateurs generally adopt a 6-inch aperture and the stability is good. The stability of the few 12-inch telescopes mounted in this manner is open to question.

B. *Equatorial Coudé.*—Loewy conceived this design that was first built in 1882 as a large instrument. It was a refractor in which the objective O and a 45 degree flat mirror M_1 were supported by a tube rotatable in declination. A smaller, second 45 degree flat, M_2, redirected the beam along a very stable polar axis. *The observer was sheltered* in a heated room. The flat mirrors, necessarily large, were fortunately enclosed in the tube. Despite this, astigmatism due to thermally induced curvature, principally in the first mirror, was usually substantial. At Besançon, we have observed an astigmatic focal difference of 18 mm in the 320 mm coudé! In the large coudé at the Observatory of Paris (D = 610 mm; F = 18,000), the large flat weighs almost 450 pounds and chronic astigmatism is even more pronounced. This instrument is known for its association with the beautiful *Photographic Atlas of the Moon* to which Lowey, Puiseux and Le Morvan devoted more than 20 years of work. In respect to resolving power for a telescope of this size; however, these photographs are very weak and show no more detail than can be seen with a 5-inch aperture, or that can be photographed, though at the cost of many precautions, with a simple 8-inch. In 1933, Bernard Lyot borrowed the objective of the 610 mm large coudé and installed it at the Pic du Midi. He folded the beam with very carefully made flats employed at *nearly normal incidence*. Under these conditions, thermally induced astigmantism was very slight and Lyot obtained lunar detail with at least three-fold better resolution than that of the Atlas.

C. *Newtonian With Fixed Eyepiece.* —Sheltering the observer using a *reflector* presents more difficulties and *even more serious disadvantages* than the equatorial coudé refractor. The design shown here schematically is perhaps one of the least objectionable because the flat, working at fixed incidence, can be protected in an enclosure sealed by a window with parallel faces. Here again we have the inconvenience of a *reversed image,* and the observer requires a comfortable, inclined chair fitted with a head-rest. A fourth reflection could reverse the image to conform to reality and eliminate the requirement for inclining the observer, but the available spaces can only be very limited if the obstruction presented by the shelter is to be minimized. *Radiation from the shelter will effect the incident beam* when the instrument is pointed toward the south.

D. *The R. W. Porter Turret.* —This instrument was conceived and built by Porter with the assistance of the members of the Telescope Makers of Springfield, Vermont. It is located at Stellafane on Breezy Hill. On this particular instrument one or more telescopes are supported on a cupola of reinforced concrete turning on a steel track which is inclined at the latitude of the locale. The cupola therefore acts as a large polar movement. A parabolic mirror M_1 in a first telescope is supported by a light framework. The stability of this mounting and the thermal characteristics of the open framework are not good. *At least one arm of the framework frequently lies within the field of view of the flat M_2,* which is rotated from within the turret. This flat perforated at its center, is naturally prone to cause astigmatism. On the other hand, a second telescope mounted as a kind of counterweight presents only the disadvantages of a simple coudé. Cassegrainian, though affected by appreciable turbulence due to the close proximity of the turret. This second telescope is not now part of the instrument which is still in operation at Stellafane.

E. *Horizontal coelostat.* —This is a classic arrangement often adopted for spectroheliographs and spectrographs that are too large to mount on an equatorial. The polar axis turns once in 48 sidereal hours and supports only a flat mirror M_1. The reflected beam is then directed horizontally by a second flat mirror M_2 which is adjustable in declination. The telescope can be installed in a shelter on a stable pier. Thermal effects in the shelter can be reduced by a window L, *but the three sections of the beam between the flats and the vicinity of the piers and the shelter are inevitably perturbed by the veins of heterogeneous air.* Only by using flats of low-expansion material such as fused silica, Cervit® or Zerodur® can the thermal astigmantism be reduced sufficiently. Even so, *the resolving power of these installations rarely attains a second of arc.*

F. *Vertical Coelostat.* —This mounting is superior to the preceding because performance is less affected by local turbulance. The two flats are better positioned, so that the light beam does no have to pass over large

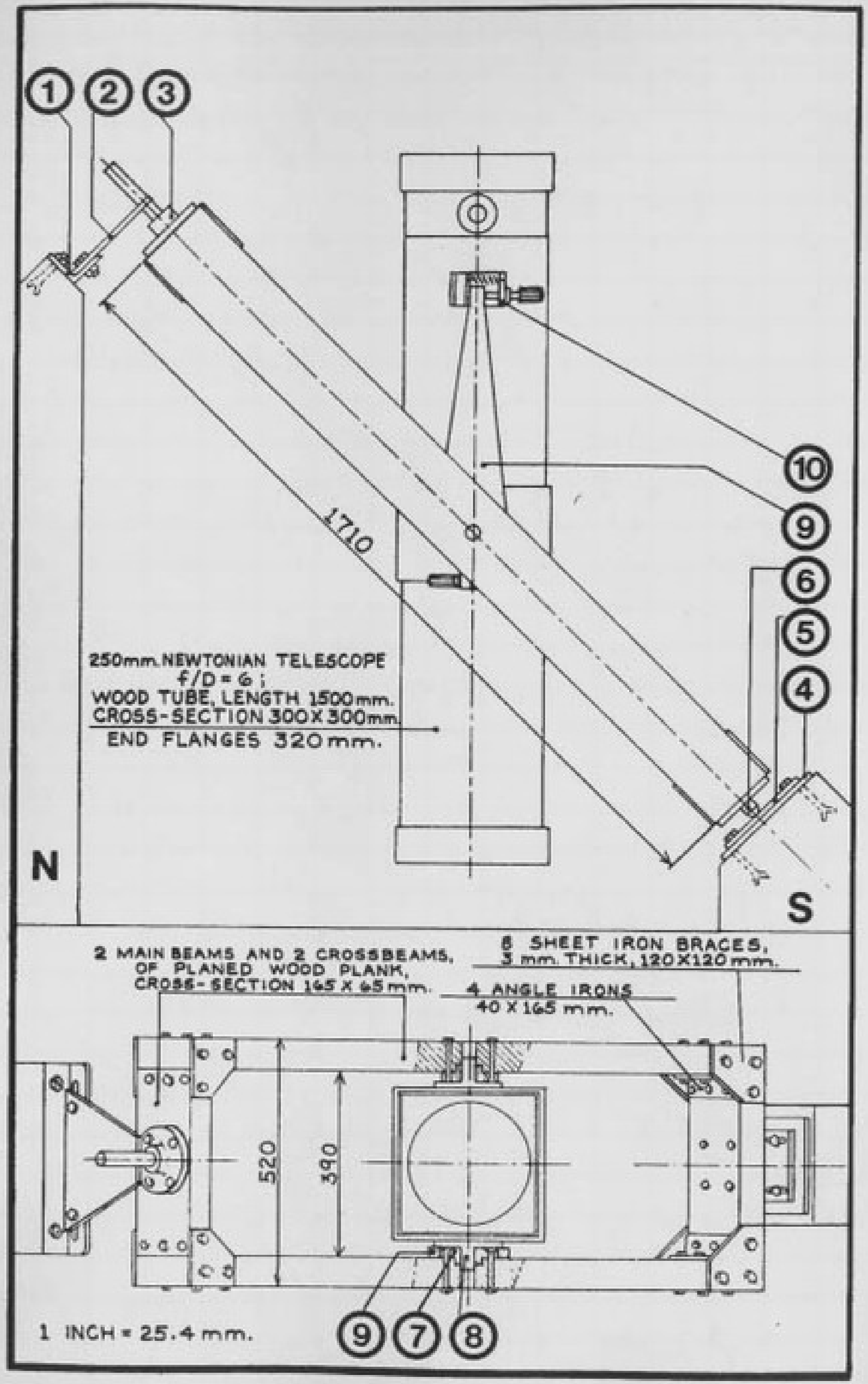


Fig. 106. Simple cradle mount assembly for a 250mm (10-inch) telescope.

thermal masses, but *it is more difficult to accommodate a large declination range.* The large 150-foot solar tower of the Mount Wilson Observatory has been very exceptional in giving good photographs. Overall, it has outperformed the horizontal coelostats. Another instrument of this type was constructed at Kitt Peak National Observatory. It is a solar telescope of 60-inch aperture and 275-foot focal length, the beam of which is supplied by a polar siderostat with a fused silica flat 60-inches in diameter mounted on a tower 102-feet high. These are not, we repeat, installations to be copied in small-scale constructions by amateurs!

XII-4. Practical Advice for Construction of a Cradle Mounting

The detailed drawings in Figures 106 and 107 relate to a 10.25 inch, *f*/6 Newtonian telescope with a wood tube 11.8 inches × 11.8 inches in cross-section and 59 inches long. All its components are easily made without precision tooling. Of all the mounts discussed here only the cradle mounting can be built with such simple tools without sacrificing performance. The following discusses various details and options:

Supporting Piers.—These may be made of concrete, lightly reinforced with 0.5-inch iron rod near the corners or made entirely of brick but with a concrete cap into which are cast the mounting bolts for the bearings. The excavation should extend below the frost line. A bed of large stones about a yard on a side may support the north pillar, the cross-section of which above ground would be 16 by 16 inches and the height, in the middle latitudes, about 55 inches. Figure 106 shows only a portion of the piers. The amplitude of adjustment in azimuth for the polar axis is ±1-inch, as provided by the angle iron identified by marker 1 (circled call-out in figure 106). The piers must therefore be positioned in the plane of the meridian to a better approximation than this. A theodolite set up for sighting the transit of a star across the meridian, with the time calculated by reference to the *Astronomical Almanac*, will give a more than adequate approximation. However, one must avoid certain common errors, for example the sign of the correction for local longitude, time of the ephemerides, etc. In case of doubt, a check can be made on a transit of a star just above or below the pole, this being easier to determine by the amateur than a transit of the sun. If a theodolite or astronomical tables are lacking, the following will suffice if done carefully. At the intended axial position of the south pier, drive a straight rod, for example, a long wooden broom handle, taking care that it is precisely vertical in position (which may be checked with a level). About three hours before transit of the sun across the meridian drive a long nail into the ground exactly at the end of the broom handle's shadow. Now cut a wooden lath to exactly the length separating the base of the broom handle from the nail. We then wait until the shadow of the broom handle, at a position symmetrical with respect to the meridian, again has exactly the length of the lath, at which time we drive a second nail into the ground at the corresponding azimuth. A line on the ground corresponding to the meridian is then given by the bisector of the angle formed by the two nails and the axis of the rod.

Cradle.—The design shown in Figure 106 is a simple wood construction. The beams are planed and have a cross-section of about 6.50 by 2.5 inches. Beams built up of boards will serve equally well. The main beams and cross members must not be assembled in the classic manner with tenon and mortise or dovetail joints. Drying of the wood could eventually loosen such joints and impair the rigidity. As shown, the four frame members are simply bolted on angle irons. All the bolts or threaded rods must pass completely through the wood members, so that the nuts and large washers can bind the beams tightly, and more importantly, allow take-up of play after the wood has shrunk. Eight brackets made from ⅛-inch metal plates are fastened at the corners in the same way as the angle irons. Positioning of the mounting holes in the polar trunnion members (markers 3 and 6, Figure 106) and the declination bearings (marker 7) should be guided by a carefully scribed drawing to assure optimum alignment of the trunnions and perpendicularity of the declination axis. The latter is especially important when setting circles are used to locate objects by coordinates. Since the declination trunnions are separated by a considerable distance, using a simple carpenter's square that has been checked for accuracy can easily confirm the perpendicularity to within several minutes of arc. This is entirely adequate in practice.

For those wanting a cradle made entirely of metal, several choices are available. Figure 110 shows an equatorial built by Saget in which the cradle is made of bent, riveted sheet metal and constitutes a very neat design. The mounting is installed in the attic of a home. Sheet metal ⅛-inch thick precisely bent and welded into rectangular beams will make better use of a given weight of metal than an assembly of standard iron I or U beams. Nevertheless, cradle mountings made with I- or U-beams have an undeniable elegance. An interesting example of this design for an 8-inch telescope is illustrated in Figure 109. The cradle frame is made of U beams, 4 by 2 inches, and its weight including the sturdy trunnion members is under 75 pounds. The piers are made of 4- by 2-inch U-beams joined together by a I-beam of 5.5 by 2 inches, an arrangement worth remembering where pier construction in masonry is precluded for one reason or another. A third possible solution is that shown in Figure 118, which is an offset equatorial cradle mount, but the concept is equally applicable to a simple cradle. The steel tubes assembled on rather simple castings provide good rigidity at all angular positions of the polar axis.

Metal Components.—These are partially detailed in Figure 107, and require little comment. The polar axis is supported kinematically in a two-contact V (marker 2) at its upper end, and in the triple point represented by the hole in the plate (marker 5) on the south pier. Pressure on this conical hole is high but heavy grease will prevent grabbing. Thrust bearings and spherical bearings would appear more mechanically sophisticated, but exceptionally free movement in an instrument is not always an advantage. We know of

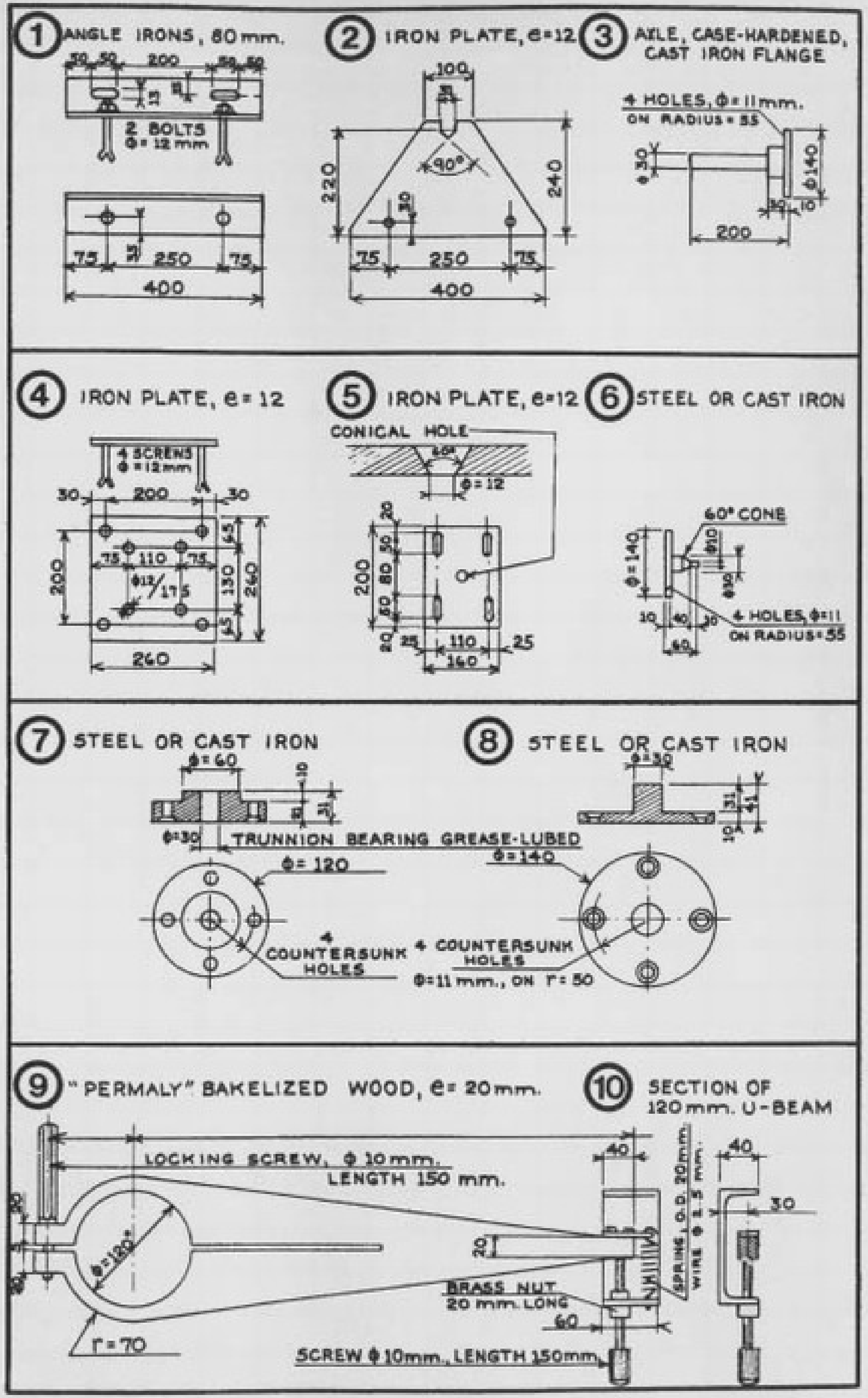


Fig. 107. Details of components for simple cradle mount.

telescopes mounted on ball bearings that ultimately needed brake pads to prevent accidental movement. The design of Figures 108 and 109 forgoes the concept of kinematic contact for the declination axis. There may be slippage at certain angles of right ascension. The unavoidable play in smooth-working declination bearings will almost never be a problem in practice. The

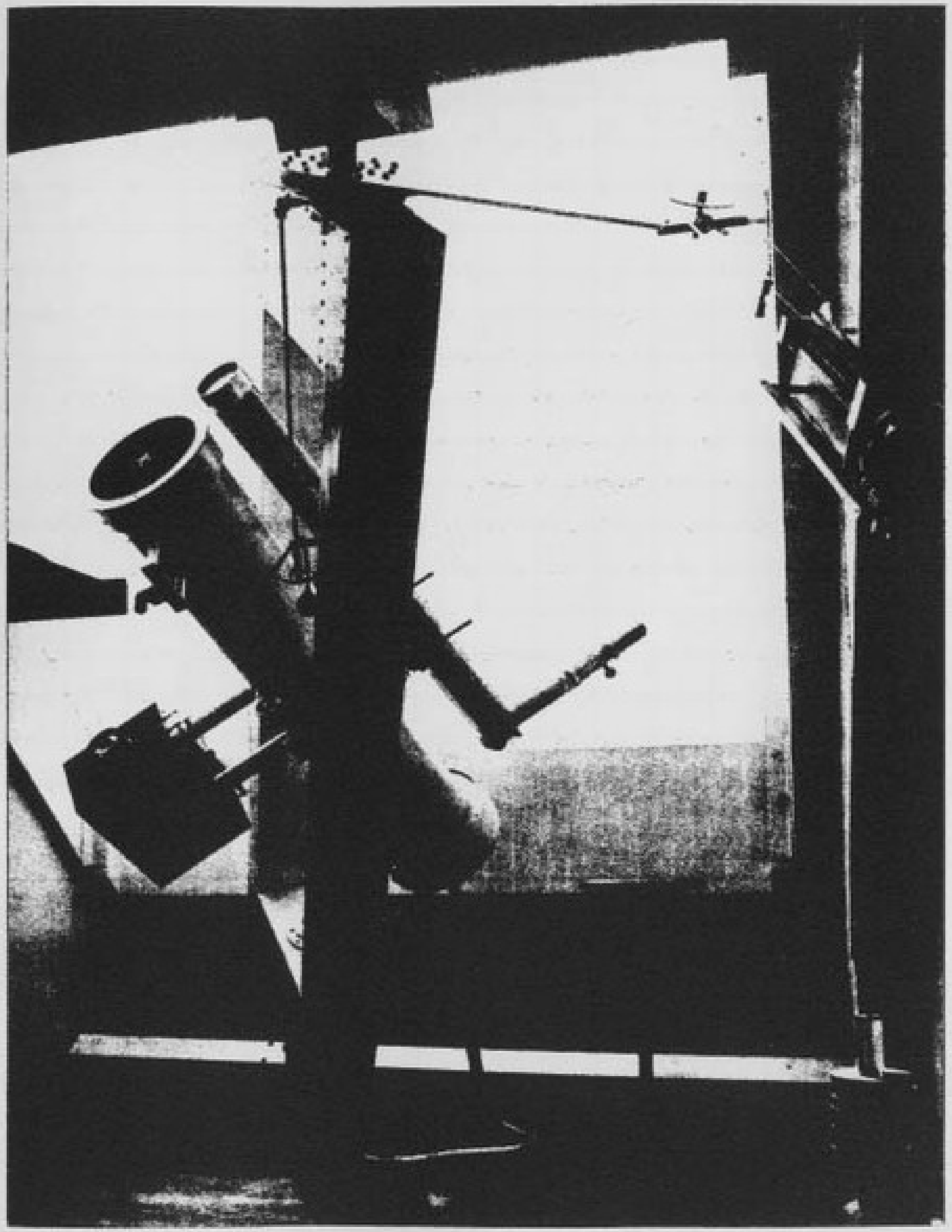


Fig. 108. Cradle equatorial fabricated of bent sheet metal. (Design by Saget)

declination clamp and the inertia of the instrument will be enough to prevent vibrations, but of course there is nothing wrong in adopting a mechanically more elaborate solution. For example, adjustable bronze pillow blocks may be used, or ball bearings—prefereably of spherical type—that will permit exact adjustment of perpendicularity of the axis. Since spherical bearings can support the axial load of the inclined instrûment, the addition of thrust bearings mounted on end-blocks becomes unnecessary.

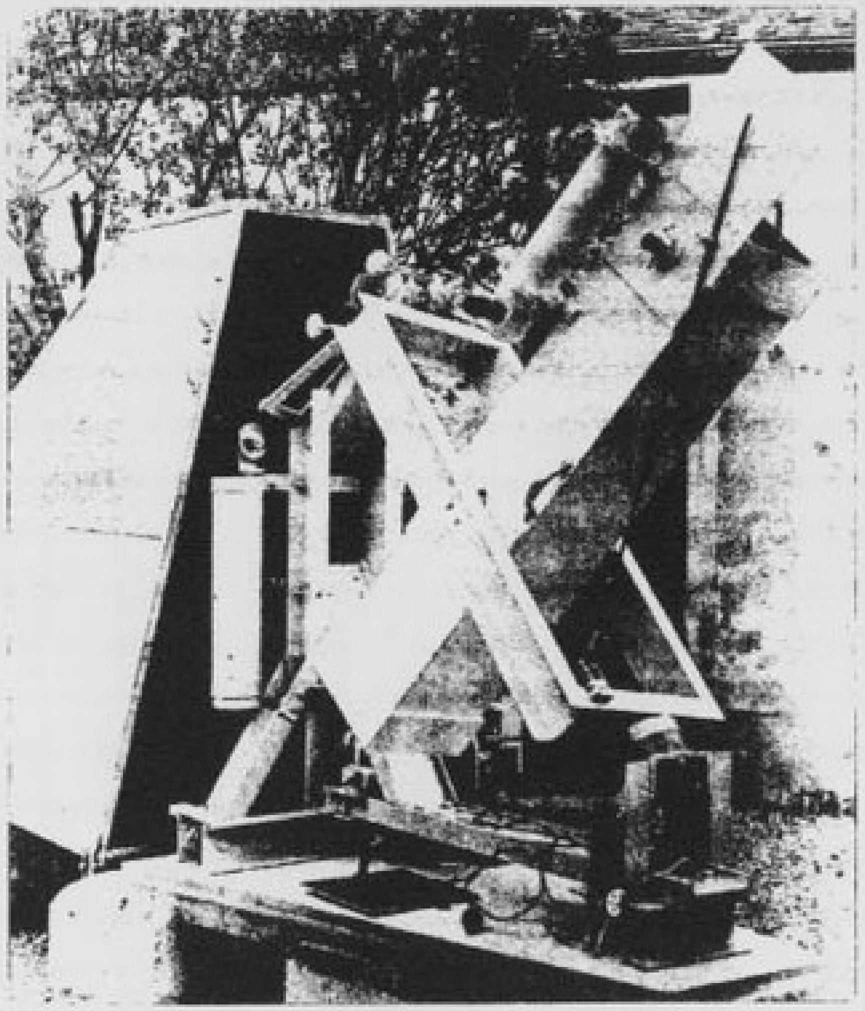


Fig. 109. Cradle equatorial constructed with U-beams. (Design by Sévoz)

The declination locking clamp and corrector, markers 9 and 10, is of classic design. The bakelized and compressed 'Permaly' wood[2] is more easily machined than a cast metal part or a part cut from a thick metal plate. The declination corrector shown, using a screw and spring acting in traction, has less tendency to grab than the *pump* arrangement with a spring used in compression. Grabbing is sometimes caused by a minute imbalance of the telescope. From this point of view, positive bi-directional motion with properly articulated screws and nuts is an advantage. However, such an arrangement requires a much more carefully designed mechanism to eliminate lost motion in the screw.

[2] See reference in Chapter IX, footnote #1.

The setting circles, optional and not shown in Figures 106 and 107, may simply consist of large draftman's protractors, now available in plastic in the form of complete circles. It is easy to interpolate by eye to a tenth-degree or 6 minutes of arc on a circle 8 to 12 inches in diameter divided in degrees. The index line against which the angle is read should have the same width as the division marks on the protractor. Naturally, when the hole is cut in the protractor it must be centered with corresponding precision. One may first cut a small, carefully positioned centering hole. A fly cutter or hole saw can then be used to make the larger hole—with care not to shatter the plastic. The protractor used as the declination circle is simple mounted with its zero aligned with the index when the telescope is in the plane of the celestial equator. We have only to add a plus sign for declinations from 0 to 90 degrees north, and a minus for declinations from 0 to 90 degrees south. On the right ascension circle one may add a scale of hours marked at 15 degree intervals, and further divided by 15 to give 4 minutes per division. The zero position on this scale does not matter if one uses only a single circle or a single index. In general, to avoid having to use local sidereal time, the amateur locates his object by temporarily marking on his right ascension circle the difference in right ascension relative to another easily locatable object. This assumes, of course, that the equatorial has an accurately positioned polar axis.

Clock drive: This subject is treated is Section XII-11. The cradle mounting is especially well adapted for rotation by a screw and sector, which is the easiest for an amateur to build with good precision. The north trunnion, marker 2 on Figures 106 and 107, is long enough to receive the drive sector which in this case would be positioned over the north pier.

XII-5. Practical Advice on Offset Cradle Mountings

Figure 110 illustrates the use of iron tubes to serve as the long cradle beams. The dimensions shown would be those applicable to a 10-inch $f/6$ Newtonian. The long beams (marker 1) are made with boiler tubes, the ends of which can be threaded and fitted with malleable cast iron flanges, marker 2, available from commercial suppliers of plumbing and heating equipment. Depending on locally available facilities, one may prefer steel tube welded onto flanges cut from thick metal plates. We envision identical base members, marker 3, made of cast aluminum alloy. Making a wood casting pattern for a flat part of this type would present no problem. The base members receive the two sturdily bolted flanges, as well as the trunnions for the polar axis, marker 4, which are solidly fitted onto sturdy hubs. Counterweights are mounted at each end on threaded rods to bring the center of gravity back to the polar axis. Unlike the arrangement in Figure 104B, these counterweights do not lie opposite the offset load. This results in increased torsion on the cradle, but this is probably less objectionable than the increased flexure that would result if the counterweights were at the center.

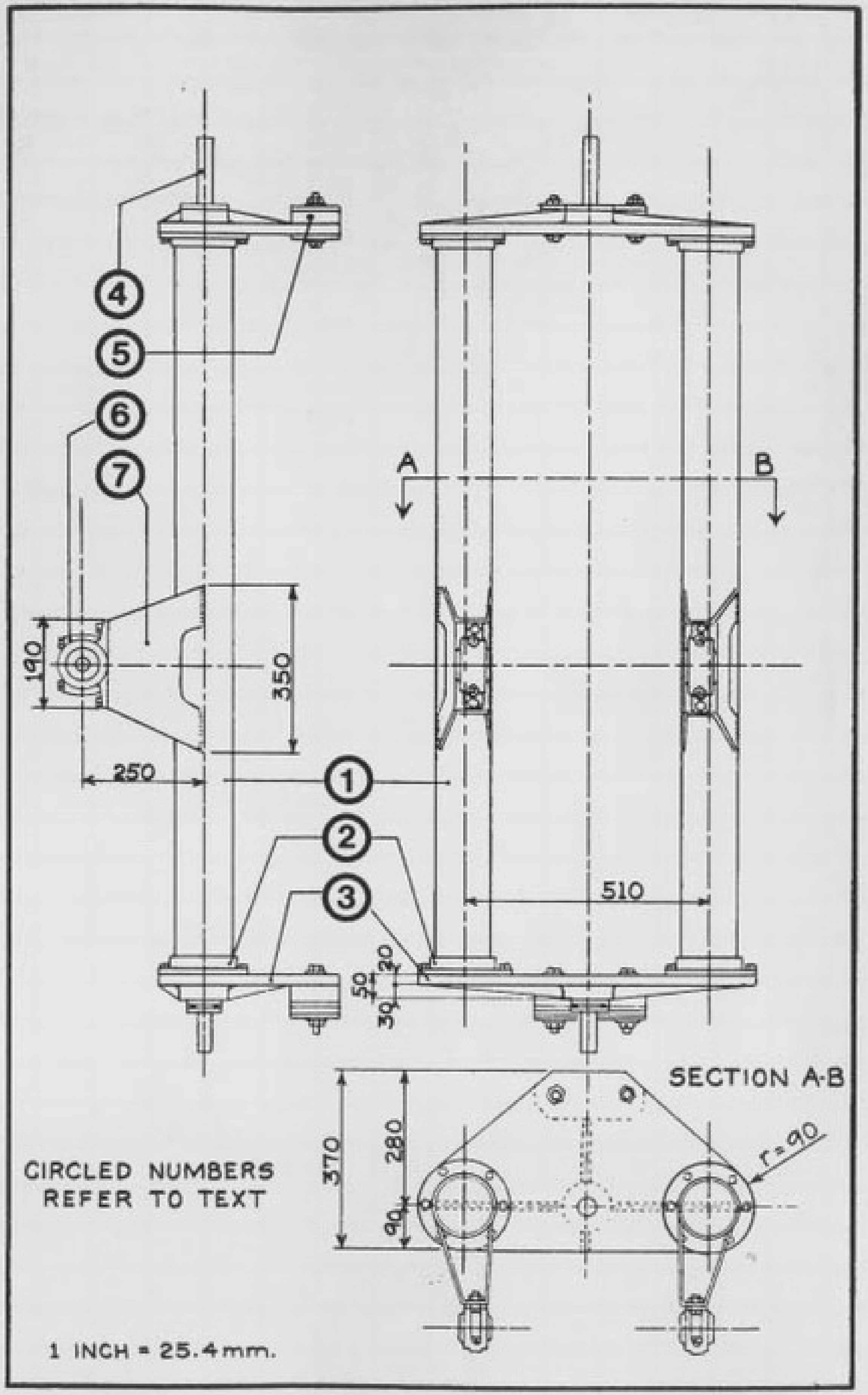


Fig. 110. Offset cradle mounting for a 250mm (10-inch) $f/6$ telescope.

The declination bearings, marker 6, are the type S1507 swivel bearings selected from an S.K.F. series. The spherical member rides on two rows of steel balls and accepts a 1.25 inch (30 mm) shaft. Only a retainer sleeve is needed to support the moderate axial load of the telescope pointed at large polar angles. As an alternative form of bearing, adjustable bronze pillow blocks would be entirely acceptable, though a little more difficult to adjust. The support brackets, marker 7, are made of 0.20 inch (5 mm) bent metal plates welded autogenously along lines parallel to the tube axis. The parts should be carefully supported to make sure they are in proper relative position when the first weld points are being made. One may prefer bearing supports in the form of two-piece cast aluminum collars that clamp the tube at an adjustable position. With the 10-inch (250 mm) offset of the declination axes from the cradle beam, a 12-inch (300 mm) tube could be aimed directly at the pole, but the price paid is appreciable torsion on the tube.

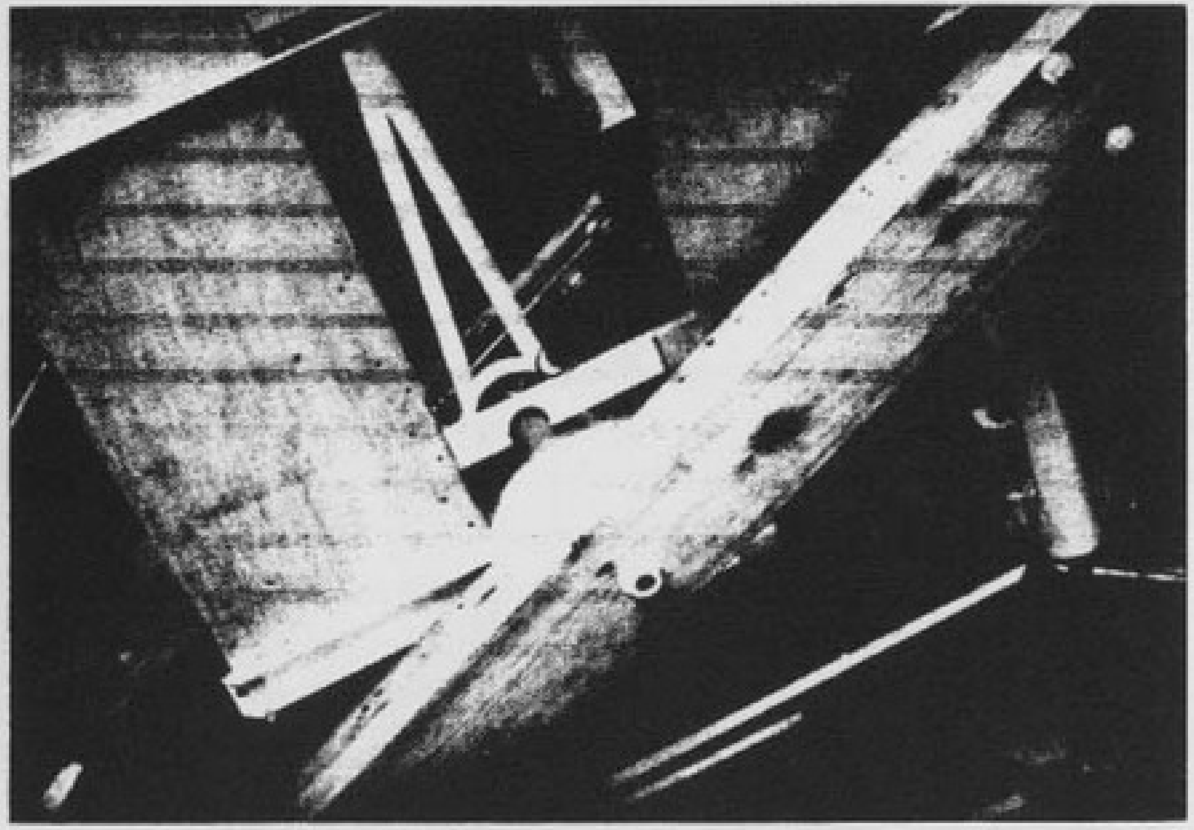


Fig. 111. Center section of a cradle mount with two offset telescopes.

A construction related to the offset cradle equatorial was built at Reims by our colleague Walbaum (Figure 111). Here the wood cradle is of classic form, but supports two telescopes balancing each other on the declination axis. The connecting U-beams and angle irons appear weak, but the performance of the instrument is excellent, particularly in long-exposure photography.

XII-6. Practical Advice on Simple English Mountings

The very sturdy classic polar axis is formed by two conical members fitted with trunnions. Strong flanges bolted on a central tube support the declination bearings (Figure 104C). The mounting made by the English firm of Grubb Parsons for the 76-inch telescope at the Observatory Haute-Provence uses a polar axis of this type which alone weighs 21 tons! As equatorials attain a certain size, we see a tendency for concern about rigidity to prevail over aesthetics and ease of construction. For example, the conical supports of the 31.5-inch telescope at Haute-Provence are an oddity. Also, the Crossley telescope at the Lick Observatory was built with the polar axle formed like a bisymmetrical cigar to bring the telescope close to the polar axis and reduce the size of the counterweight.

But let us discuss some simple polar axis designs more useful to the amateur. We start with four sturdy boards, slightly bowed and assembled to form a double pyramid with a square base. The ends are truncated and fitted with firmly attached metal trunnion supports. This assembly is very sturdy, although it is subject to humidity. Figure 112 illustrates a similar design where the panels are made of sheet metal. This mounting, built by Gauthier at Sanary, carries a 13-inch Newtonian and is made largely of salvaged auto parts and parts from surplus military instruments. Gauthier has been able to monitor thousands of objects listed in the *Revue des Constellations*[3] and to follow visually the motion of the planet Pluto.

The idea of using the rear axle of a large car or truck as the polar axle appears to have originated with the American amateur, Maxwell. He mounted a 12.5-inch telescope on the banjo-type rear end of a Chevrolet,[4] the drive pinion of which is replaced by a large ball-bearing crown for rotation in declination.

Although the wheel bearings on an automobile rear axle can be used for the polar rotation, it is more practical to cut off the end of the axle housing and to make a support for a self-centering bearing which will facilitate alignment of the axle. Figures 113 and 114 show a typical conversion of an automobile rear axle.

Whatever the form of the polar axle, we know that the weak point of the simple English mounting is the cross section of the cantilevered output end of the declination axle. Figure 112 shows the use of a 2.36-inch declination axle mounted between two Timken tapered roller bearings. The external 4.92-inch bearing races are mounted in ribbed, cast-iron plates. A flange is mated to the steel axle, and on this either an intermediate part or the telescope cradle itself is sturdily bolted. One end of the declination axle is threaded and fitted with a nut and lock nut to permit pre-loading of the bearings. Up to several hundred pounds can be pre-loaded with no adverse effect on bearings of this size. Note the independent welded sheet metal part that supports the counterweight and

[3] Publication of the Astronomical Society of France, at the headquarters of the Society.
[4] Amateur Telescope Making, 4th edition, Figure and drawing on page 65.

encloses the declination circle. A counterweight merely mounted on the end of the axle would probably be a source of vibration.

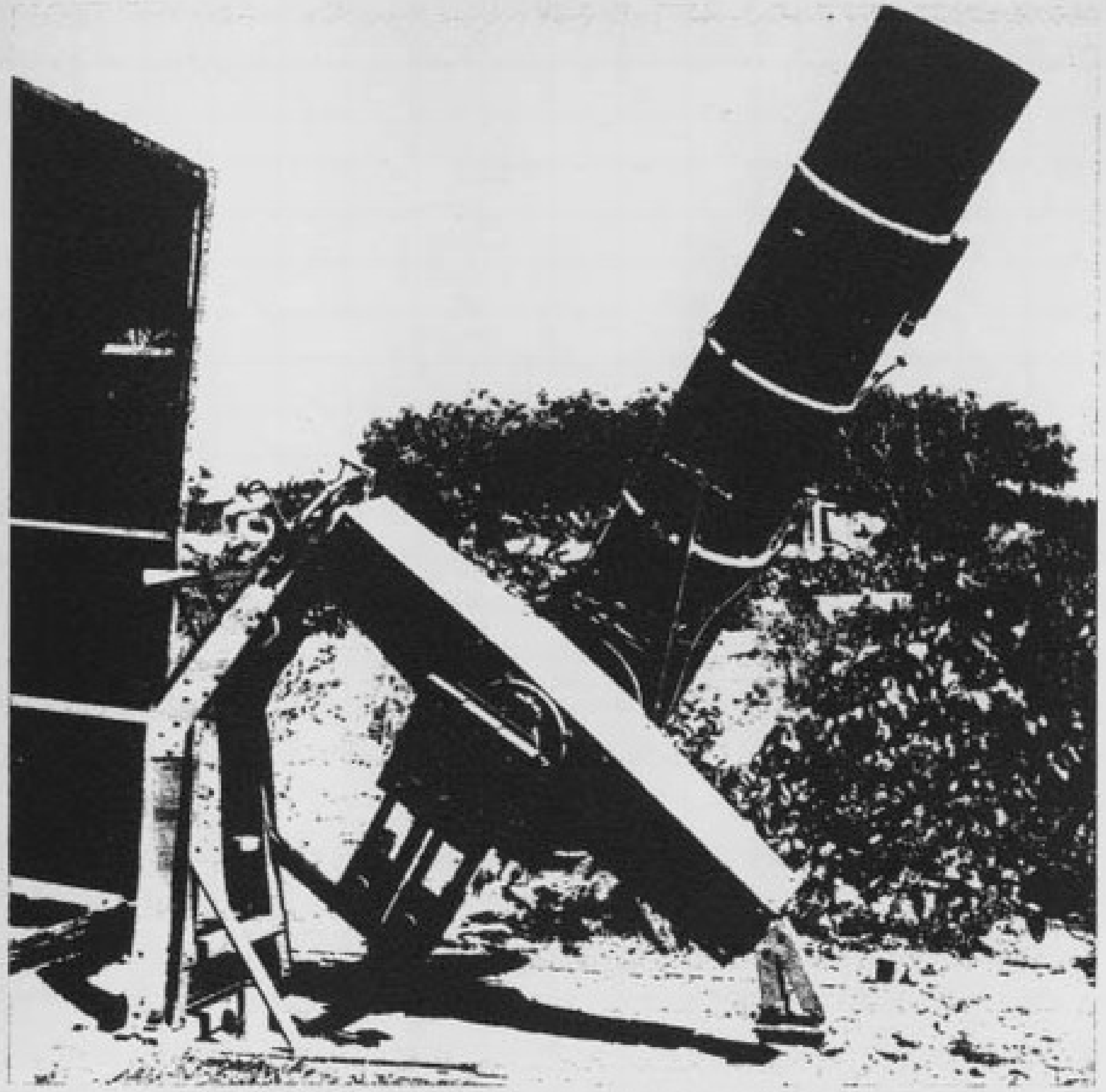


Fig. 112. 330mm (13-inch) equatorial built by G. Gauthier.

XII-7. Practical Advice on German Mountings

Amateur German mountings are often sad, *pot luck* assemblies of second-hand machined parts. We will not involve ourselves in details of the various designs to be avoided. We wish only to point out the most common errors.

A drawing by R. W. Porter was the inspiration for Figure 115A. It is a caricature, with little exaggeration, of certain designs assembled from pipes and fittings. If it is ease of construction we want, it is much better to stay with the standard altazimuth design. The lengths of the cantilevers and the axle weakness at stressed points P and P′ are the source of unacceptably large, poorly damped vibrations. In contrast, the elegant design of Figure 115B

Fig. 113. 10-inch equatorial adapted from an automobile rear-end assembly.

applies maximum reinforcement at the loading points P and P′ by the use of elaborate castings. The cost of patterns and machining involved in this design would be better applied to a fork mounting, at least for mounting a reflector.

Acceptable alternatives between these extremes are available, basically using transmission bearings assembled with angle iron and welded plate supports or even using a strong wood frame. An inclined lathe head-stock is another possible solution. Figure 116 illustrates a mounting built by Faure-Geors for a standard 8-inch $f/7$. The original wooden tripod is reinforced by a strong column cut at an angle. A drive pulley on a shaft, unfortunately only 1.25 inch in diameter, provides the polar rotation. A thick sheet metal part supports the declination bearings. The declination axle is weak but a reinforcing bar, J, tying the end of the tube to a bushing on the axle, effectively damps the vibration. The large assembly at the eyepiece location is a camera and its support structure. The camera is pointed toward the eyepiece which projects an image into the camera, usually at high magnification. The excellent results obtained with this instrument must be credited in large part to the competence, patience and care of the user.

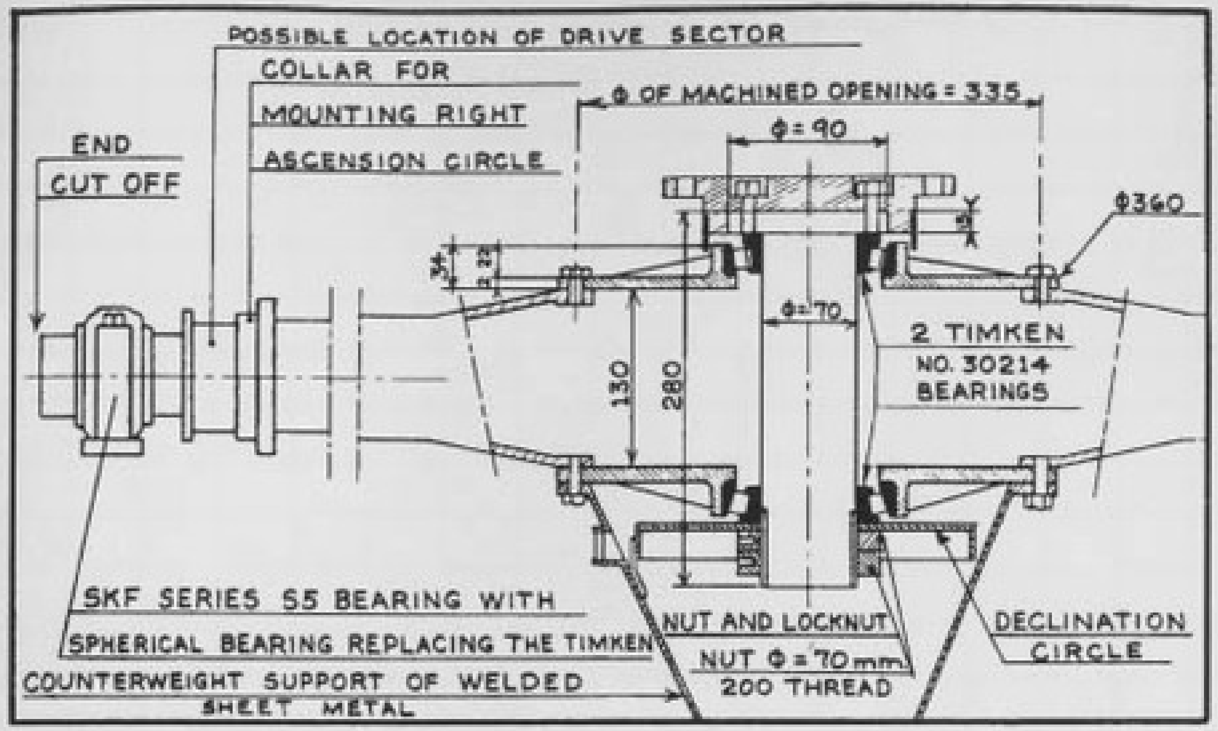


Fig. 114. Adaptation of automobile rear-end assembly.

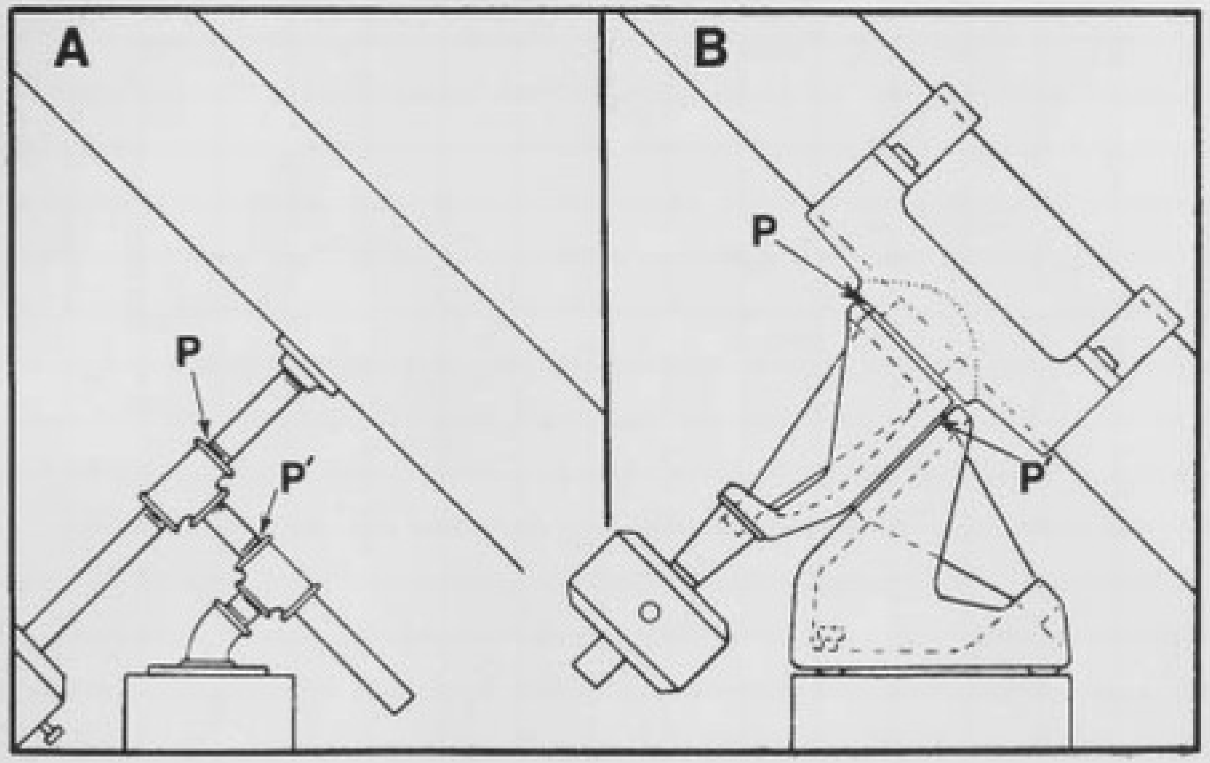


Fig. 115. Comparison of an extremely flexible German mount with a rigid but costly mount.

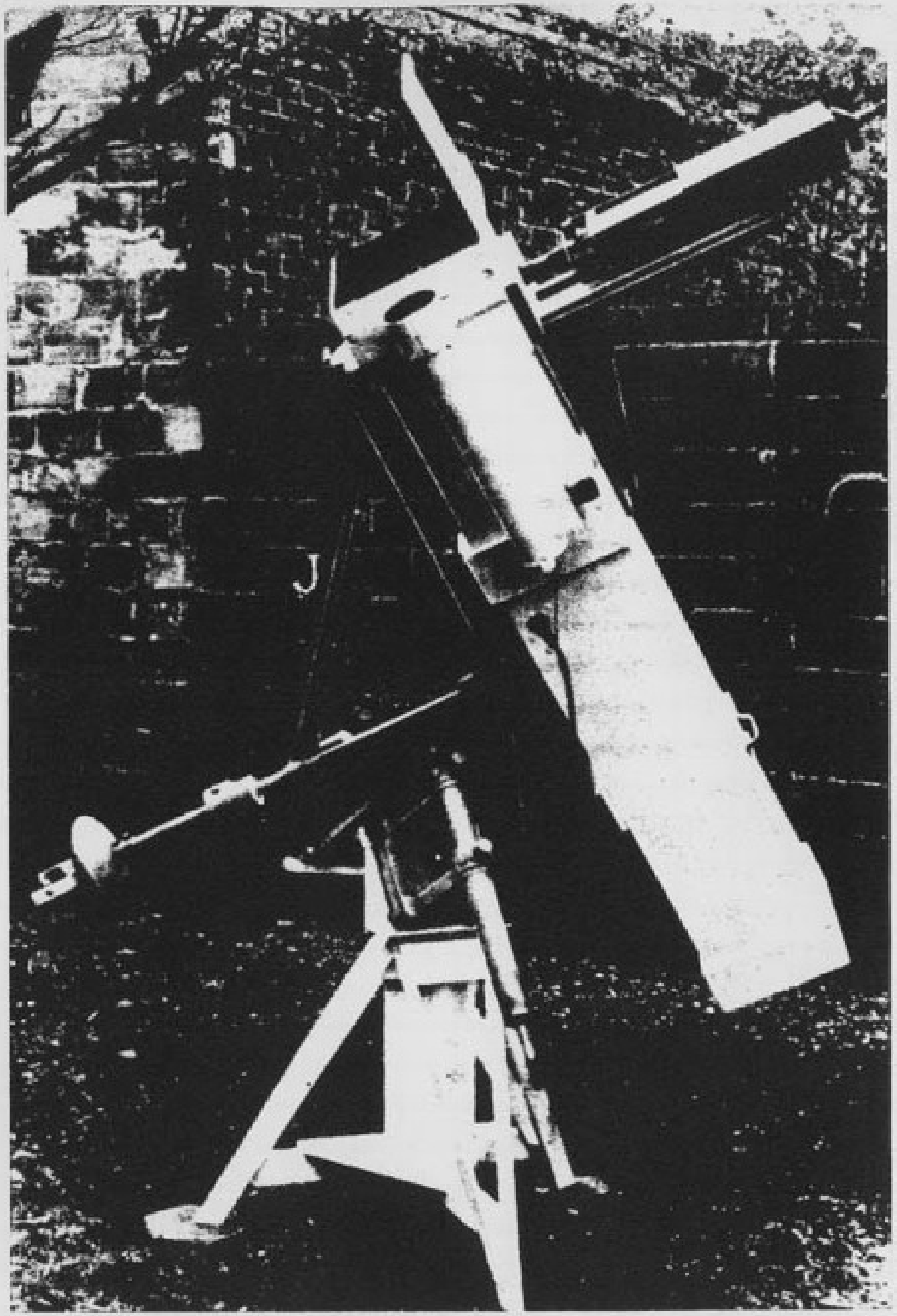


Fig. 116. German equatorial with a standard 8-inch telescope.

XII-8. Practical Advice on Fork Mountings

We consider first the case of the mobile equatorial. This is considered heretical by some, but is perfectly acceptable if certain precautions are observed. The fork mounting, with its well-centered and compact design, lends itself well to transport over level ground. The rolling equatorial is especially attractive for those who have a concrete terrace and shelter at their disposal, but would not consider building a special shelter with rolling roof or cupola. A possible solution is sketched in Figure 117. The base of the equatorial is a rectangular casting fitted with three rubber-rimmed, ball-bearing casters. One of these casters swivels on ball bearings and together with the handlebar facilitate movement of the unit. Accuracy of adjustment for azimuth and height is achieved by engaging the tips of heavy positioning screws with steel insets cemented flush in the paving and arranged to define a *hole, line and plane.* The tip of a first positioning screw, in the form of a ball A, engages the *90 degree conical hole* A′ in the first inset. This eliminates three degrees of freedom. The end of a second screw, B, also spherical, settles on the *line* B′ in the form of a 90-degree V oriented along a line intersecting hole A′. This eliminates two more degrees of freedom. The sixth and final degree of freedom is then eliminated by contact of the slightly rounded end of the third screw C against the *plane* C′. Once the three screws have been adjusted for inclination of the axis and at a height which insures that all the casters are raised, the nut and lock nut on each are run down and permanently locked together, acting thereafter as stops for repositioning the screws to their correct heights. Adjustment in azimuth is obtained by shifting the line B′. It is helpful to form the V of two pieces, since a fixed V cannot be cemented with sufficient precision. The procedure of setting up the instrument in this way hardly requires more time than opening a fixed shelter.

The design of an equatorial fork mounting must emphasize, above all else, the rigidity of the fork and the heavily loaded north bearing. It is tempting to elongate the arms of the fork to grasp the telescope near its center and reduce the range of eyepiece movement. However, *flexure increases as the cube of the cantilevered length.* A solution to this dual problem that cannot be faulted is illustrated by Figures 118 and 119 showing an 8-inch, *f*/6 Newtonian constructed by Boudrant. The arms of the fork are heavily ribbed castings with a wide base. They are bolted to a plate 24 inches in diameter, which is actually the upper end of an unusual polar axle and serves also as a circular track for two steel rollers spaced 90 degrees apart on its periphery. Figure 119 shows one of the rollers mounted on a Timken bearing and serving at the same time as a frictional polar drive. The load-carrying plate is cast as a single piece and heavily ribbed to assure perfectly rigid coupling to the south trunnion. The latter, of modest size, is mounted on a Timken bearing which acts secondarily to carry the thrust. A heavily ribbed triangular base supports the total assembly. All the castings are made of aluminum, and in view of their dimensions the rigidity leaves nothing to be desired. Naturally, the cost of

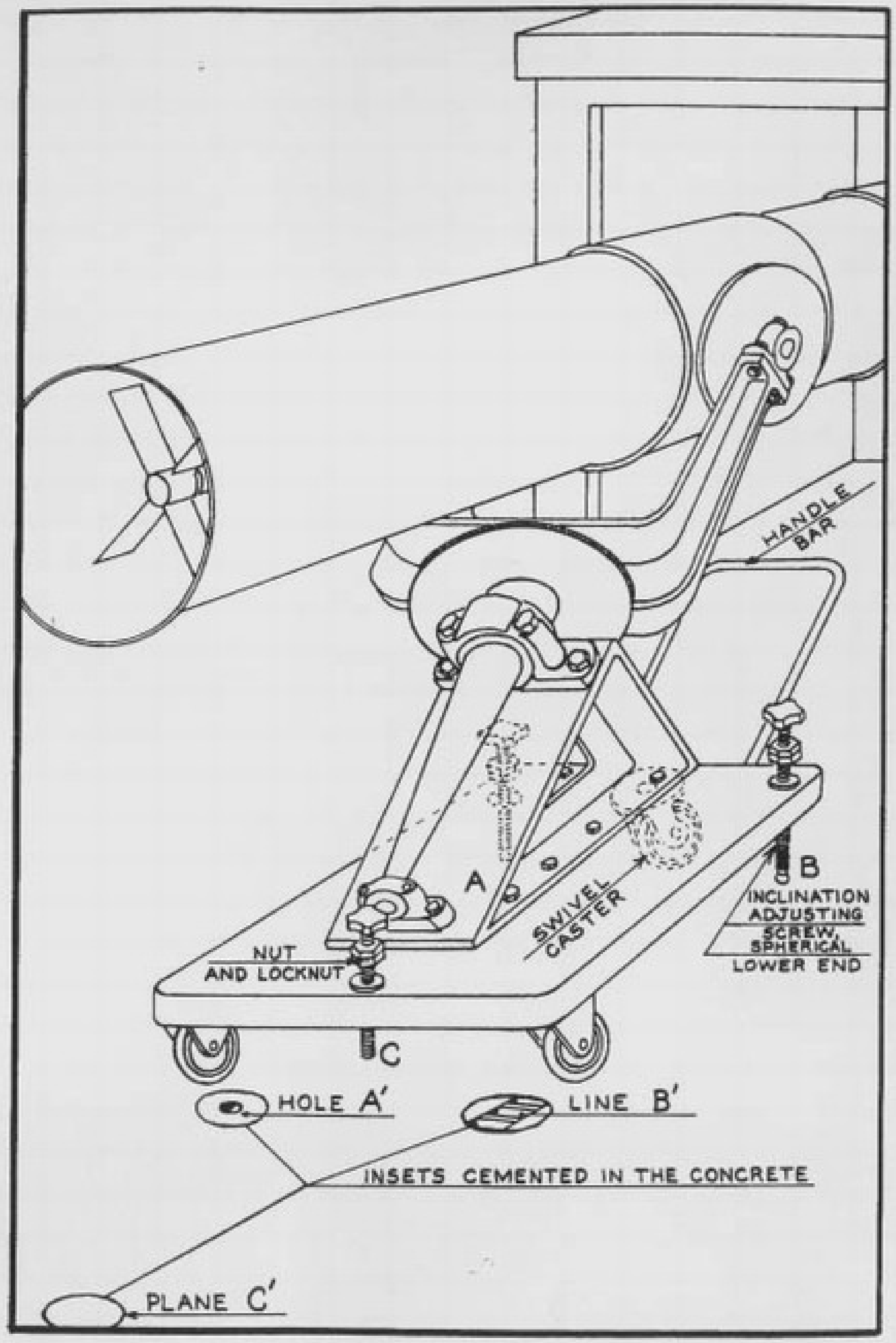


Fig. 117. Mobile equatorial adapted for positioning on inserts defining hole, line and plane.

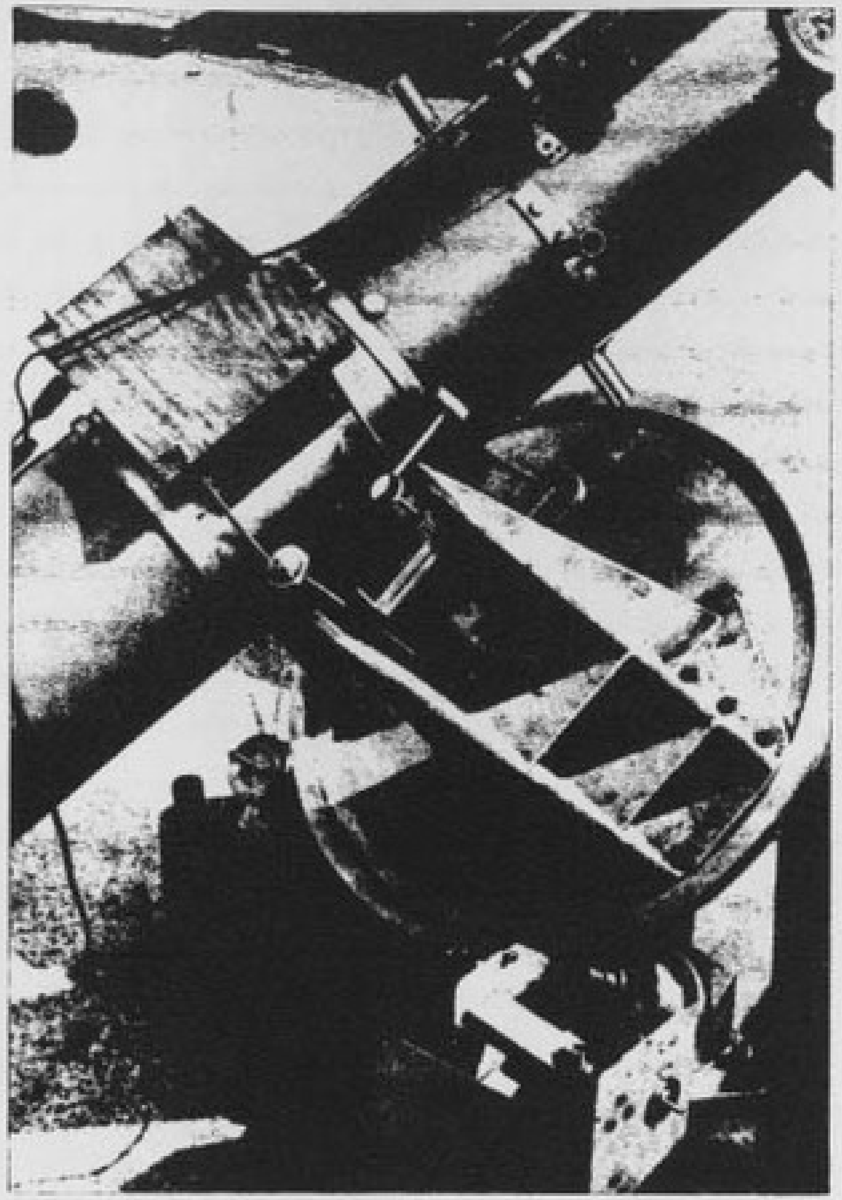


Fig. 118. Fork equatorial. (Designed by Boudrant).

making the patterns could not readily be amortized on a single unit. One could dream of a cooperative, owned by amateur clubs, that is richly stocked with patterns and to which members would bequeath their equipment. Still, for most amateurs, there would remain the difficult problem of machining parts such as these.

Assembling the arms of a fork on a base need not be as expensive as this. Leon Foucault adopted the fork design as early as 1860 and had several models built, first by Secretan and later by Eichens, for 8- and 16-inch aperture telescopes (Observatory of Paris) and even a 32-inch (Observatory of Marseille). These forks were built mostly of wood, and present-day amateurs would have little interest in copying their complex design. However, it is possible to find ready-made a heavy lathe head-stock still fitted with a large cast-iron face plate on which one need only to bolt two very simple cast arms (Figure 120). Since the axle here directly carries the load, one should choose a

head-stock with a spindle at least 2.38 inches in diameter to support a 8- to 10-inch telescope. The cast metal plate should have a minimum diameter of 20 inches. Figure 120 indicates some of the dimensions for fork arms designed as very simple, inexpensive castings. The lathe head-stock can be mounted at the required inclination on a base of the type shown in Figure 117.

Forks cast as a single piece are more elegant and equally rigid. The best designs are of hollow cross-section with smooth edges of large radius, but it takes a professional pattern maker for a design this complex and they require large core boxes. A simpler fork mounting is the one shown in Figure 117. Figure 121 illustrates a model manufactured commercially by Florsch. This fork equatorial was delivered either assembled or in separate parts. In a similar vein, we might mention the fork equatorial that was manufactured by Mévolhon (Figure 122).

We advise against fork models made by assembling I- or U-beams or even by welding metal parts cut from metal plate. These assemblies may actually be rigid enough, but the vibrations are never as well damped as in a cast part made with large hollow cross sections.

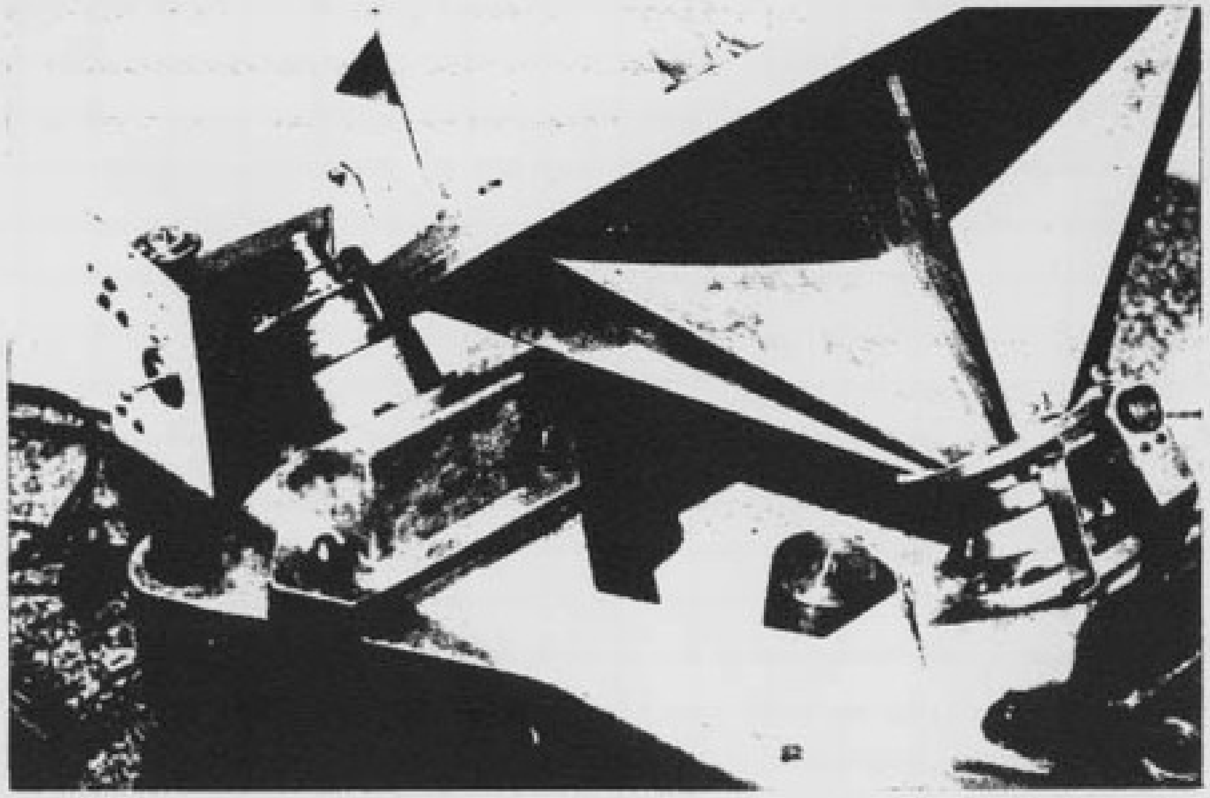


Fig. 119. Detail of polar axis on Boudrant equatorial.

XII-9. Practical Advice on Mountings with a Table Atop the Polar Axis or Inverted Fork

The polar axis should be dealt with the same as that in a fork mounting. The declination bearing assemblies can be bolted directly on top of the lathe face plate or its equivalent. The declination counterweights are troublesome;

to keep them from becoming a source of vibration, they should be mounted on shafts of large cross section, and clearance alongside the equatorial support should permit free passage of the weights at angles far from the pole. Figure 123 displays in part the Belgium Astronomical Societie's equatorial designed by André and built by Dubois at Linkebeek, near Bruxelles, for a 10-inch Newtonian. It is a good example of a construction using tubes and welded sheet metal. Note the importance given to the supporting framework and the extension carrying the north bearing. However, vibrations are not as well damped as in a mounting made with castings. Extra points of contact on the ground do, however, improve the steadiness of the mounting.

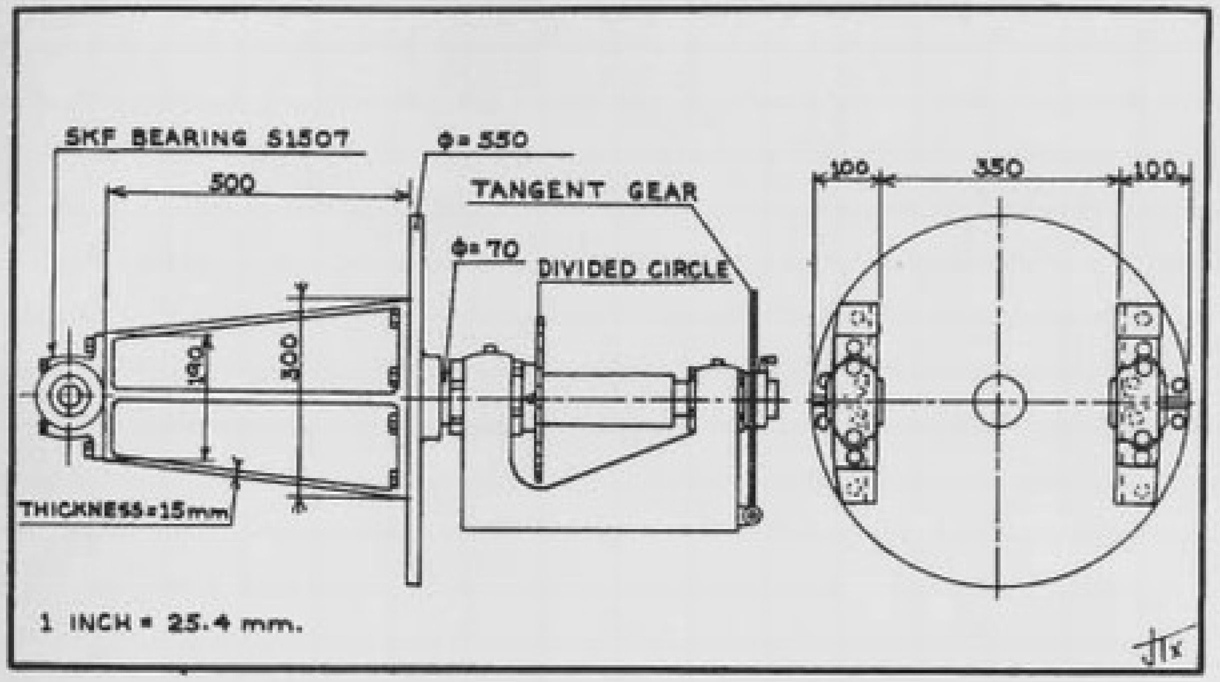


Fig. 120. Fork mounting on lathe headstock and face plate.

XII-10. Generalizations Concerning Clock Drives

Depending on how the telescope is used, a polar drive may take very different forms. For visual use and even planetary drawing, the object has to remain only approximately in the center of the field, say within 1 minute of arc. This can easily be achieved with simple mechanical means. For example, a speed reducer taken from a barbecue spit, or an old cream separator or even a cylinder-phonograph drive can be used, to name just a few. *Long-exposure photography* on the other hand, requires a much more carefully made drive. Under good conditions, photographic images of stars subtend an angle of 3 to 4 arc seconds at the focal plane of an amateur telescope of 10- to 12-inch aperture. They will appear well rounded only if the diurnal movement is precise to about 1 arc second. Now, 1 arc second corresponds to 1 μ (0.000039 inches) of movement at the teeth of a worm wheel gear 16.22-inches

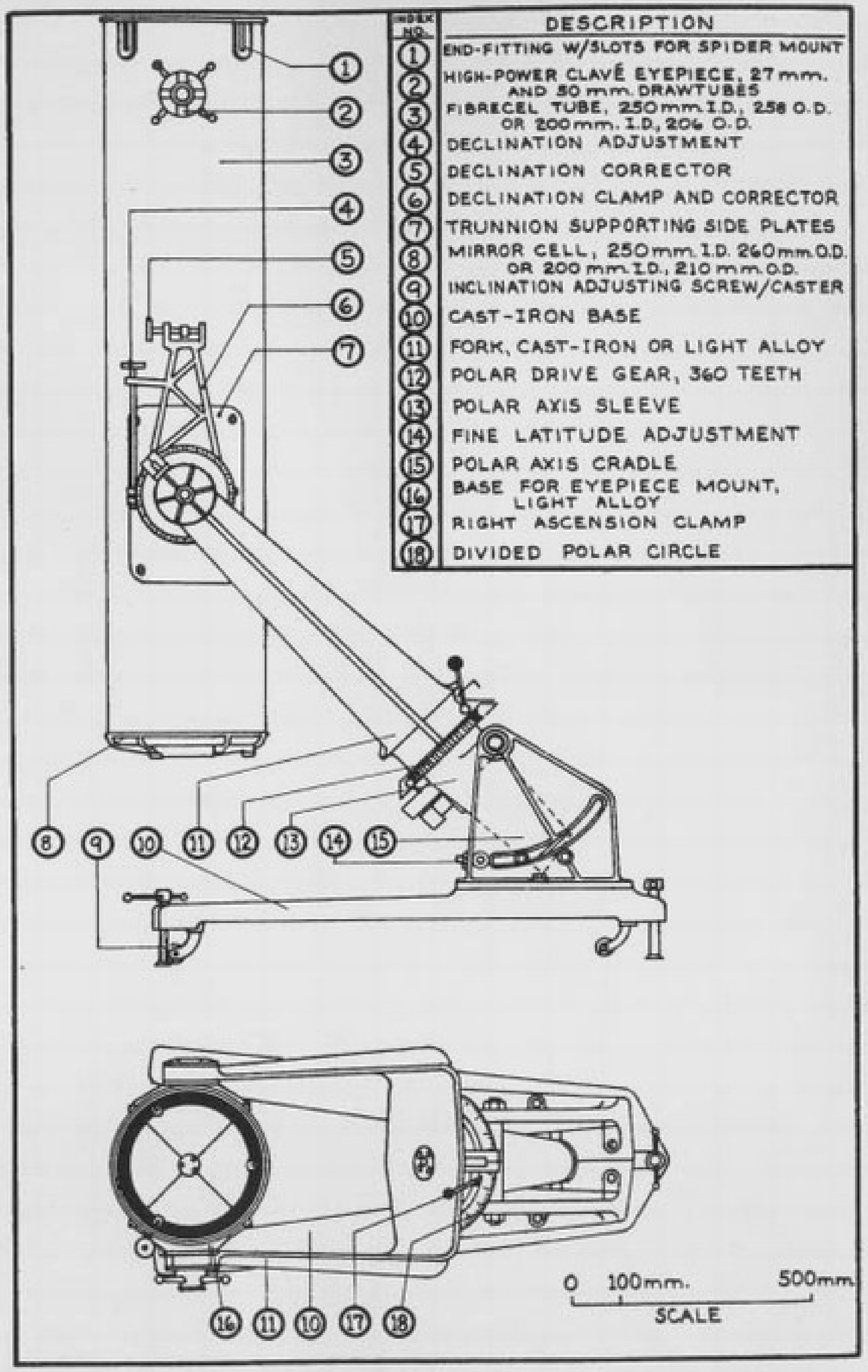


Fig. 121. Fork equatorial in commercial production (France) constructed by G. Florsch.

Fig. 122. Fork equatorial produced commercially by Mévolhon. Light alloy body, fixed latitude, bolted on bed plate and backplate. Polar axle diameter 60mm, ball bearing mounted; can be increased to 70 mm. Bronze drive wheel, 360 teeth diam. 265mm, stainless steel worm; synchronous motor with speed reducer. Setting circles indicate R.A. in minutes and declination in 15 minutes of arc divisions. Fork assembly for 150, 210 or 360mm telescopes (310 mm, axles increased to 70 mm diam.) Overall dimensions: width 40 mm, length 800 mm; height of bearings 800 mm weight 72 to 90 kg.

in diameter. The gear teeth and their spacing should therefore be *well rounded* to this precision. Experience shows that the amateur can achieve good results only at the cost of following the image attentively through a guide-scope or on-axis guider and making frequent corrections. Even if the mechanics were ideal, atmospheric refraction would still make guiding necessary. But having recognized the need for manual correction, we must still construct a logical design directed toward achieving both rigidity in the equatorial mount and smooth and accurate drive.

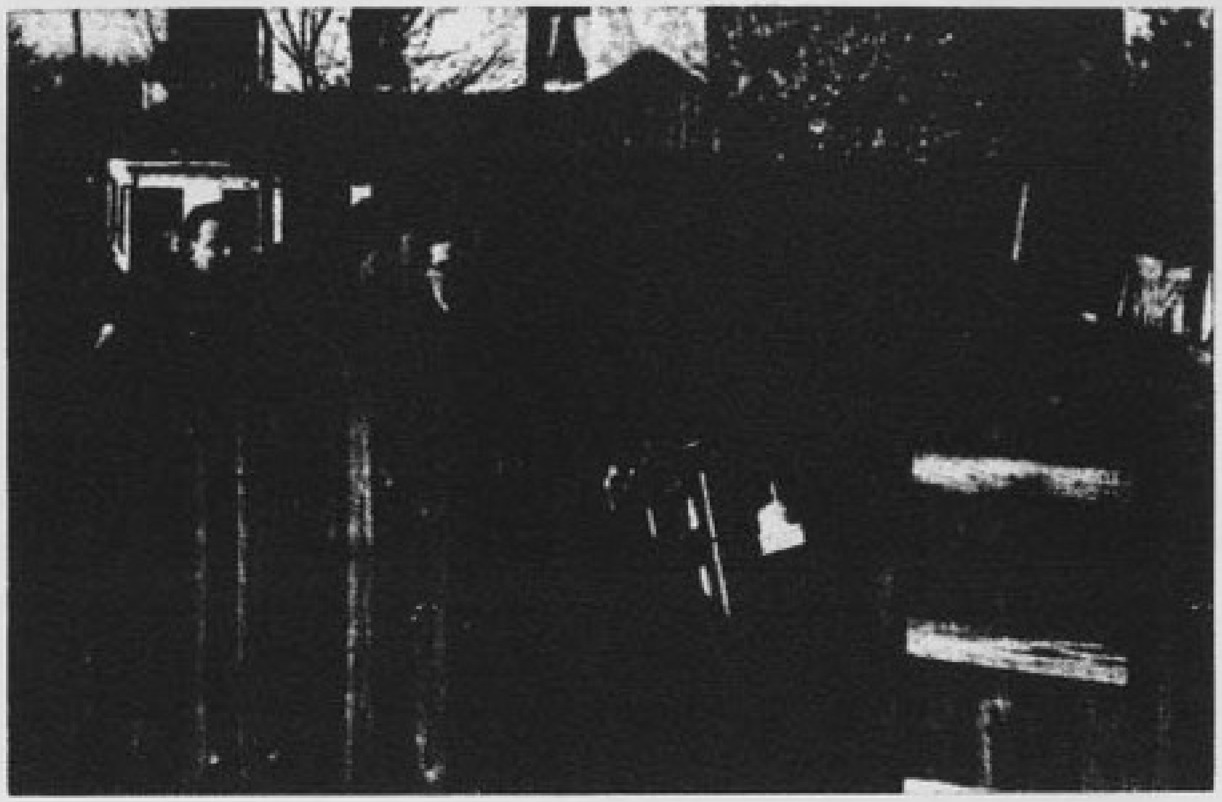


Fig. 123. 10-inch equatorial built by J.S. Dubois and the Author, 1949.

It is worthwhile to classify the list of unavoidable drive imperfections because they vary greatly in practical importance, and doing so helps to determine where our effort should be directed for maximum effect.

Cumulative advancement error.—For example the motor may be too fast or too slow; the reduction gear factor may be in error, in some cases because it neglects the difference (1/360) between the solar and the sidereal day; or the large drive wheel on the polar axis may be eccentric, giving a cyclical error with a 24-hour period. This class of defects is the least troublesome, requiring correction only about as often as those for extra-instrumental effects unless the rotation rate is greatly in error. Modern electronic oscillators make this error simple to correct. See Appendix H.

Sinusoidal errors.—Eccentricity of a *slowly moving drive member*, for example, the worm driving the large polar wheel, is a serious source of potential defects since the error amplitude easily attains 10 to 20 arc seconds for only 0.004 inch error in roundness. Corrections for this error would have to be made first in one, then in the other direction at a fairly rapid rate. The eccentricity of a *rapidly turning drive member*, rotating for example at 1 turn per second could hardly be compensated for manually, but fortunately its effect on the polar rotation would always be very small if not undetectable. Speed reducers supplied by manufacturers of small synchronous motors are therefore quite acceptable, at least for the first stages of reduction.

Gross random errors.—These are the most dangerous; the observer must be unfailingly watchful and have good reflexes if he still wants a good photograph. Local machining defects in the worm or the large polar gear are especially to be feared because even small errors begin to cause unacceptable image shifts. Grabbing in the drive is usually due to a stiff polar axis or faulty balancing of the equatorial (Secton XIV-4).

The big question, then, is how to make a large drive wheel of the necessary accuracy. The classic arrangement of a large polar gear driven by a tangent worm is unavoidably difficult and costly if built properly (Figure 124). The diameter must be as large as possible to reduce angular error caused by inevitable machining defects, and cutting the numerous teeth ties up a valuable machine for long perids of time. This is not something easily arranged by a lone amateur for a single order. A friction drive using a roller to engage the smooth edge of a polar disk (Figures 118 and 119) is an entirely acceptable arrangement and much more easily achieved.

The most attractive solution for the amateur, however, is the use of a smooth sector and a tangential steel ribbon driven by a nut running on a threaded rod. This arrangement was originally used, apparently, in the second mounting for the Crossley telescope at the Lick Observatory in 1908. J. Saget constructed a version of it in 1933 that is still a useful model for the amateur. The obvious disadvantage of the sector is that it requires periodic interruption of the drive (about every three hours in practice) to reset the nut to the starting position. It is much easier, however, to fabricate a threaded rod and its nut to a higher degree of precision than a worm and wheel combination. Further, it would usually be impossible to make such a wheel with a radius as large as that possible with a sector. Though many variations are possible in the design of a sector drive, we offer two examples.

XII-11. Drive Using a Screw and Smooth Sector

Figure 125 is not a working drawing; it specifies only some of the dimensions of a three-hour sector drive that is especially appropriate for the simple cradle equatorial of Figures 106 and 107.

Sector—Bakelized wood of the *Permaly* type is almost as stable and durable as metal but much easier to machine. If the amateur lacks suitable machine tools he has only to be very careful in boring the hole that receives the north trunnion of the polar axle. If the curve of the sector is cut with a coping or band saw, the irregularities must be patiently removed with a wood block covered with sandpaper while the sector is temporarily pivoted back and forth

Fig. 124. A high precision worm, wheel, and setting circle manufactored by Thomas Mathis.

on the polar axle. The sector should be thick enough so that the steel drive ribbon plus a second ribbon or cable drawn by the counterweight to take-up play can lie side by side on the sector rim. The radius of the sector is easily calculated: in the example shown, the screw has a thread spacing of 2 mm (0.0787 inch) and turns at 1 r.p.m. (mean time). The polar axle should make one revolution in a sidereal day of 23 hours, 56 minutes, or 1,436 minutes. If the circumference on which the ribbon is wound were a full circle, its length would be $1436 \times 2 = 2{,}872$ mm ($1436 \times 0.0787 = 113.07$ inches). Dividing by 2π, we have for the desired radius 457.1 (17.995 inches) which we round off 457. To be precisely accurate we should reduce the radius by half the thickness of the drive ribbon.

Ribbon.—The rolled-steel band should be thin enough to avoid excess rigidity. A thickness of 0.008 inch should suffice, and width of 0.5 inch. If necessary, the steel banding used for crating will serve. Naturally, the piece of banding selected should be free of bends or creases. The ribbon is clamped (Figure 125) on a yoke coupled to the nut by two metal bands, these being very loosely held by shouldered screws.

Screw and nut.—These are precision parts that require the most careful attention. The screw is cut on an accurately aligned lathe in semi-hard steel. The nut is made of bronze, and long enough to reduce random errors. The nut should not be too tight; on the contrary, it should be very free. Axial play is taken up by traction supplied by the weight. Rotation of the nut is prevented, without constraining it, by a side lug bearing on a long straight-edged steel bar. The precision of the screw will be equivalent that of the lead screw on the lathe which generates it. The lathe's lead screw may be worn on certain sections (for example, near the head-stock) and therefore may be a source of cumulative error. Heat generated in the machining of a long, relatively thin piece may likewise be a cause of cumulative error, but this defect, like that of a small constant error in motor speed, is hardly troublesome. In general, recourse to a precision screw cut with a master milling tool on a special machine does not appear useful. Actually, plain, commercially available threaded bar stock will serve for a drive which, if not perfect, is in any case quite acceptable. The majority of this rod manufactured in the United States is made by rolling bar stock between precision dies. Many pieces will show a cumulative error of only 0.0001 inch over 1.0 inches of travel. This type rod is available in various diameters and lengths up 6 feet. It is also available in brass, mild-steel, and stainless steel. These rods work well if burrs are removed by using grease loaded with 10-minute emery and running the nut many times over the length of the screw. Naturally, after this lapping of the screw and rod assembly, the parts are carefully cleaned with solvent before applying the working lubricant. In Figure 125, axial thrust of the screw is taken up by a 5 mm (0.20 inch) ball seated in the enlarged centering hole at the end of the screw and bearing against the hardened flat end of a second screw. This arrangement eliminates periodic error found in conventional end-bearings

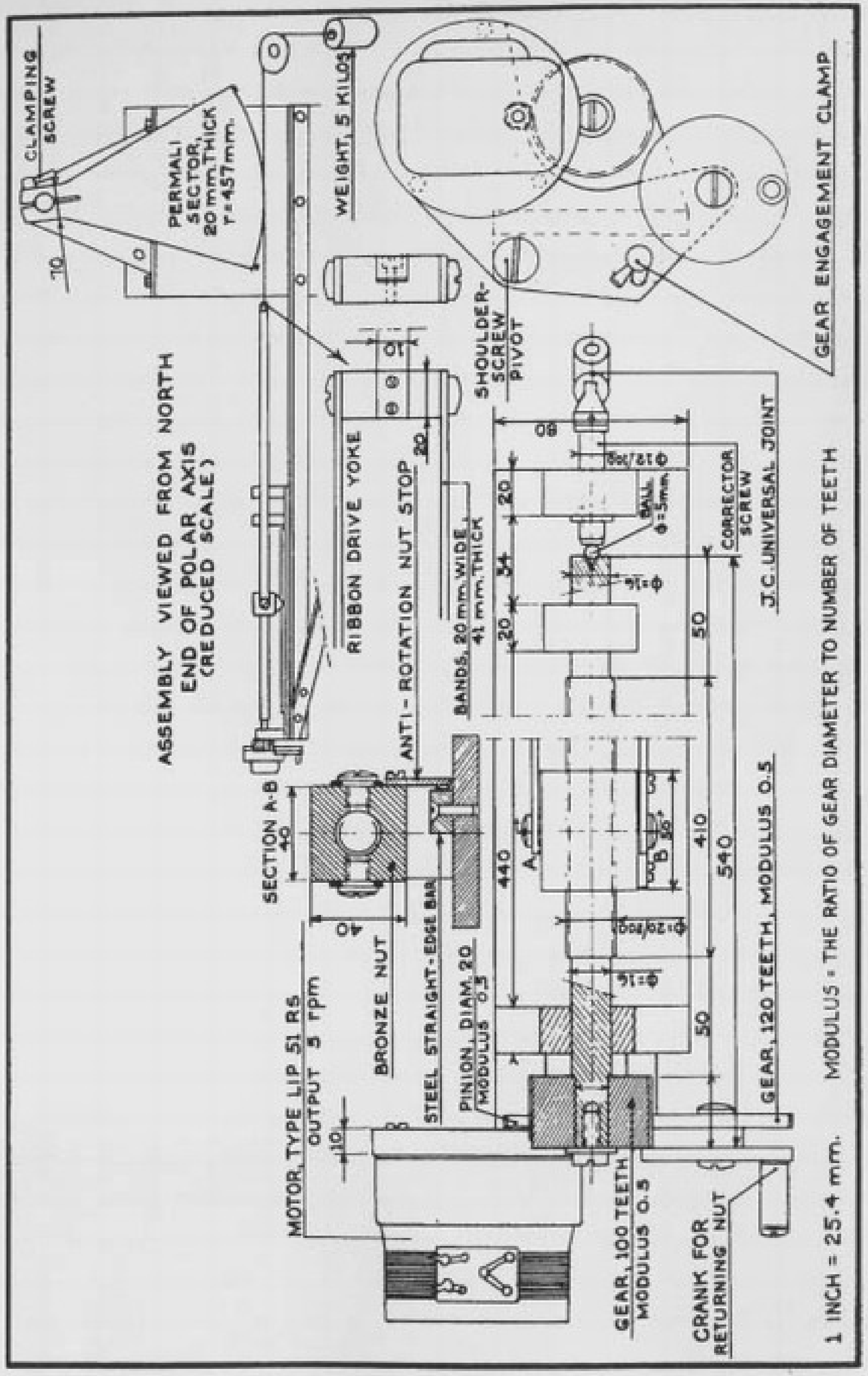


Fig. 125. General configuration of screw-and-sector drive.

and makes possible very precise correction for image drift. This has two disadvantages: first, the correcting screw is not easily accessible; a linkage through several universal joints would be needed to bring the operating control near the eyepiece. Second, the gear fastened on the screw would have to be special,[6] i.e., extra-long in the axial dimension, or else coupled to the screw in an extendable manner. Finally, the dual positioning system could introduce errors if not carefully made.

Motors.—The classic arrangement of a suspended weight controlled by gears driving a speed regulator is entirely practical, especially if the regulator is precise. Even the governor of an old wind-up phonograph drive with rotating double pendulum and friction disk will work, but the distance over which the weight can drop is usually not long enough to avoid frequent interruptions during an exposure.[7] It is much more practical, if electrical current is available, to use a small electric motor.

The most convenient are *synchronous motors.* So long as the load is less than the threshold where phase slippage occurs, their speed is constant and depends only on the frequency of the a.c. supply. In the United States the long term stability—hours and days—is very high. However, because the load on the system is constantly changing, the rotational frequency (nominal 60hz) varies slightly from minute to minute. These variations are not a problem for the visual observer; but they are a problem for the astrophotographer. Therefore, the observer must make corrections with an electronic *drive corrector.* (See Appendix H for circuit).

In Europe a particularly useful synchronous motor is the L.I.P.[8] model 51S, operating at 3,000 r.p.m. on a 50 Hertz supply with a power of 8 watts and a synchronous torque of 10 gram-cm. Similar motors are made by Hurst [9] and Bodine[10] in the United States. The low torque on a rapidly-turning shaft of the motor cannot be directly coupled to a worm and worm wheel; the friction is too high. It is better, at least for the first stages of speed reduction, to use a spur-gear reducton train commonly supplied with such motors. These have reduction ratios that are very practical for our requirements. Figure 128 shows the use of an L.I.P. reducer whose slow shaft turns at 5 r.p.m. and delivers a synchronous torque of 3,200 gram-cm (similar U.S. motors are rated at 100 ounce-inches). This is more than enough to overcome the usual friction of the screw nut and its bearings. Since the slow shaft projects from both sides, the desired rotation direction is always available simply by reversing the motor position. We advise against using reducers whose slow shaft turns less than 1 r.p.m.), since the teeth in the gear train can be over-stressed if the load

[6] For example, universal joints from Comptoir Central D'outillae Mechanique., 22, avenue Daumesnil, Paris-12^e or Stock Drive Products, 55 South Denton Avenue, New Hyde Park, NY 11040.

[7] Lunettes et Telescopes, p. 348.

[8] L.I.P., Industrie, 25, boulevard Malesherbes, Paris-8^e.

[9] Hurst Mfg. Corp., 1551 E. Broadway, Princeton, IN 47670.

[10] Bodine Electric Co., 2500 W. Bradley Pl., Chicago, IL 60618.

unexpectedly stalls the motor. Preferably, as shown in the figure, the final speed reduction is achieved with a sturdier, external gear train. Matched pinions and wheels are regularly stocked by precision gear makers and specialty houses.[11] The motor in this case is supported on a pivoted plate to provide for simultaneous disengagement of the motor and engagement of a hand-operated gear for the rapid return of the nut.

Figure 126 shows a slightly different arrangement made by Walbaum. The motor is mounted directly to the end of the screw. The screw is mounted along a section of U-beam. Note that the sector is formed out of angle iron.

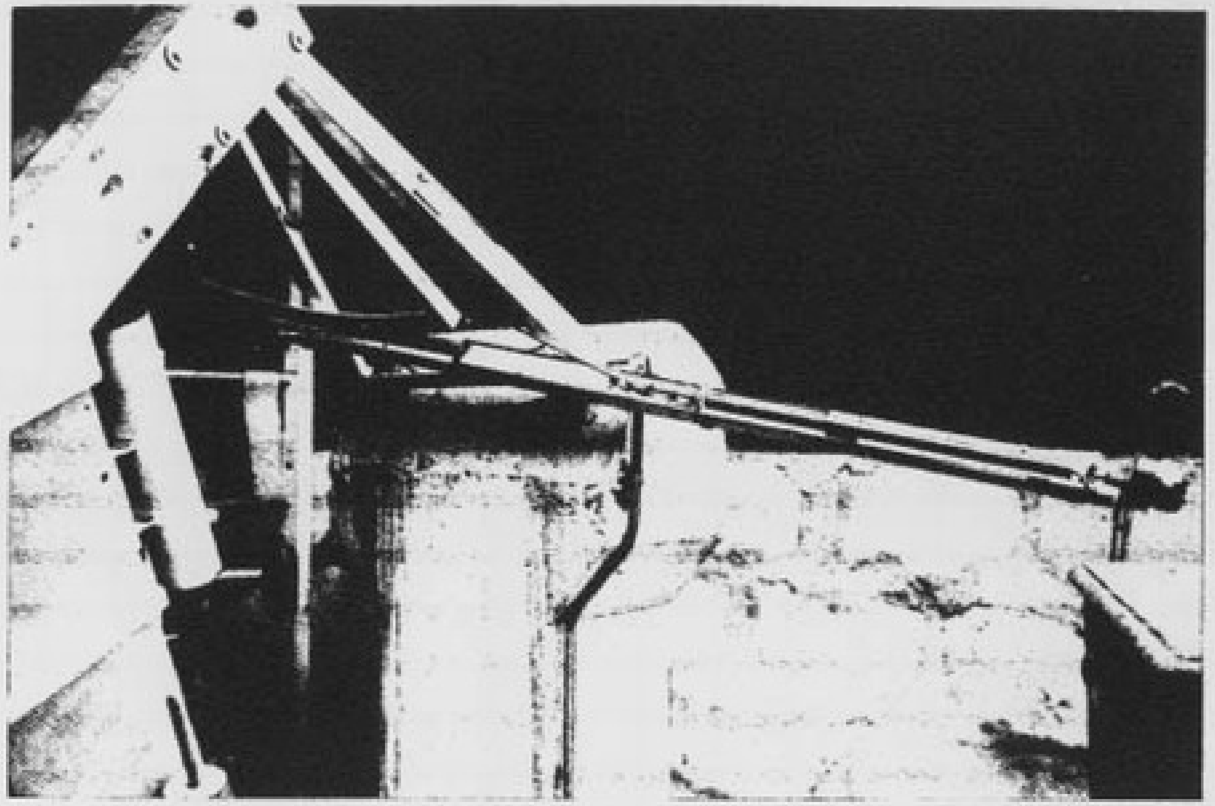


Fig. 126. Screw-and-sector drive (constructed by Walbaum).

XII-12. Classic Drive Using Worm and Wheel Combination

Because the clearance on German fork mountings is limited, installation of a ribbon-driven sector is often difficult. It is usually necessary to fold the drive ribbon down along the supporting pier by using several pulleys. Also, there is the inconvenience of drive interruptions to return the nut when it has run its course. With a friction drive against a larger smooth wheel, various precautions are necessary to insure a smooth, positive rate without exceeding the torque load limits on the drive. For these reasons the classic worm and worm wheel combination is still widely used. Many old equatorials were designed with a disengagable worm, the wheel being permanently bolted to

[11] S. A. Horlogerie R. Belot, 55, rue de Saintonge, Paris-3^e or in the United States, PIC Design, Box 335, Ridgefield, CT 06877.

the polar axis and in some cases supporting a setting circle. It is better to provide a wheel with a clutch to disengage the axis, thereby always keeping the worm engaged with the wheel. This assures uniform wear along the worm's surface and avoids damage of the teeth on the wheel by sloppy engagement of the worm. Using worm and wheel combinations salvaged from used machinery can cause problems. The fact that there may be only a small number of teeth is not *per se* an indication of poor precision, but the mounting of such gears is difficult to adapt properly to an equatorial. Custom fabrication of a worm wheel 12 to 20 inches in diameter is a difficult task, and one is never quite sure that the necessary precision has been achieved. Unless one has access to a professional machine shop that specializes in gear cutting, it is best to find a supplier who routinely supplies the astronomical trade.[12] Of course, the dedicated amateur may want to tackle even this phase of construction.[13]

Even when the screw is not intended to be disengaged, it is often mounted in a swinging cradle with a weight or spring forcing the worm into the worm wheel's teeth. We prefer to reduce friction to a minimum by allowing a slight amount of play between the worm and the teeth of the worm wheel. The use of springs or weights to compensate for thermally caused expansion presupposes a problem not found in most amateur instruments. The play itself is not evident except where the corrections are made in reverse and the rate of correction is greater than the diurnal motion. Periodic error in the motion of the worm will be reduced by axial abutment on a ball (Figure 127). A corrector acting on the screw abutment is as applicable here, as in a drive using a threaded rod, nut, and sector (Figure 125). This saves the cost of a differential corrector, where cumulative play can be a problem on the slow-turning output.

As a concrete example, we present the following details of a motor and reducer assembly we built for the German equatorial mounting of the 6-inch refractor for the Astronomical Society of France (Figs. 127 and 128). These details need not be followed to the letter; since they were adapted to components available at the time, particularly the polar gear with its disengaging worm and the first reducton stage designed by Manent.

Polar Gear.—The worm wheel has 360 teeth and a diameter of 8 inches. Note that if there were 359 teeth, we would have a good conversion from mean time (motor turns) to sideral time. The conversion on an existing equatorial could be made by using an epicyclic gear train, but the complication might be more annoying than useful. The error of $1/360$ is usually hidden in other causes of drift; change in power line frequency, refraction, etc. In a 10-inch or 12-inch equatorial telescope it would be wise to provide a polar worm wheel that is larger (for precision) and sturdier. A suitable diameter would be 12 inches.

[12] Thomas Mathis Company, 2353 American, Hayward, CA 94545

[13] Machinery's Handbook, Ed. Paul B. Schubert, 21st Edition, 1981, Industrial Press Inc., 200 Madison Ave., NY NY 10157.

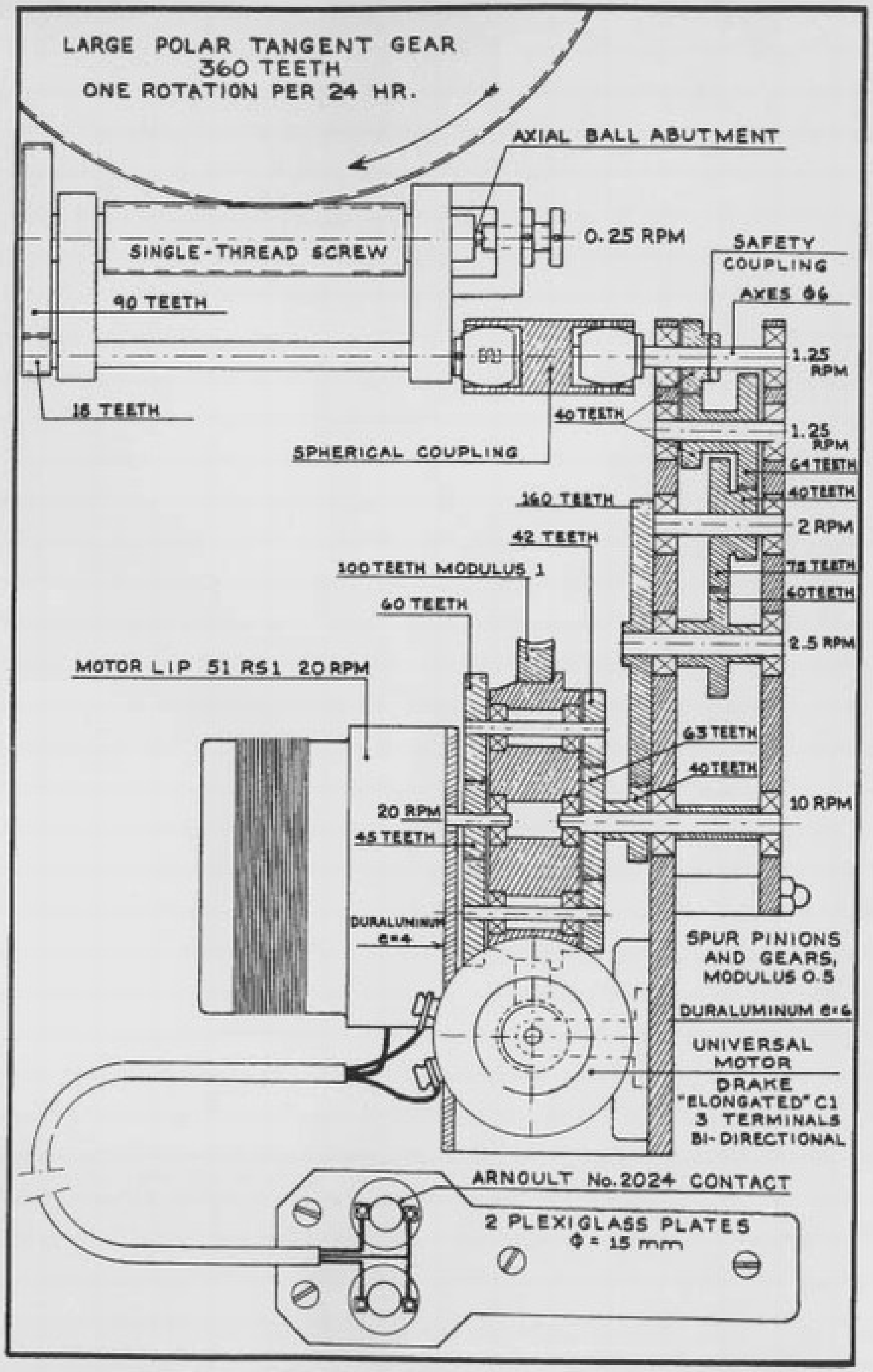


Fig. 127. Schematic assembly of motor and reducing gears on the 153mm equatorial of the Société Astronomique de France.

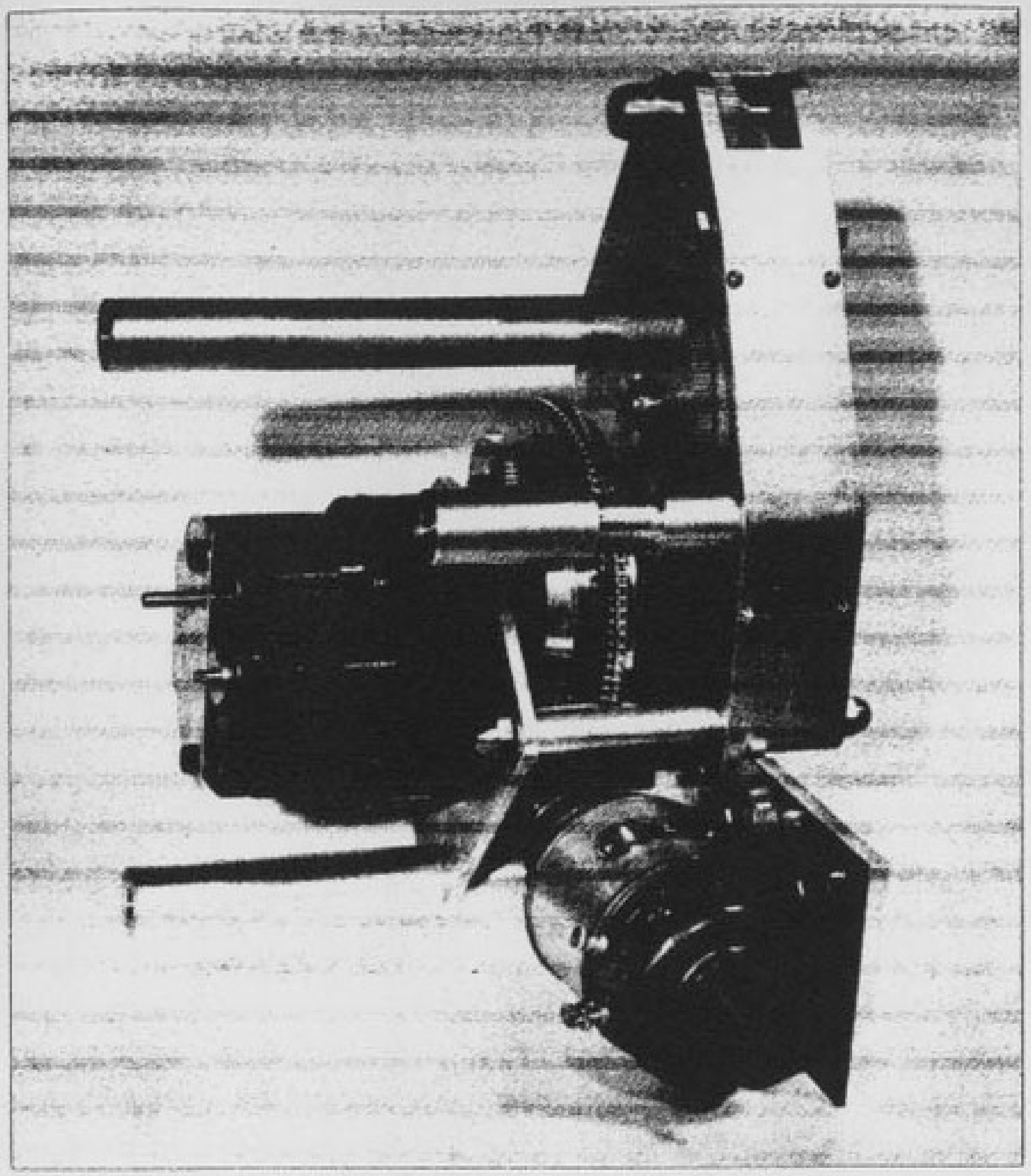


Fig. 128. Motor and speed reducer for the 153 mm equatorial of the S.A.F.

Reducton Gearing.—To be sure of having a sturdy and compact unit, we adopted a design requiring a substantial amount of precison machine work. The possibility of fatigue in the small L.I.P. speed reducer was avoided by selecting an output shaft speed of 20 r.p.m. Mounting of the spur gear shafts on ball bearing races assured good efficiency and a minimum of maintenance. Spur gears are preferred for high to low speed reduction. A reduction assembly using a worm and worm wheel had to be taken out of service in a few years due to excessive wear. The rato of 8:1 in the large reducer could have been accomplished in a single stage, but because the motor had to be recessed in the

base to minimize interference with the telescope tube as it approached the meridian we used intermediate gear stages.

When correctly balanced (Section XIV-3) and lubricated, the equatorial required a driving torque of 0.5 kilograms-centimeters, due mainly to friction of the worm against the worm wheel. This torque is measured on the shaft turning at 1.25 rpm. The reducer will drive this axis with 25 kg-cm torque without loss of synchronism in the 8-watt drive motor.

A fail-safe segment on the output pinion is designed to shear if the torque becomes as high as 30 kg/cm. These values are indicative of the application range of small motors and reducers. In practice, much more friction can be tolerated than in this example, but it is best not to exceed ⅓ of the available torque on a newly assembled and adjusted instrument.

Differential Corrector An electrical corrector using a reversible motor permits the insertion of a differential between the rather rapidly turning elements of the drive if, as in the present case, the satellite carrier wheel is driven by a tangent wheel to insure irreversibility. The proportions of the planetary and satellite gears detailed in Figure 127 are multiples of a differential calculated by Couder for a table equatorial with a 1,100 pound load. Note the symmetrical arrangement of *two axes* supporting the satellite-carrying ring, so that power is transmitted as pure torque on the axis and lost motion is reduced. Speed reduction between the input axis and the output is equal to 2. If the satellite ring turns at the same velocity as the input axis, the output axis has a velocity that either cancels or doubles the input velocity, depending on the direction of correction. Corrections under these conditions are made at a velocity equal to the diurnal movement, which is rather high for fine photographic corrections that are typically 1 arc second in magnitude. However, a second, slower speed may be obtained when desired by using a push button switch to insert a series resistor into the circuit.

Hand-held control.—The dual push button control of corrections is a mounted Plexiglass paddle to keep weight to a minimum. The electrical contacts must be of excellent quality to assure long life and precision in making short corrective actions.

ACCESSORIES, MIRROR COATING PAINT AND METAL PART FINISHING

XIII-1. Finders

Telescopes having a field of view of less than half a degree require some form of finder if they are to be aimed conveniently. We shall describe several types of finders which either are in common use or can be easily built and applied to the Newtonian telescope.

The simplest is a sighting arrangement (Fig. 129A) that employs no optics at all, but merely a field stop and a sighting aperture. For easy visibility against the night sky, the field stop takes the form of a fairly broad ring. The side facing the observer may be painted white, and if need be, illuminated faintly by the light used in taking notes. Luminescent paint has also sometimes been used. An ingenious amateur has even described a finder consisting of a glass tube the inner, protected surface of which is coated with luminescent material.

Despite such refinements, simple aiming devices are of little use for stars as faint as third or fourth magnitude. The eye cannot focus simultaneously on the star and the field stop, and centering of a selected star is quite difficult. It is not extravagant, therefore, to provide a small telescope as a finder.

Many amateurs may already possess a small telescope with a 20- to 40-millimeter diameter objective. If it is of the collapsible type, made in several sections, it must be properly braced; otherwise, it will be insufficiently rigid to insure that the optic axis remains parallel to that of the main telescope.

Another excellent possibility is a monocular prism telescope (Fig. 129B), of 30-millimeter objective diameter, for example. This is usually 8-power and has a field angle of 6° or 7°. The eyepiece is usually of positive type (a Kellner or one of its adaptation); therefore a cardboard stop can easily be mounted just ahead of the field lens to support cross hairs that will be in focus at the same time as the image. A suitable V-notch support and clamping collar can mount the telescope safely without marring it. A finder which gives an upright image is best; at small magnifications, with wide fields of view, the observer can compare the image directly with a nearby star atlas. Some prism monoculars are much more powerful; artillery telescopes, for example, may have 75-

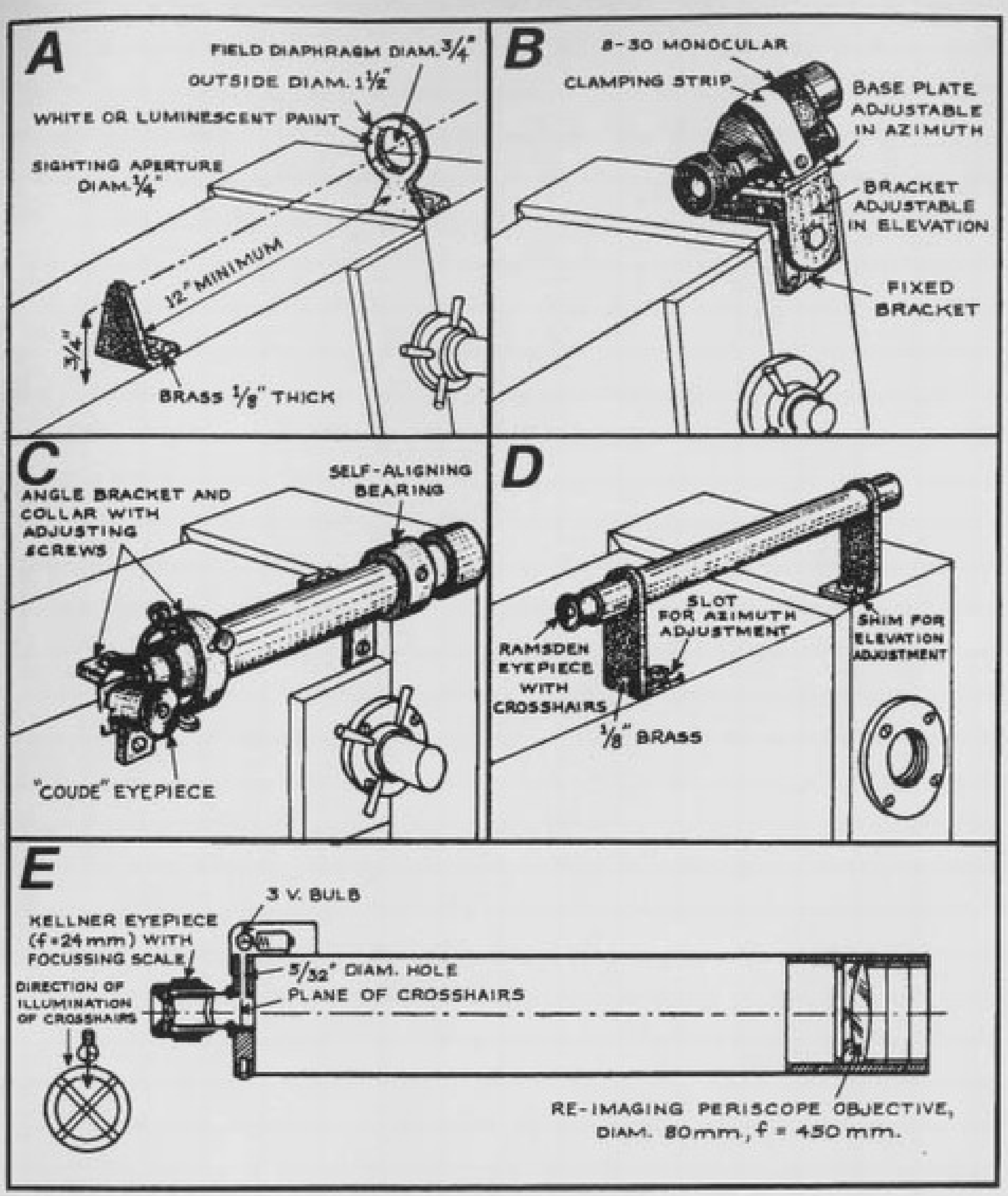


Fig. 129. Various types of finders.

millimeter objectives and be of 15 to 20 power. Their weight and cost, however, do not make them a logical choice for our standard instrument.

Figure 129C shows a classic mounting for a 40-millimeter telescope using two angle-brackets and a centering collar. The tube is often reinforced where it is clamped by the centering screws. At the other end, the tube is supported in a self-aligning bearing. Alternatively, identical centering collars may be used at both ends. A rotatably mounted total-reflection prism permits convenient

positioning of the eyepiece with minimum interference from the main telescope tube. The author prefers the straight finder telescope, however, because comparison of the image with a star chart is easier, even if (with noninverting eyepieces) the chart must be inverted. The elbow-eyepiece gives a *mirror* image, so that charts must be viewed either through the back (against a light) or in a mirror. The finder, after all, is not for hunting stars merely—true to its name, it should help find!

Figure 129D shows a more modest finder which the amateur may build for himself. The telescope is smaller than that of Fig. 129C: objective diameter is 20 to 30 millimeters; focal length is 200 to 300 millimeters. The objective may be an achromatic doublet, of the Clairaut type, for example, or the front element of an old rectilinear camera lens. The eyepiece is a Ramsden (Section IV-2), about 30 millimeters in focal length, ahead of which are mounted crossed wires, 0.002 to 0.004 inch in diameter (e.g., copper, B & S gage 18 to 24), heavy enough to be visible, if desired, without special illumination. The tube is soldered to a rather high pair of uprights—3½ to 4 inches—so as to be easily accessible at least to the left or the right eye; the observer chooses the side of the main telescope body which will be more convenient. (Figure 129, for example, shows mounting for use by the left eye.) The finder is adjustable in azimuth by virtue of the transverse slot at the base of one of the uprights, and adjustable in elevation by the insertion of shims as necessary under the other upright.

Ideally, what are the characteristics of the finder? The field of view should probably be between 3 and 6 degrees wide. Take the smaller of these figures: assuming that the eyepiece has an apparent angular field of 50°, we find the magnification ought not to exceed about 17; and if the exit pupil is 5 millimeters, we shall need an objective aperture 17 times as large, or 85 millimeters. It should be possible to make a powerful finder of nearly these characeristics fairly easily and inexpensively, using surplus optics. A design currently in use by the Paris Observatory group (Fig. 129E) is 19-power, has a field of 2°45′, and an aperture of 80 millimeters. The exit pupil is therefore about 4 millimeters. The telescope weighs only 3 pounds, and permits very easy location of any object shown in the large *Argelander* atlas. The Lyra nebula, for example, is easily recognizable. It is a veritable *richest-field telescope*. Figure 129E shows the arrangement for lighting the cross hairs: a small 3.5-volt bulb illuminate the cross hairs at a grazing angle against the dark background. The small square (about 1/16 × 1/16 inch) framed by the cross hairs at the center of the focal plane allows precise aiming without eclipsing the star under view.

XIII-2. Photographic Plate Holder and Lateral Eyepiece

Our discussion on equatorials and polar drives (Chapter XII) makes it clear that almost continuous monitoring and frequent adjustment of telescope position is needed in order to obtain well-rounded photographic star images at the focus of an amateur telescope of 6-inch or larger aperture. This is

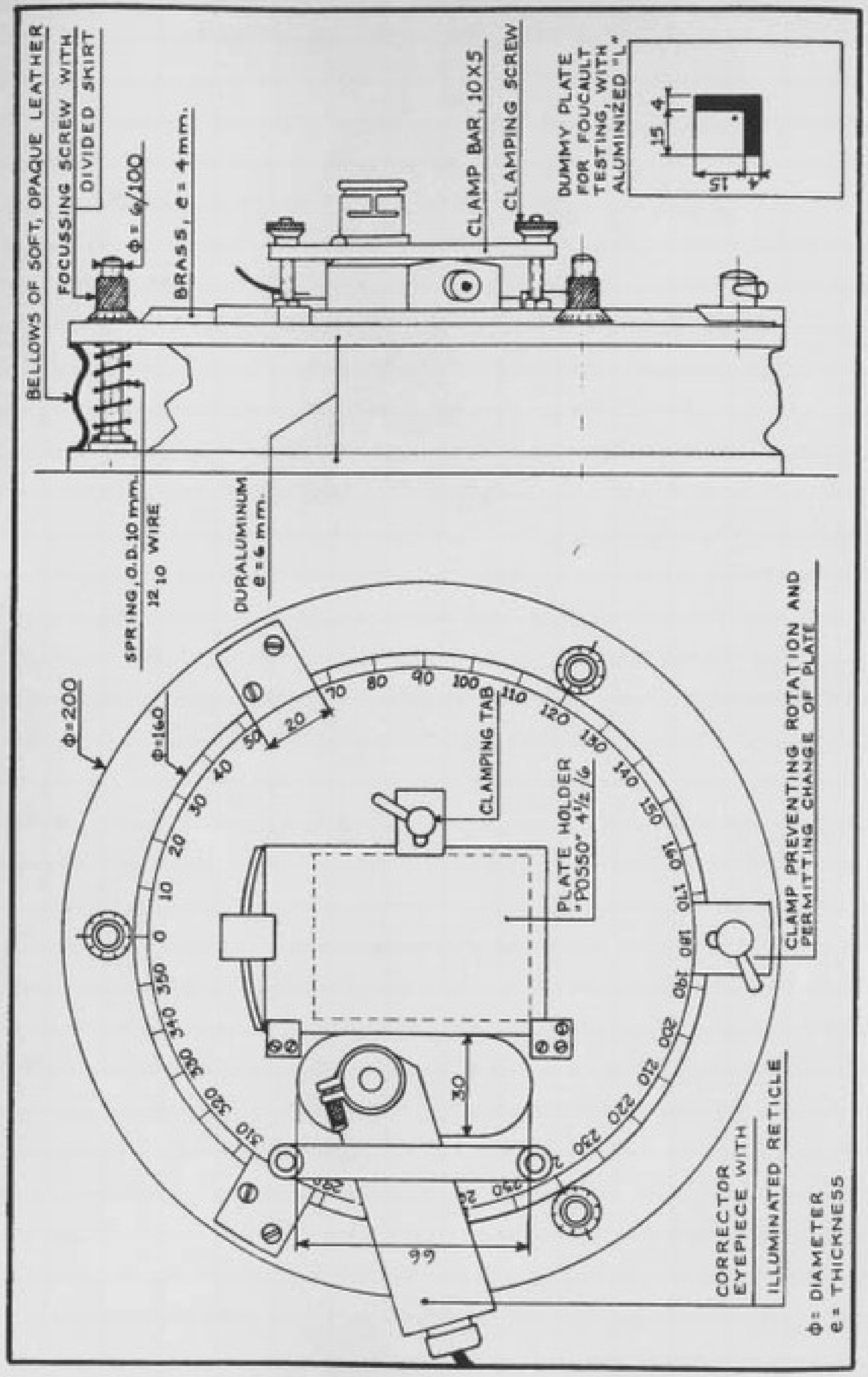


Fig. 130. Photographic plate holder with lateral corrector eyepiece.

the problem of *correction*. There are astrographs of several meters focal length which have a *guiding refractor* of comparable power and focal length. This arrangement is not precise because there is always some *differential flexure* between the astrograph and its guiding reflector. Corrections made at the reticle of the refractor are therefore not strictly valid at the astrograph's photographic plate, particularly if the exposure is long and the angle from the pole is large. There are acceptable solutions for refractors, for example, the use of identical steel tubes in carefully designed twin arrangement. But to eliminate all causes of drift at the focus of a Newtonian reflector, for example, it is absolutely necessary to make the corrections through the reflector itself by surveillance of a off-axis star just outside the photographic field. This is done with a special laterally-offset guiding eyepiece fitted with an illuminated reticle. The concept of a photographic plate mounting with an offset eyepiece originated with the English amateur Common (1890). On large instruments, especially in the early days when exposures were very long, a second corrector eyepiece has been necessary on the other side of the plate to detect and allow correction for rotation of the field caused by atmospheric refraction. The single eyepiece will suffice on an amateur instrument used near the meridian for exposures up to 2 or 3 hours. However, the object must be at least 20 degrees above the horizon and the instrument's polar axis aligned with the refracted pole (Section XIV-4). The dimensions of the diagonal flat in a Newtonian should be calculated to adequately illuminate the photographic field; yet, this mirror must not be oversized. The pupil will therefore almost inevitably be vignetted in the guiding eyepiece. This defect, combined with the substantial off-axis coma of the paraboloid, markedly cuts down the image intensity and requires a fairly bright guide-star. A principle goal in designing the plate carrier must therefore be to reduce the off-axis distance of the eyepiece to a minimum. The selected eyepiece position should correspond to the useful field of the mirror (See Table 6, Chapter III), and the diameter of the eyepiece itself should be as small as possible.

On large telescopes, where the high inertia precludes correction by changing the pointing position of the instrument, the photographic plate is mounted on an x-y positioning carriage permitting very fine adjustments. This refinement is not necessarily advantageous on an amateur instrument, where inertia is less likely to be troublesome than vibration caused by the slightest touch of the eyepiece and where correction applied to the drive can be vibration-free.

These principles are illustrated in the design, Figure 130, of a plate mount of 4.5 × 6 cm format that is well suited to a *f*/6 Newtonian of 10- to 12-inch aperture.

Plate Assembly—Two rings of ¼"-thick aluminum form the body of an adjustable focusing cell. The space between is enclosed by an opaque bellows. Focusing is done by adjustment of three rods threaded 100 turns per cm, each fitted with a milled brass nut carrying a scale with 1/10th mm divisions readable to an estimated 1/100 mm. By individual screw manipulation, the plate can be made perpendicular to the optical axis. This is facilitated, if necessary, by reflection in a parallel-face plate laid against the disk. Once perpendicularity is obtained, the readings are noted on the three milled nuts and focal adjustments are thereafter made by *equal rotation* of the three nuts. The brass disk is fitted with small squares that locate the position of the plate holder. A rather large window provides a search area to find a star accessible to the corrector eyepiece. These stars are rare in the regions of high galactic latitude where galaxies are photographed; it is often necessary to search all around the field. For this reason, the brass disk is bevelled and rotatable in angular position. It is also helpful to know the orientation of the plate with respect to the diurnal movement. This can be determined by reference to a scale, divided in degrees, on the bevel of the plate. The locking tab is slotted to allow rapid removal of the plate holder and substitution of a similarly dimensioned dummy plate fitted with a capstan eyepiece mount for visual observation in the usual way. If the focal plane does not extend out far enough, the eyepiece mount can be recessed.

Photographic Plate Holder.—Professional instruments are equipped with machined metallic holders that precisely locate the photographic plate. This permits interrupting long photographic exposures for refocusing by the Foucault test. The holder is then returned to its working position with a precision of about 0.0004 inch. For the more modest present mounting, we settle for an ordinary commercial cut film plate holder. Dismounting of the holder during an exposure is not recommended. The focusing tolerance for an $f/6$ beam is 0.002 inch, a precision difficult to attain on a ground-glass screen even if it has a fine grain. Focusing must therefore be done on a bright star by *Foucault testing*. Because turbulence (Chapter XV) is often troublesome, the brightness of the right and left sides of the mirror have to be mentally averaged. To do this test, the ground glass is replaced with a clear glass plate of the same thickness. This may be a photographic glass plate from which the emulsion has been removed, and on which an opaque area in the form of an L has been formed by aluminizing (Section XIII-6). The inner edges of the L serve as two mutually perpendicular Foucault knife edges oriented 90 degrees apart (Fig. 130). When the glass is sent out for aluminizing, it is accompanied by a metal foil mask with an L-shaped opening of the desired dimensions. It is wise to confirm that the position of the emulsion in the plate holder is precisely the same as the plane of the Foucault edges. Insertion of the knife edge can be made by slow corrective movement of the telescope, if necessary, by pressing lightly on the tube to flex the mounting. A dummy plate holder fitted with a weak eyepiece is convenient for visual centering of the object to be photographed.

Corrector Eyepiece.—Figure 130 illustrates a unit we used on the 31.5- and 47.25-inch reflectors at the Observatory of Haute-Provence. It is now produced commercially by Clavé. The overall size of the eyepiece is small enough to use with the small plate mountings described here. An 18 mm O.D., 16 mm I.D. drawtube accommodates special Plössl eyepieces of $f = 12$ or 20 mm. This drawtube supports the reticle and can be secured in the focal plane. The reticle is far enough from the inside of the plate mounting to avoid fogging caused by cross-hair illumination. A hole bored in the eyepiece mounting accommodates a low-voltage lamp as well as a diaphram with a decentered opening which must be adjusted by each observer, depending on the lamp selected. To cut out the shorter wavelengths of the light that might affect the photographic plate, a green filter may also be inserted. A rheostat is also provided for controlling the light intensity. This allows adjustment to maintain night vision, yet track on the selected guide-star. The eyepiece mount is clamped flat on the brass disk in the selected position by a yoke and two fastening screws. Although many attempts have been made to engrave reticles on glass in various ways, it seems impossible to avoid light scattering due to soil or dust. The easiest reticle to illuminate properly against a completely black background is one made with spider filaments. This makes precise corrections easier, especially when the guide-star is faint. Spider filaments are not provided by the eyepiece maker. However, it should not be difficult for the observer to mount or replace filaments rapidly. Here is how to go about it:

First assemble the following materials:

(1) *A spider cocoon of good quality.* Common garden spiders such as *aromaeous diadematus* spin round webs with single or multiple strands that are coated from point to point with a sticky substance. These prove to be unusable for our purposes. At the beginning of winter, the spiders make cocoons that they prefer to hide in window corners or in other rarely used openings. These cocoons are small, irregular packets of grey to light yellow color. They are formed of non-sticking filaments 8 to 10 microns in diameter extruded by the spider from a special spinneret. The cocoon is considered good if the filament is not wavy and is elastic enough to be pulled straight with slight tension.

(2) *A rosin stick,* obtained by pouring the following mixture, prepared in a small casserole, into a paper mold. About 100 grams of rosin is melted, for example, and 25 grams of beeswax then added. If the reticle is to be used at temperatures above 80 degrees F, the wax content may be reduced to 18 or 20 grams to avoid slippage of the filament. On the other hand, it may be increased to 30 grams if the temperatures may go below 32° F.

(3) *A small spatula,* made by flattening the end of a ⅛-inch diameter grass wire. To use this tool, it is heated in a gas pilot flame or an alcohol lamp, or simply with a match. It will then easily melt and gather up a small quantity of rosin.

The reticle ring is made with 4 notches, 90 degrees apart, in which the cross-hairs are positioned. An external bevel receives the small drop of rosin, which should not extend past the plane of the reticle or the diameter of the mounting. Following this procedure the filaments are not dislodged when the reticle ring is later slipped into position inside the eyepiece barrel.

The rosin will adhere well only if the metal is warm. Preferably, the reticle ring is first heated to 110 or 140° F; then with the spatula heated so that it will melt and remove some rosin from the stick, a thin film of rosin is deposited on the bevel adjacent to each notch. The cooled assembly is supported on a small cylindrical holder. Four or five inches of filament are pulled from the cocoon, the latter being used as a hanging weight to insure that the filament is not wavy and to prevent the free end from flying away. The stretched filament is easily directed into the two notches on the reticle ring, and its ends then folded back on the bevel and the cylindrical section where they can be held under tension by the thumb and the index finger of one hand. With the other hand, the spatula is first applied to the flame, then to the rosin stick; a further reheating is useful before touching the two spots where the filament passes over the bevelled edge.

The advantage of rosin over laquer-based cements, for example, is that it solidifies in only a few seconds. The filament can be released and the ends extending beyond the seals can be cut. This avoids the painstaking manipulation of small balls of wax which must be used as weights to maintain tension while the cement dries. However, modern fast drying glue now available is even easier to use.

XIII-3. Paints and Metal Part Treatment

The wood tube of the standard telescope should be protected against humidity change which can rapidly affect the telescope adjustments. In addition, a finish made with a very bright pigment, preferably an absolute white, is always desirable to minimize daytime heating by the sun, a source of instrumental turbulence. Shellacs and marine varnishes do not satisfy the latter requirement because the binders in these materials all absorb strongly in the infrared at wavelengths of a few microns. Only exposure in direct sunlight makes clear the superiority of a white paint. A treatment we can recommend is the following: 1.) saturate the wood with as much linseed oil as it will absorb, and allow it to dry thoroughly; 2.) lightly fill in any cracks or gaps, and smooth with sandpaper; 3.) apply two coats of pure white enamel. When using varnished Bakelized paper, it is advisable to apply a white primer coat before applying the enamel in thin layers to avoid running. The best metal tubes are those made of polished aluminum. These should never be painted. However, the irregular *bloom* of the aluminum rapidly reduces its reflectivity and makes it a repository for dirt. If possible, it would be best to *anodize* the tube. This consists in forming a thin, uniform aluminum oxide film several tens of microns thick. Although this absorbs more infrared than new, untreated aluminum, aging will be unnoticeable.

It is hard to be overly careful about preventing rusting of any iron components. After an initial trial assembly of the instrument, note all surfaces that need protection: threaded holes, etc. Dismember all the parts, remove

rust, clean, and apply at least two coats of genuine *red lead* before painting with the two coats of white enamel. This may appear fastidious to some, but the effort will be repaid generously by long service.

The inside of the tube and all parts lying in the beam must be a *very flat black*. This applies especially to parts of the tube facing the plate holder in a photographic Newtonian, in the event that urban light cannot be avoided. To minimize weak reflections at grazing incidence, nothing compares with black velvet. The tube can be lined with velvet by securing it with one of the contact type cements used to bond plastic laminate kitchen countertops to the wood underlayment.

Flocking produces a velvety coating that is less matte than velvet but very effective. However, bits of the flocking fiber are always escaping from the surface after drying and necessitate more frequent cleaning of the mirrors.

The following is a formulation for a black matte paint that will be satisfactory in most cases: shellac thinner (methyl alcohol), 100 cc; shellac flakes, 20 grams; lampblack, 20 grams. Allow the shellac flakes to dissolve completely in the alcohol. Then slowly mix in the large volume of lampblack.

Blueing of brass parts improves their appearance and their resistance to natural oxidation that rapidly makes even the best fitted drawtubes unpleasantly hard to operate.

The brass parts are first meticulously cleaned, especially if they are not newly machined. They are carefully degreased with a solvent such as mineral spirits, or with dishwashing detergent (typically lauryl sulfate) followed by thorough rinsing. Small parts are hung on an iron wire for immersion in the blueing bath, which has the following composition: water, 250 cc; ammonium hydroxide, concentrate (27 to 30% NH_3), 750 cc; copper carbonate, 100 grams. This is stored in a large, straight sided glass jar covered with a ground glass plate to contain the irritating ammonia fumes. After ten minutes of immersion, the parts take on a brownish hue, then become bluish violet and even black if the action is allowed to continue. The oxidation is stopped by rinsing with water, drying, and rubbing the parts with an oiled cloth to finish the operation.

Bright nickel plating followed by *chrome plating* makes a very durable finish, but the sliding action of a chrome plated draw tube is rarely pleasant. Chrome plating with a matte finish is very attractive, and primarily of interest for the clamping and corrector knobs.

XIII-4. Reflective Mirror Coatings

Two processes are currently used to furnish reflective coatings on telescope mirrors: *chemical silvering* and *vacuum aluminizing*.

The very old process of reducing a silver salt with sugar, originated in 1843 by Liebig and Drayton, permits us easily to deposit a thin coating of silver (about 1/10 micron) on the glass. Foucault applied the process to telescope mirrors as early as 1857. The method remains as useful today as before: the reflectivity of silver is very high in the visible wavelength range and in the infrared may reach 98 per cent (Section I-6; Fig. 9). The operation is straightforward, and for the isolated worker eliminates the need of shipping the mirror and the risks involved. The disadvantages of silvering are:

1.) *Optical defects introduced by uneven thickness of the silver.* Since the thickness is of the order of a tenth-micron, the amplitude of these defects is always less than a quarter-wave. They are not necessarily negligible, however, because their complex structure may contribute to strongly inclined elements on the wavefront. Fig. 131, obtained by phase contrast, shows an example of this type of defect. The strong contrasts seen here are due to the extreme sensitivity of the method, not the seriousness of the defects, the amplitude of which, in this case, are no more than a *thousandth of a wave*! It is only the number of defects and their slopes which, as discussed in the case of micro-ripple (Section II-34, Fig. 41) could result in troublesome light-scattering in certain applications.

2.) The coating tarnishes rapidly in the presence of hydrogen sulfide (vapors from the kitchen, for example), causing the reflectivity to fall off rapidly, particularly in the blue and ultraviolet. Keeping the mirror in first-class condition requires repolishing the coating about twice a month and resilvering twice a year. Frequently, however, the deposit remains useful (for purely visual work) for several years if the sulfur content of the air is low (in areas far from factories, for example) and the humidity is not excessive.

3.) A final disadvantage is that the silver scatters some light as a result of the millions of tiny sleeks or fine scratches that are inevitably produced when the film is polished.

Vacuum aluminizing, introduced by Strong in 1931, furnishes a truly faultless reflective coating that requires no final polishing. The metal film apparently reproduces perfectly the character of the glass surface itself, and does not diffuse any detectable amount of light. With a few elementary precautions, the uniformity of the layer is such that even the most sensitive optical tests reveal no change with respect to the glass surface, either in the larger features or in such detail as micro-ripple. (See Figs. 131*A* and *B*). Reflectance in the visible range is only about 88 per cent, but this is not seriously inferior to the silver. In the infrared, aluminum is inferior in about the same degree; in certain applications the aluminized mirror may therefore be more susceptible to heating effects. On the other hand, reflectance of aluminum in the ultraviolet is much higher than that of silver; and if we compare the aluminum with silver that has once begun to tarnish, its superiority extends very rapidly also to short visible wavelengths such as the blue and violet. Aluminum coatings resist well the effects of weather and atmosphere. The transparent, extremely thin film of aluminum oxide (corundum) that forms spontaneously on the surface greatly inhibits chemical attack even in humid air. But, as with silver, ultimate deterioration is caused chiefly by grime and dust that settle inevitably on the exposed surface and finally result in appreciable diffusion of light. The advantage of aluminum in this regard is that it stands up quite well under washing.

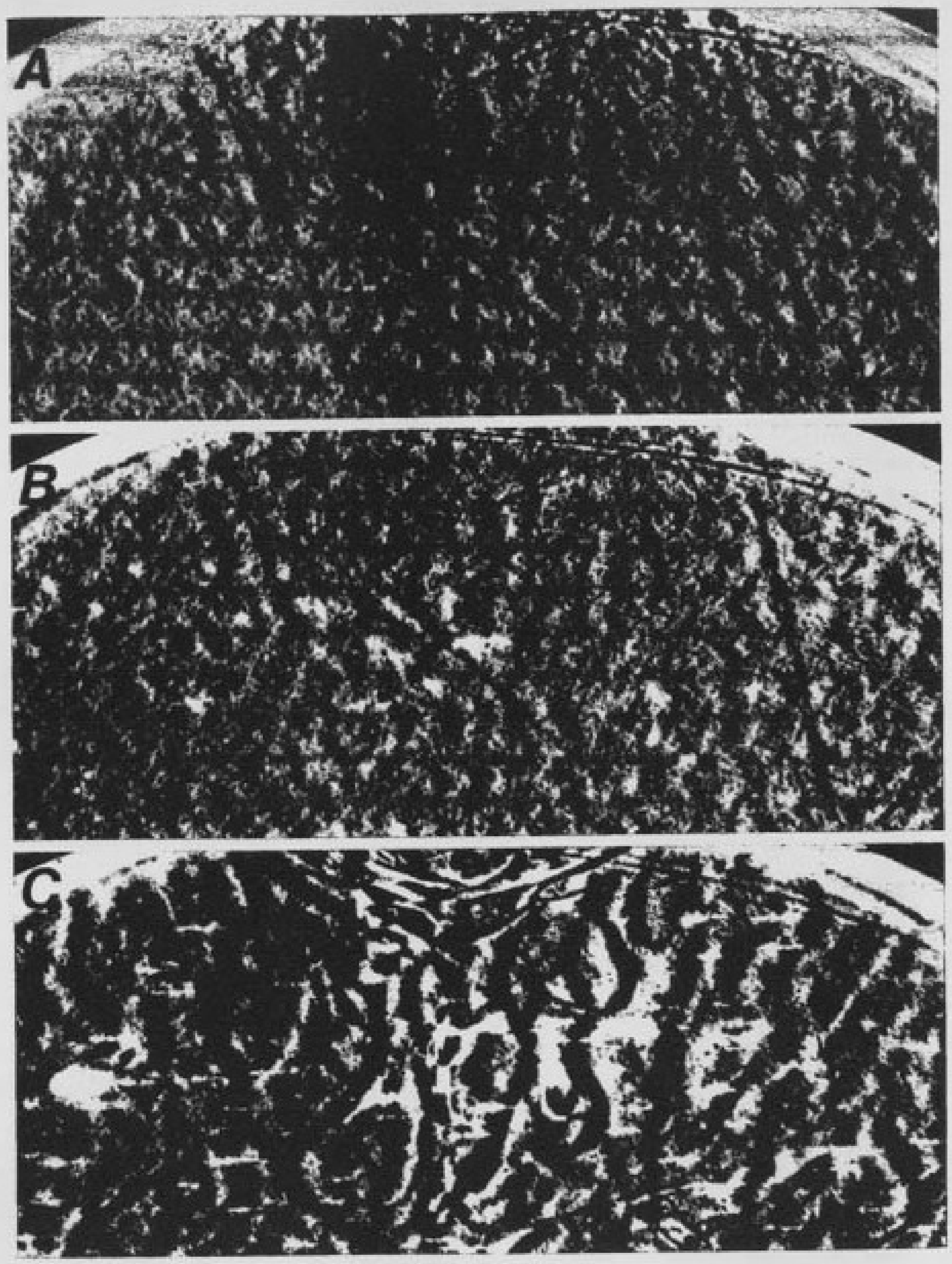


Fig. 131. Three photographs of the same area of a highly polished mirror taken by the Lyot phase-contrast method (phase-plate optical density 2.81). (A) Bare mirror surface. Height of average irregularity: 1 Å. (B) Same surface aluminized. Height of fine surface detail remains unchanged. White spots are caused by light scattered from fine dust particles. (C) Same surface chemically silvered. Defects are as much as 6 Å high.

XIII-5. Chemical Silvering

The four processes most commonly used are the formaldehyde, the Rochelle salt, the Brashear, and the Martin.

The formaldehyde process (described by Lumiére) and the Rochelle salt process (described notably by Draper) are perhaps the easiest to use. The first of these gives much the less satisfactory results, and the second, because it deposits the film only very slowly, is better adapted for making partially silvered than fully opaque coatings.

The widely used, excellent Brashear process has been described in great detail.[1] The author and his co-workers, however, prefer the so-called Martin process, which requires less precise handling. This method, probably originated by Foucault, has been described by A. Danjon.[2] The modified procedure we give here[3] makes the method even more reliable by replacing aqua ammonia (the nominal "Baumé" value of which is always open to question) by ammonium nitrate, which can be weighed out easily and accurately.

Accessories needed for silvering are the following: an enamelled pan slightly larger than the mirror; a sufficiently large and very clean vessel in which to rinse the mirror; a 1-liter flask for preparing the solutions; a 250-milliliter graduated flask; a glass stirring rod; absorbent cotton; and a pair of rubber gloves.

At least 5 liters of distilled water are needed for preparing the solutions and for rinsing. This should be a high-quality product marketed in sealed containers. The fuming nitric acid used for cleaning the disk, as well as all chemicals used in the solutions, should be of high purity and, if possible, of recent purchase.

The vessels must all be extremely clean; for example, the slightest trace of salt from the operator's fingers may spoil the operation. Clean rubber gloves will both protect the hands from nitric acid and caustic potash, and protect the mirror and silvering bath from contamination with perspiration.

Four separate solutions are prepared as follows:

A.	Silver nitrate crystals	60 grams
	Distilled water to make	1000 milliliters

Store in a glass-stoppered bottle. The operator must avoid getting this solution on his hands; it blackens skin as readily as it does a silvering vessel.

B.	Ammonium nitrate crystals	90 grams
	Distilled water to make	1000 milliliters

[1] *Amateur Telescope Making*, 4th ed., pp. 397–428.

[2] *L'Astronomie*, **38**, 255 (June, 1924).

[3] Described previously in *Lunettes et Télescopes*, Section 118, p. 551. Editions de la Revue d'optique théorique et instrumentale, Paris, 1935.

Store in a glass-stoppered bottle.

C.	Pure potassium hydroxide	150 grams
	or	
	Pure sodium hydroxide	105 grams
	Distilled water to make	1000 milliliters

Store in a rubber-stoppered bottle. The solid sodium or potassium hydroxide is preferably purchased in the convenient pellet form. If either is purchased in stick form, however, and requires crushing, the operator should wear glasses.

D.	White table sugar (sucrose)	100 grams
	Tartaric acid	5 grams
	Ethyl alcohol (90 per cent)	150 milliliters
	Distilled water to make	1000 milliliters

These are used to prepare the reducing solution as follows: Dissolve the sugar and tartaric acid in a small quantity of distilled water in a small, very clean beaker or enameled saucepan. Bring the solution to a boil and simmer over a small flame for 10 or 15 minutes to effect "inversion" of the sugar (i.e., conversion to so-called "invert" sugar). Cool by adding a little distilled water. Add the alcohol (this acts as a preservative), and finally transfer the mixture to the measuring flask and add distilled water to make 1 liter. This solution is allowed to age for a least one week before use. This improves its action considerably.

Solutions *B* and *C* must be used quite fresh, however; otherwise they are unreliable. It is best to prepare these a short while before use, employing chemicals of recent purchase which have been kept in carefully sealed bottles.

Cleaning the Mirror. The adhesion and toughness of a silver film depend to a large extent on the cleanliness of the underlying glass surface. *Perfect* cleaning of a glass surface is very difficult. Depending on the condition of the surface prior to silvering, its history, and the chemical resistance of the glass, results in silvering may vary considerably. Fortunately, experience shows that a relatively simple cleaning operation often suffices. A hard-rubber tray is convenient; otherwise improvise a small wood frame—fitted at the sides with cleats—on which the mirror may be supported in a sink while it is rubbed vigorously with the prescribed reagents. If the mirror is soiled with adhering particles of pitch, rub the back and edge with a cloth moistened in mineral spirits or turpentine. Polishing rouge adhering to the disk may be remarkably resistant to chemical reagents; it must be removed by mechanical action. A good method is to soap the back and edge, then to rub these surfaces with a wetted, slightly abrasive eraser (for example, a typing eraser). The chamfer is cleaned last, with special care taken not to let the eraser slip onto the optical face. Eraser particles are then washed off carefully, without rubbing, of course.

The optical face is rubbed with fuming nitric acid, using a large cotton wad. The hands are protected with rubber gloves. If the surface bears a previous silver coating, the acid destroys it immediately. In this case the mirror is then rinsed and cleaned afresh with more acid and cotton. If the mirror bears an old *aluminum* film it may be removed completely, before applying the nitric acid, with some hydrochloric acid or a small quantity of solution *C* (sodium or potassium hydroxide). The fuming nitric acid is a powerful oxidant for any organic contaminant on the surface. As greasy matter disappears from the surface in the course of two or three changes of acid and cotton, we finally hear the characteristic squeak of cotton against clean glass. Often a single acid cleaning step is sufficient. The mirror may then be rinsed thoroughly and immersed in distilled water until ready for silvering.

Sometimes cleaning is more difficult, and a more powerful reagent, or mechanical action, must be employed. An extremely effective reagent is sulfuric-chromic acid mixture (the chemist's "cleaning solution"), especially when used hot. But the hazards, or at any rate the difficulties, of using this solution have not encouraged any wide use among amateur telescope makers. A good alternative procedure is that which Foucault himself employed: the application of an ammoniacal calcium carbonate paste. A thin paste is prepared of precipitated chalk, ammonia, and a little distilled water. This is spread across the entire mirror surface and allowed to dry thoroughly. Then with several successive wads of cotton (avoiding contamination of the surface with perspiration or finger grease), the chalk is gently rubbed off. At first a blue film persists on the glass, but with increased pressure and *prolonged* rubbing this too disappears. The operation may be judged successful if the "breath" pattern obtained by breathing on the glass is a uniform gray film of microscopic droplets, free of streaks or other irregularities. If necessary, the operation is repeated a second or third time, the disk being finally swabbed with concentrated nitric acid. Once thoroughly cleaned, the mirror is not allowed to dry, but is kept immersed in distilled water.

"Mordanting," by general consensus, is a helpful, though not indispensable, operation at this stage in improving the adhesion and quality of the silver film. The cleaned mirror is immersed in a 0.1 per cent stannous chloride solution for 5 minutes. Just before the mirror is placed in the silvering bath, it is rinsed thoroughly in distilled water.

Possible Silvering Arrangements. One of two methods may be used:

1. Mirror facing upward (Fig. 132 A). This method consumes less silvering solution and is therefore more economical, especially for large mirrors. However, it is difficult in this method to avoid completely the occurrence of tiny pinholes in the silver layer. The mirror serves as the bottom of an improvised silvering dish. The wall comprises a wide band of wrapping paper that is first waterproofed by dipping in melted paraffin, then wrapped around the mirror edge and secured with several turns of elastic cord. The edge of the disk is vaselined lightly to minimize leaking.

2. Mirror facing downward (Fig. 132B). A flat-bottomed dish slightly larger than the mirror serves as the silvering vessel. An inexpensive enameled pan is quite satisfactory. In order to raise the mirror from the bottom of the pan and to permit it to rock slightly, four short paraffined wood bars are fastened in the form of a cross to the bottom of the pan with a little rosin; two

of the bars, forming one arm of the cross, being about $\frac{3}{8}$ or $\frac{1}{2}$ inch thicker than the others. Metal bars may not be used; even a relatively inert metal such as lead, by forming an electrolytic couple with the silver, may cause severe local nonuniformities in the deposit.

Depositing the Silver. Proper temperature is essential to success. A good working range is between 18° and 24°C. (65° to 75°F.), though Ellison, working in tropical Ceylon, has reported good results with the Martin method at temperatures of 30°C. (85°F.) and above. We must consider not only the air temperature but the temperature of the solutions and the mirror as well (in the latter case by checking the temperature of the water in which the mirror has been immersed).

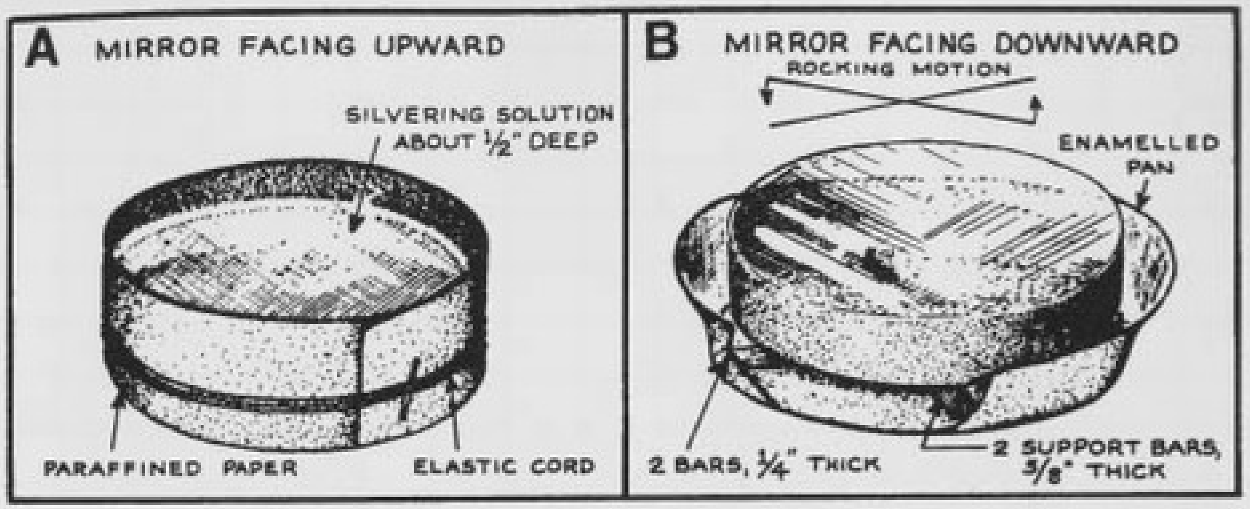


Fig. 132. Two arangements for silvering.

It is best to determine in advance, by measuring with water, how much silvering solution will be needed for the bath. If the mirror is supported face down, and in particular if the back of the disk is clear, the liquid should extend only halfway up the mirror's edge. In this way the progress of silvering may be observed directly through the glass.

To avoid wasting expensive silvering chemicals, figure that about 50 milliliters of solution *A* will be required for every 15 square inches of mirror surface or, for an 8-inch mirror, about 150 milliliters. Measure this amount of solution *A* with the graduated cylinder into the 1-liter flask. Then rinse the graduate, measure out an *equal volume* of solution *B*, and add it slowly to *A*, meanwhile stirring the mixture vigorously with a glass rod. Again rinse the graduate and add an *equal volume* of solution *C*, with continued stirring. Ideally, the last few drops of solution *C* cause the solution to become slightly turbid; if viewed against bright light, the solution has a light tea color. If the solution remains clear, however, add immediately a few more drops of solution *C*. If, on the other hand, the solution has turned dark brown, discontinue addition of solution *C*; the deposition of silver from such a solution will be rapid and brilliant, but thin. The difficulty of adjusting the mixture is sometimes exaggerated. The tolerance in the Martin method is actually quite wide. Use the mixture thus obtained immediately (unused excess must not be left to evaporate, for example, left exposed to the sun; on extremely sensitive material which can detonate spontaneously). If the volume of mixture is less than that previously estimated as necessary to fill the silvering bath, add distilled water as required. Now remove the mirror from the distilled water and place it in contact with the silvering mixture. A quantity of reducing solution *D*, equal to one-third the volume used of solution *A*, is now added to the mixture.

The reaction begins immediately; the solution darkens, then turns completely black. The mirror is rocked gently and randomly, so as to obtain as uniform a deposit as possible. In 2 to 3 minutes, assuming a temperature of about 20°C. (68°F.), the mirror acquires a beautiful metallic appearance. Resist the temptation at this point to lift out the mirror and examine it. Before the silver film can become quite opaque, the mirror must be kept in the bath at least another 10 to 15 minutes. Deposition may be considered complete when the solution clears and a muddy aggregation gathers on the surface. If the mirror is being silvered face up, it is best to keep the mud from depositing on the glass; the particles at least are kept in motion by passing a wad of cotton lightly over the surface while the mirror remains immersed in the solution. The mirror is now removed from the bath and again immersed in distilled water for rinsing. The thickness of the deposit may be checked by raising the mirror momentarily against a light. If the deposit is sufficiently thick, the sun's disk, or the filament of a bright lamp, is hardly visible. However, even when one can discern objects silhouetted against the daytime sky, the silver coat may be quite serviceable. If the film is too thin, prepare immediately a second silvering bath with which to build up the deposit.

The mirror should be dried rapidly; after preliminary draining, hold the mirror in a nearly vertical position, and wash it down with a small quantity of strong alcohol. A fan is helpful. Drops gathering at the bottom of the mirror are picked off with blotting paper.

Polishing the Silver Deposit. The silver film is at first nearly always covered with a whitish haze. Once dry, however, the silver can quickly be made brilliant by dry-polishing with chamois skin. A thick, dull coat may prove virtually unpolishable; it should be removed and the mirror resilvered. For a surface of moderate size, such as our standard mirror, a piece of chamois skin is stuffed with absorbent cotton to form a small pad. The chamois must be new, thoroughly degreased, and of the best available quality. The chamois is inspected and brushed carefully (note that manufacturers abrade these skins with *silicon carbide stone*!) The pad diameter is 1½ to 2 inches; and the velvety surface (flesh side) is on the outside.

The pad is first tested on a piece of plate glass, preferably a silvered piece, to make sure it will not seriously streak or scratch the surface. The entire mirror surface is then rubbed with figure-8 strokes. If silver particles adhere to the pad, they are removed with a toothbrush. This preliminary rubbing tamps down the film, preparing it for the polishing operation proper. A very small amount of dry optical rouge (Section II-5) is now spread on the pad with the

toothbrush and worked into the surface by rubbing against the glass test plate. The pad may then be applied to the mirror. After a few minutes of polishing the whitish bloom disappears and the coat becomes uniformly clear and bright. If necessary, stubborn areas are cleared by breathing on the surface in order to deposit a little moisture, after which further rubbing is used. In general, however, rubbing is kept to a minimum; otherwise the millions of streaks or "sleeks," which are formed, and which scatter light near the axis, become just as objectionable as a slight residual bloom on the mirror (visible, for example, when the mirror is viewed at a grazing angle).

XIII-6. Aluminizing

We shall describe this technique only briefly, primarily to satisfy the amateur mirror maker's curiosity, and also to help him avoid certain errors, though not in sufficient detail to permit him to perform the operation himself. For the average amateur, the equipment necessary for aluminizing would be quite costly.[4]

The aluminizing process was developed largely by John Strong.[5] Small "riders" of the very pure aluminum wire are suspended in the vacuum space on coiled tungsten filaments. The filaments are electrically heated, melting the aluminum at 600°C. to form small droplets that "wet" the tungsten and therefore do not fall off. The aluminum then evaporates from the hottest portions of the filament (about 1200°C.). If the vacuum is such that the mean free molecular path is of the order of the vacuum space dimensions, the molecules of aluminum radiate in straight lines directly from the filament to the glass surface. This requires a relatively high vacuum: about 10^{-4} or 10^{-5} millimeter of mercury. The metal is deposited as a thin film which reproduces faithfully every feature of the optically polished glass. The surface, therefore, does not at all resemble that of a mechanically polished, solid aluminum body. Figure 133 illustrates an arrangement that will deposit the aluminum quite uniformly on a small mirror. The tungsten evaporators are arranged in a crown of approximately the diameter of the mirror, and at a distance above the mirror equal to the mirror radius. The heaters are made of approximately 0.7 millimeter (0.028 inch) diameter tungsten wire and draw a current of several tens of amperes from a 10- to 20-volt supply. An evaporation period of 10 to 20 seconds gives an opaque deposit about 1/10 micron thick.

A primary requirement in aluminizing is that the mirror surface be perfectly clean. This is an absolute necessity for a tough, adherent coating. The cleaning requirement is more severe than for silvering; the surface must

[4] A number of amateurs in the U.S. do their own aluminizing. In France, aside from the laboratories of the Optical Institute and the Institute of Astrophysics, most large optical houses have equipment for vacuum deposition of metals and fluoride coatings. Also, several companies have specialized and highly refined this technique, for example: M.T.O., 5, passage de Melun, Paris-19ᵉ.

[5] Limited solubility of tungsten in evaporated metals. Strong, 1931. Aluminizing of the first large astronomical mirror, Strong, P.A.S.P., vol. 46, 1934, p. 18–26.

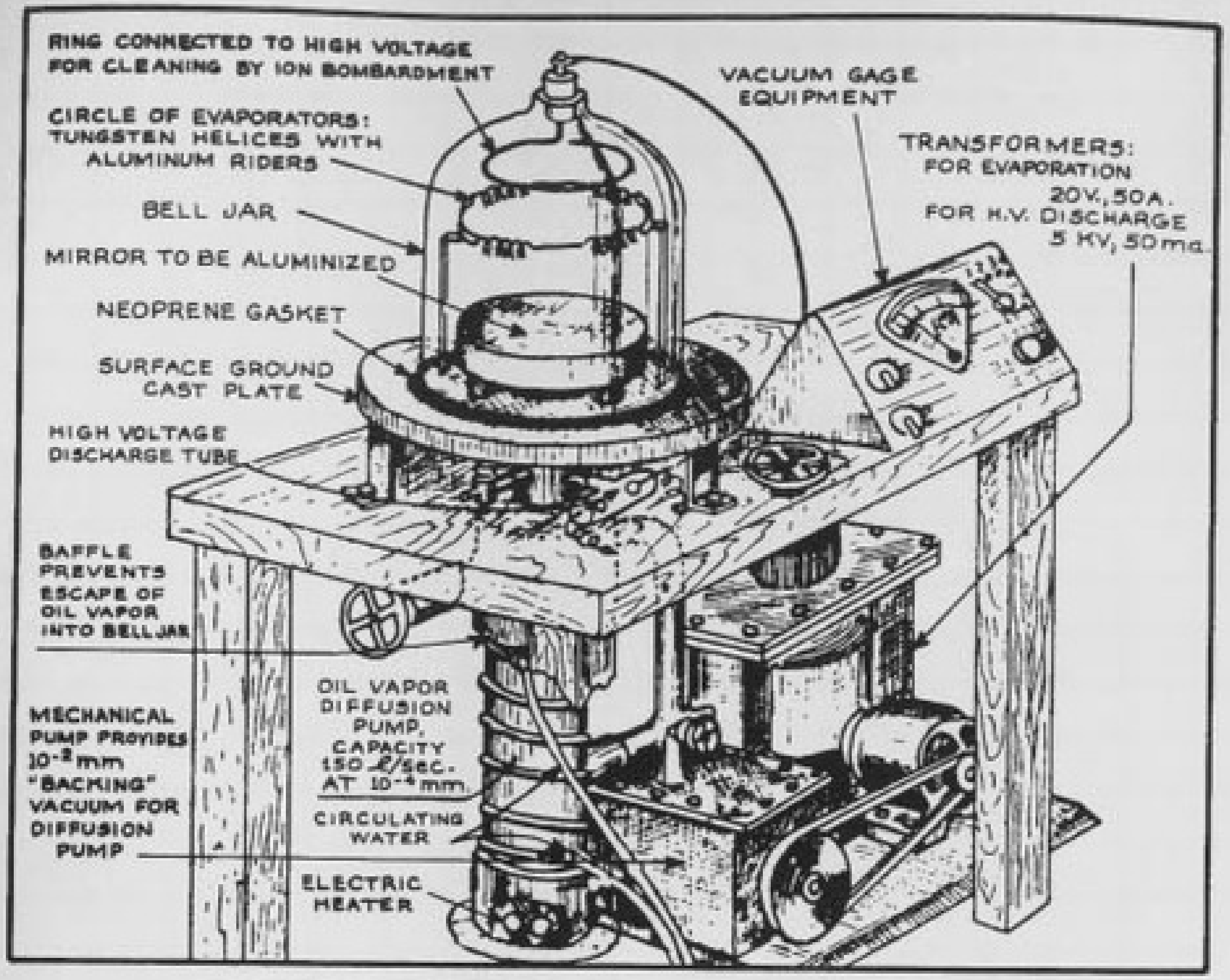


Fig. 133. Equipment for small-scale aluminizing.

simultaneously be both *clean* and *dry*. The uniform gray breath pattern we described in Section XIII-5 was not so much evidence of a perfectly clean surface as of an extremely thin and very uniform residual film of fatty acid. In aluminizing, this may be sufficient to cause, ultimately, an appreciable deterioration of the coating. Alkali-metal ions in the glass surface have an affinity for certain contaminants that makes perfect cleaning of certain glasses virtually impossible. Drastic chemical action—2 hours immersion in boiling chromic-sulfuric acid mixture (400°C.), for example—is effective,[6] but this obviously is no way to treat a high-precision optical element. The preferred method of cleaning is by ion bombardment of the surface during pumping, with a high-voltage discharge (5,000 to 10,000 volts). Even this procedure, however, is not exempt from difficulty, as workers who have used the method will know.

The difficulties of obtaining a high vacuum are better known and perhaps more easily surmounted. Invisible leaks occur constantly which must be tracked down and eliminated. Even extremely small leaks are troublesome unless the pumping system is of fairly large capacity. To remove only a cubic

[6] R. Merigoux, *Revue opt.*, 16, 280–296 (Sept., 1937).

millimeter of air (measured at atmospheric pressure) that may have entered the system, several tens of liters must be pumped out at the residual pressures of 10^{-3} to 10^{-5} millimeter. Drying agents, sealing waxes, or stopcock greases anywhere in the system must have extremely low vapor pressures. Surfaces that may have adsorbed gases may require preheating.

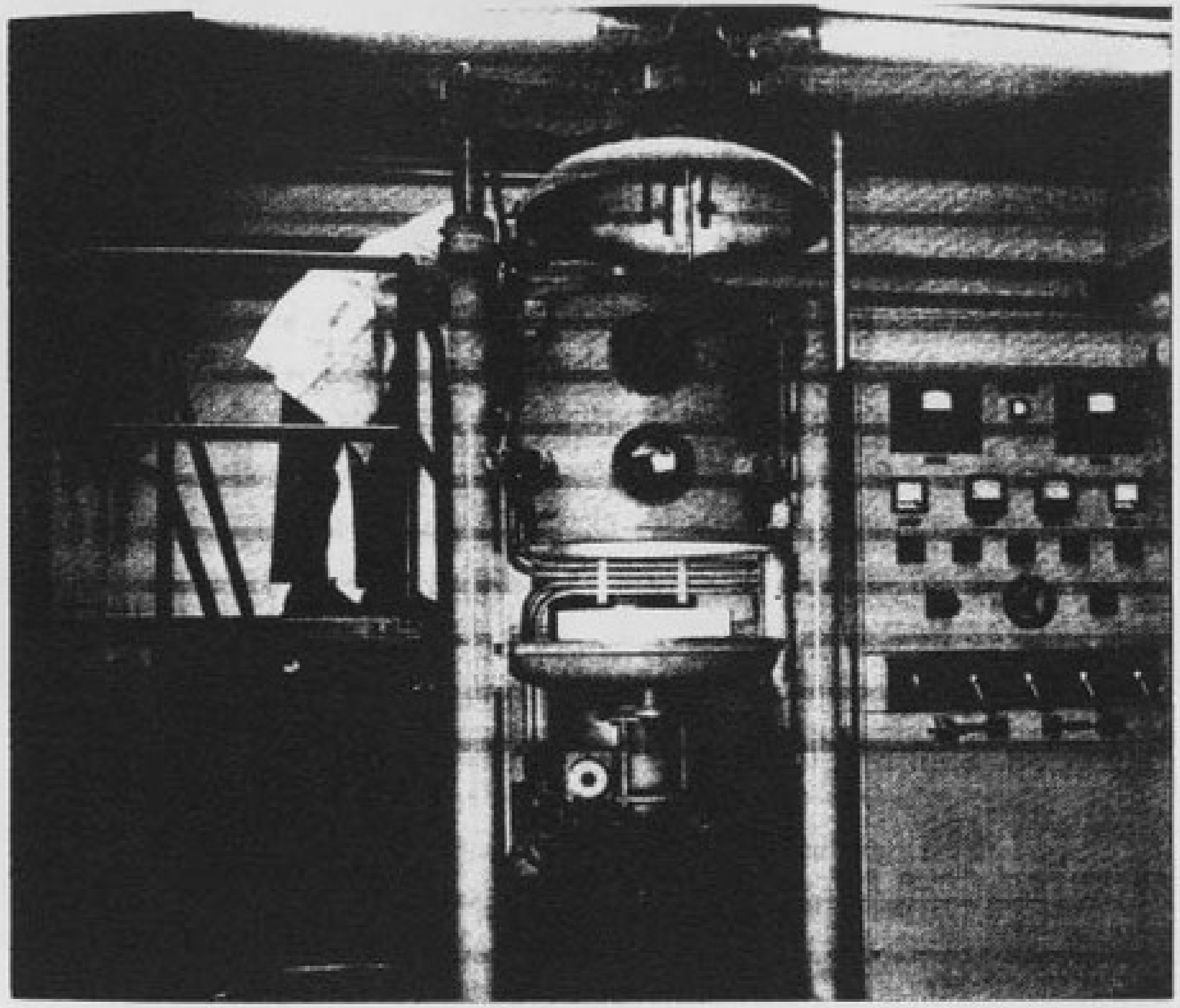


Fig. 134. Heraeus aluminizing station with 31½ inch bell jar (Société M.T.O.).

A small laboratory setup might be limited to an assembly such as that illustrated in Figure 133. However, rapid develoment of the technique has led to the manufacture of large vacuum deposition stations fitted with very powerful pumping equipment. Figure 134 shows a station built by Heraeus and installed at the M.T.O. Company. It has an 800 mm diameter vacuum bell chamber, and its main oil-vapor diffusion pump, partly hidden in the photo by the chamber, has a pumping capacity of 5000 liters per second. A 600 mm mirror is seen resting on the vacuum chamber base plate. The control and test panel at the right includes the displays of a Pireni gauge for the lower vacuum levels and an ionization gauge for residual pressures of 10^{-5} millimeters of mercury and less. The interior of the chamber contains several types of individually heated and controlled evaporators. This permits coating of the reflective layer with silicon monoxide, for example, this being a coating regularly applied to aluminized surfaces prepared at M.T.O. (coating Amplivex 90). Much more complex multiple layers can similarly be deposited.

Assuming that the glass has been perfectly polished and that aluminizing is successful, the result is a perfect reflecting surface. Polishing the deposit is unnecessary, and scattered light at any angle of examination is imperceptible. On the other hand, if even the slightest pit has passed unnoticed through the polishing stage (Section II-18), it now becomes cruelly evident. This often takes the careless worker by surprise. It is useless to blame the aluminizing, and any attempt to erase the pits by polishing the fresh aluminum with chamois would be disastrous. The freshly deposited coating is quite soft; the slightest rubbing will leave sleeks. Even dusting with a camel's hair or badger brush may be damaging. On continued contact with the air, however, the aluminum does form a thin and extremely hard transparent film of aluminum oxide (alumina) which at the end of about several weeks provides excellent protection.

Defective coatings may have several causes. One of these is evaporation in insufficient vacuum (caused, for example, by leaks, unexpected outgassing of enclosed parts, etc.), which is evidenced by a yellowish or even blackish surface. Even when the defect is slight, the loss of reflectivity at short wavelengths may be considerable. The defect may be spotted by holding a sheet of bright white paper next to the mirror and comparing its color with that of the reflection seen in the mirror at a glancing angle. Both should appear equally white. Other causes of defective coatings are impurities in the aluminum, or the dislodging of greasy particles from the apparatus during ion bombardment, either of which may cause large black dots to appear in the deposit.

The commonest cause of failure, however, is imperfect cleaning prior to aluminizing. Typically, such mirrors emerge from the vacuum equipment appearing quite faultless. But after about 48 hours (though sometimes after as much as a week) a rash of microscopic blisters, each several microns in diameter, appears on the surface. These may be dense enough in some places to scatter much more light than even a *gray* or pitted surface. Only one recourse is available: to realuminize the mirror.

XIII-7. Shipping the Mirror for Aluminizing

The mirror shipped for aluminizing should be well polished, of course. It should also be reasonably clean. This simplifies the aluminizing and helps to insure a good coating. Cleaning the optical face is naturally the duty of the person who does the aluminizing; however, the back and edges of the disk should be free of adhering pitch or rouge. Pitch may be removed with mineral spirits; the rouge by soaping the disk, then rubbing with an eraser. These surfaces, being often rather coarsely ground, may retain sufficient contamination so that during pumping the outgassing may interfere with a good vacuum.

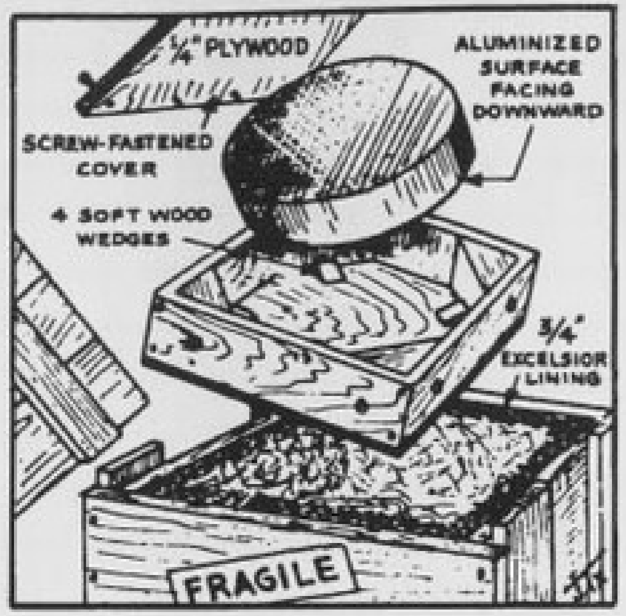


Fig. 135. Double packaging for shipping aluminized mirrors.

In shipping the mirror, provision must be made not only for safety of the glass but, on return of the disk, for the safety of the film as well. The coating has not ordinarily been treated to surface-harden it, nor has time been allowed for an oxide film to form naturally. The aluminum therefore is quite tender. Figure 135 shows a convenient method of packaging. The mirror is first enclosed in a very clean shellac-finished inner box. The optical surface is supported about ¼ inch from the bottom by four wedges that come in contact with only the mirror edge. *Nothing may come in contact with the aluminized surface*. It is desirable also to seal this box against entry of dust. This may be done easily with a strip of Scotch® tape applied to the edge of the cover. Packing methods that permit the aluminum to come in contact with tissue paper or absorbent cotton should be avoided, as these materials sometimes contain harmful traces of chlorine. Shipping by public carrier requires an additional outer case about 2 inches larger in all dimensions than the inside box. The space between is carefully padded with excelsior.

XIII-8. Care of Aluminized Mirror

Even after several weeks of hardening, the only contact permitted with the aluminum is that of a soft badger brush used to remove dust. Rubbing with cloth or chamois skin especially must be avoided. If dew forms on the cold mirror surface, one must wait for the mirror to reach operating temperature and for the moisture to evaporate; the moisture may not be wiped off. The aluminum resists the effects of moisture well. A too-frequent cycle of condensation and evaporation should be avoided, however, especially where the air may contain salt.

Dust is another source of deterioration. A plate-glass cover, ground to fit against the edge of the optical face when the telescope is not in use, gives good protection. This has been traditional for protecting silvered mirrors. For aluminized mirrors, however (assuming that the telescope structure is otherwise closed), it is sufficient merely to provide a close-fitting cover for the top of the tube. A good practice also, when the telescope is not in use, is to keep the telescope tube horizontal. This prevents deposition of the heavier, greasy particles, which dusting tends only to smear over the mirror surface.

After a year or two of use, the surface may be noticeably soiled and diffuse an appreciable amount of light. The reflective power of the underlying aluminum is undiminshed, however, and once washed, the coating is again usable. Only a mild, very nearly neutral detergent may be used, such as Palmolive® or Ivory® dish washing liquids, or the neutral laboratory soap sold in paste form under the name of Orvus®. The mirror is completely immersed in water, and a wad of cotton saturated with the soap solution or detergent is passed very gently, with minimum pressure, over the aluminized surface. The mirror is then immediately carefully washed free of all traces of detergent, using a fresh cotton wad and pure water, and promptly dried.

With reasonable care, an aluminum film gives good service for about 5 years. If the aluminum was originally thick enough to remain opaque despite progressive oxidation, reflectivity during this period remains high. Ultimately, however, contamination causes the coating to deteriorate, and diffusion becomes excessive for optimum instrument performance.

XIV

ADJUSTMENTS OF MIRRORS AND MOUNTINGS

XIV-1. Aligning the Mirrors

Adjusting the primary and the diagonal mirrors is a simple operation with which the user should be familiar. If the telescope tube is made of wood and is exposed to appreciable humidity change, the owner should not hesitate to check and adjust the mirror alignment periodically.

The adjustment is usually made in two steps: (*1*) *preliminary adjustment*, by which the optics may be aligned geometrically in a few minutes in full daylight, and (*2*) *precision adjustment*, in which one sights on a star with a high-power eyepiece and by trial and error finds the adjustment giving the best possible image.

Preliminary adjustment is made very simply as follows: the telescope with its two aluminized or silvered mirrors uncovered is aimed toward any extended bright area, the daytime sky, for example. Removing the eyepiece and looking down the axis of the drawtube, we see the diagonal mirror directly (Figs. 136*A* to *C*, outer outline). Its projected form appears circular, octagonal, or square, depending on the diagonal mirror shape. If the eye is at the focal position, and the diagonal is of proper size (Section III-2), we see slightly within the edges of the diagonal the outline of the main mirror. Finally, by double reflection, we see a third, much smaller outline: the reflected image of the diagonal, which in turn encloses an image of the eyepiece mount and the observer's eye. In general, the two mirrors at the beginning will be badly misaligned; the appearance may be that of Fig. 136*A*, where none of the outlines are concentric. The first step is to orient the *diagonal mirror* correctly by adjusting its positioning screws to center the outline of the main mirror within that of the diagonal. The appearance may then resemble that of Fig. 136*B*. We verify, of course, that the eye is accurately aligned with the axis of the eyepiece tube. A temporary sighting aperture is helpful, for example, the eyecap of a high-power eyepiece from which the lenses have been removed. Since the two mirror contours differ only slightly in size, the accuracy of this adjustment is sufficient without further checking. In any case, small residual alignment errors in the diagonal at this stage are unimportant; their effect is merely that the fully illuminated field area is not precisely centered in the eyepiece. We must verify also that the axis of the eyepiece tube (made perpendicular to the telescope by construction) is aimed directly at the center of the diagonal mirror. If not, then though the beam reflected from the main mirror may be accurately on axis, it may form a slight angle with the axis of the eyepiece. Eyepiece mountings are sometimes provided with adjusting screws to correct such an inclination, but this is a luxury and can be dispensed with. Orthoscopic eyepieces in any case tolerate an inclination of the beam of several degrees without difficulty, thus permitting an ample positioning error. On the other hand, if one is to use properly a Barlow eyepiece recessed within the eyepiece mounting tube, the alignment must be quite accurate; otherwise, this negative eyepiece introduces coma.

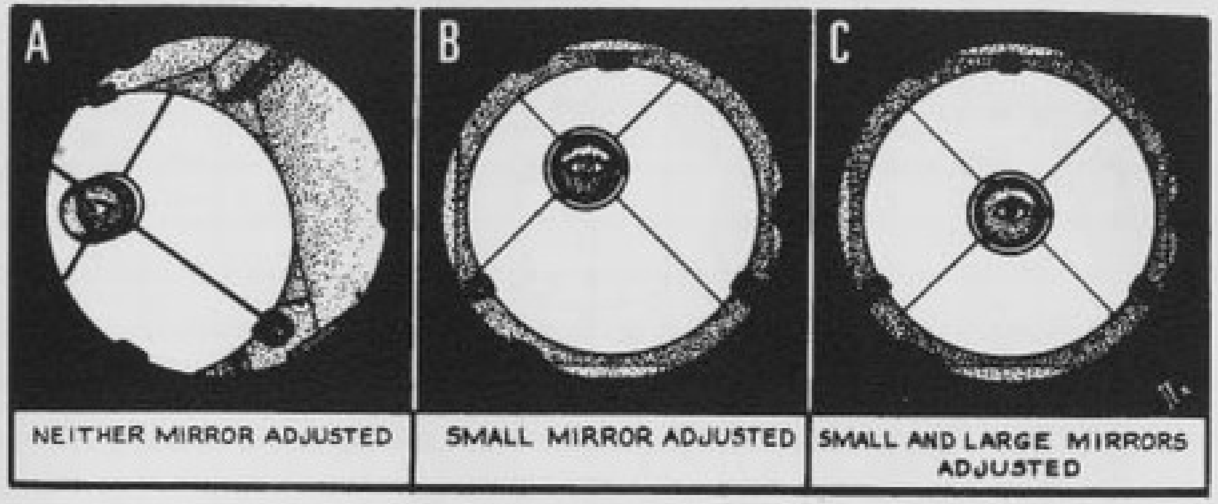


Fig. 136. Preliminary adjustment of mirrors by daylight.

For preliminary adjustment of the *primary mirror*, we consider now the small, silhouetted reflection of the diagonal mirror. This must be centered within the outline of the primary mirror by adjusting the mirror support screws (numeral 15, Fig. 56) to obtain the appearance of Fig. 136C. The diameters of these two outlines are quite different, so that centering of the primary mirror at this point is only approximate. Writers on the subject have conjured up a whole arsenal of devices for this purpose: screens, diaphragms, pinholes, and the like. We feel that these are of little interest, however; they all assume that the mirror is precisely a figure of revolution. It is best not to make this assumption but to rely for final adjustment entirely on the appearance of the star image as described below. This procedure may result, in some cases, in an optimum positioning of the beam somewhat off the primary mirror axis—if, for example, the mirror is slightly astigmatic.

Final adjustment by sighting on a star requires care, but the difficulty need not be exaggerated. As an indication of the sensitivity of this adjustment, we note that if an $f/6$ mirror is tilted to shift the image in the focal plane by 0.10 inch, it produces a perceptible coma. If the mirror positioning screws have 20 threads per inch, this corresponds to a quarter-turn on the screw.

Under optimum conditions, the effect even of 1/10 turn may be perceptible.

For an 8-inch mirror, a star of about third or fourth magnitude is best. We choose a star quite high in the sky; this improves the chances for a good image. Also it avoids possible loss of contact of the large mirror against the positioning screws, which may have to be retracted somewhat during adjustment. In putting the final touch to the adjustment, it is best, of course, always to advance the screws.

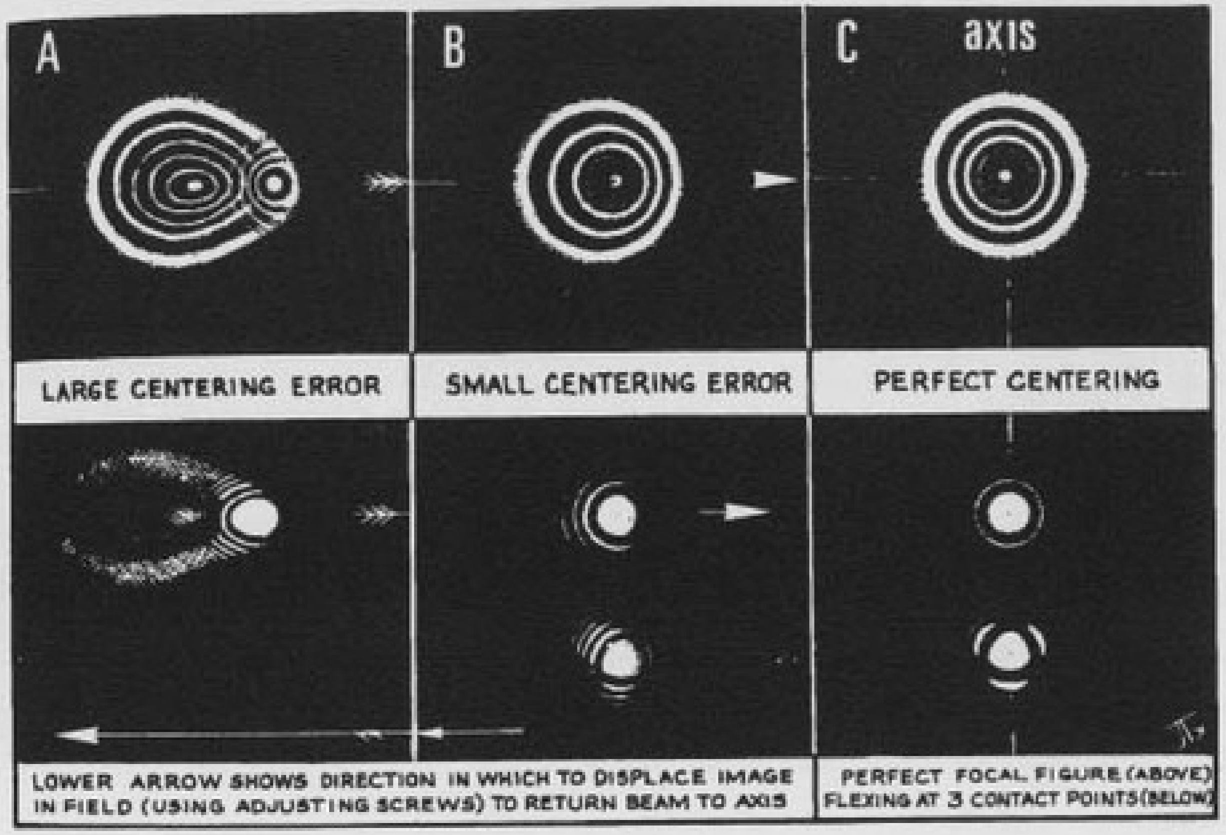


Fig. 137. Centering the main mirror on a star.

Since the inclination of the large mirror is not yet fixed, we are not yet able to align and use the finder for locating the star. Instead, we locate and center the star by using the least powerful eyepiece available. In Fig. 137*A* we see the complex star image (combining effects of coma, astigmatism, and diffraction) that may be seen far off-axis in an $f/6$ mirror. Even the crudest preliminary adjustment will not decenter the mirror quite this badly. In any case the distortion due to coma is dominant, and indicates clearly to which side of the eyepiece the beam axis lies (shown in Fig. 137 by arrows alongside the star images). The upper half of Fig. 137 shows the defocused images as they appear a few millimeters outside of the optimal focus. The images are viewed here with a medium-power eyepiece strong enough to show the direction of eccentricity and to permit making an initial correction. For the operator working alone, it is faster to work by trial and error than to attempt to reason if coma will be reduced by advancing or retracting a particular screw. If an assistant is available, the process is simplified; the operator then keeps his eye uninterruptedly at the eyepiece while he calls out such adjustments as will displace the image always in the direction toward which the image flares (Fig. 137, arrows at bottom of figure). If the eyepiece is not too strong, this can be done even without letting the star out of the field. In Cassegrainian telescopes of moderate size, mirror adjustment is especially easy—the observer can adjust the positioning screws himself without taking his eye from the eyepiece.

As the image approaches the axis (Fig. 137B), examination of the defocused image with a medium-power eyepiece is no longer sufficiently sensitive. We now insert the strongest available eyepiece (3 millimeters, for example), and after each adjustment examine the image at the plane of optimum focus (Fig. 137, lower half). In Fig. 137B, lower illustration, we see first the unevenness of the diffraction rings caused by a very slight coma (a half turn of the screw would probably correct this) and second, the added effect of three-way flexural distortion of the mirror on the positioning screws.

Final adjustments on the screws are made by quarter- or eighth-turns. If the observer is fortunate enough to have a reasonably undisturbed diffraction image, a precise adjustment is effected quickly. Otherwise a slight error may remain, but this is scarcely noticeable in images of average quality.

Figure 137C shows the perfectly centered image. The lowermost figure shows the local thickening of the rings due to flexure of the mirror on the screws. By proper adjustment the thickened portions may be made symmetrical. Turbulence may itself cause a similar appearance, but such effects are transient and may be disregarded.

We could discuss centering procedures further, but there is little point in belaboring this. Like focusing, the operation is almost instinctive; it is easier to carry out in practice than to read about and understand even with the best instructions.

XIV-2. Aligning the Cassegrainian

The procedure here differs little from that described for the Newtonian, and Figures 136 and 137 remain applicable. The preliminary mechanical adjustment begins in the same way with the orientation of the small mirror. With the telescope pointed at a bright uniform background, one sights along the axis of the eyepiece mounting through the eye-hole of a strong eyepiece from which the lenses have been removed. The secondary is correctly oriented when the image of main mirror, seen in the small mirror, is concentric with the outer edges of the small mirror. This is easier to do with precision than in a Newtonian since the secondary here is quite circular and it appears only slightly larger than the apparent diameter of the large mirror. The dark, narrow ring separating them is very sensitive to the slightest misalignment. Preliminary adjustment of the large mirror is also easier than in a Newtonian because its central aperture forms a reference circle that is ideal for centering the reflected outline of the secondary, both of these having a very similar apparent diameter. The first adjustment may be retouched if the initial error in inclination was too large. For final adjustment on a star, any slight retouching that is necessary would be applied only to the inclination of the large mirror, but the operation is much easier and faster than with a Newtonian. Looking at the image of a star near the zenith, we take note of the direction of the flare due to coma. This indicates the direction in which the image must be displaced by adjusting the inclination screws. The screws can be conveniently adjusted *without removing the eye from the image* to verify that it is actually moving in the right direction and to re-position the telescope before the star leaves the field. Naturally, final retouching has to be done when the turbulence is minimal. Even if this condition is not satisfied, we advise that use be made of the high magnification characteristics of a Cassegrainian. On an 8-inch instrument a magnification of 800 or even 1000 may be selected. One then sees only the central spot of the diffraction pattern and the arcs of the first ring to the exclusion of most of the light that is diffracted by small turbulent irregularities and obscures the brighter image seen in a normal eyepiece at $M = 400$ or 500. With telescopes of greater than 24-inch aperture, turbulence is a practically unremitting and it may be better to confine the observations to a slightly defocused star image (upper part of Figure 137).

If the telescope is fitted with a window (Chapter X), it is advisable to incline the window with respect to the axis by an amount about equal to half the field of the eyepiece, for example, at an angle of about 20 arc minutes on a 10-inch Cassegrainian with an $f/5$ primary. This avoids superimposing a faint gost image, due to reflection from a glass surface, which would be noticeable with an intense source if the window were exactly normal to the beam. The slight window inclination obviously introduces no signification aberration.

XIV-3. Balancing the Equatorial

Safe use of the instrument and uniform motion in the polar drive rate requires careful balancing. Frequently, a telescope that one thought to be balanced will take off spontaneously at certain positions. There is no mystery in this; it merely indicates that the center of gravity of the moving parts is not exactly at the intersection of the axes. To satisfy this requirement, we have to proceed methodically. The operations are essentially the same regardless of the type of mounting, even if there are no main counterweights. Assuming the mounting is of simple English type (Fig. 138), we lock the telescope in the plane of the meridian, remove the cover from the tube, and insert a standard eyepiece in the drawtube:

A. *Tube in horizontal position*: Assume, for example, that the instrument is too heavy on the side supporting the eyepiece. We re-establish balance by means of a weight P_1 temporarily mounted at D. The center of gravity then lies on the line *a-a'*. If there is appreciable friction in the declination axis, we compare the effort needed to tip the tube in either direction, or better, use a

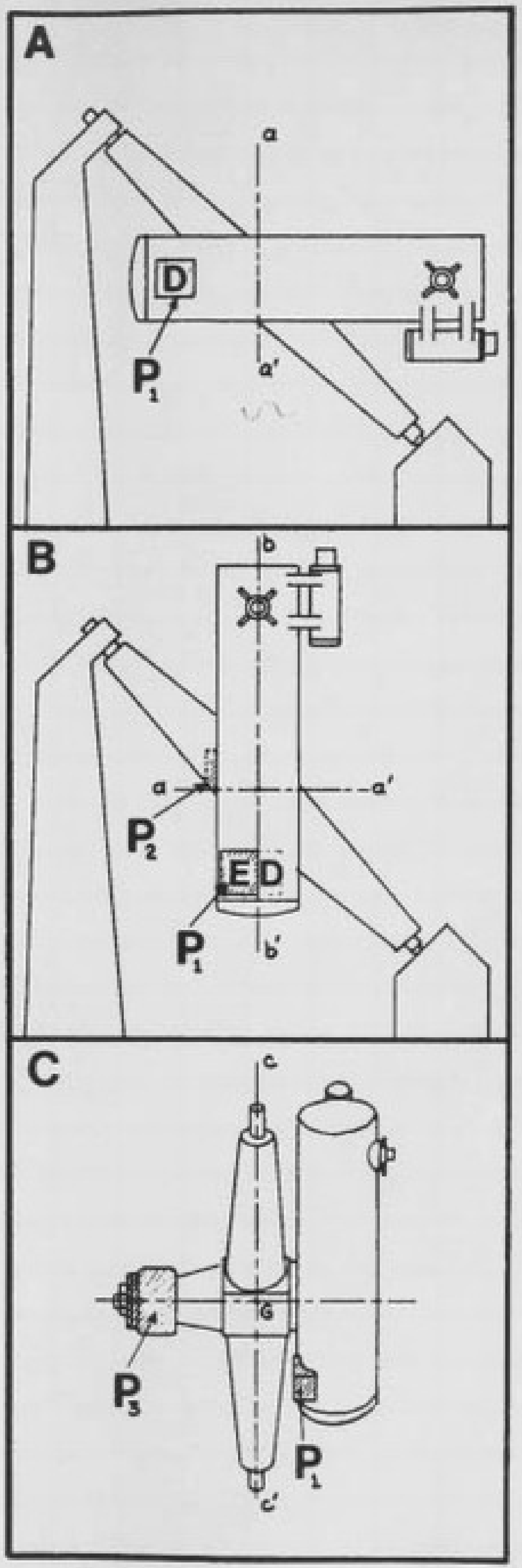


Fig. 138. Balancing of an equatorial.

precision spring scale to confirm that the force for upward and downward movement is the same.

B. *Tube in vertical position*: The tube is not now necessarily balanced when it is vertical, particularly if accessories have been installed in offset positions. The center of gravity may be brought back to the axis *b-b'* by a weight P_2, but it is simpler to relocate P_1 to position E and to try accomplish the entire balancing with this single weight. This avoids useless extra weight and extraneous projections. With a little thought and the example we give here, the user should be able to determine the position and weight of the mass P_1 in any given case. The important thing is to confirm that balance is perfect in at least two very different positions of declination. The center of gravity is then at the intersection of the lines *a-a'* and *b-b'*, i.e. on the declination axis.

C. *Balance in right ascension*: The polar axis is released. We now need only to adjust the mass and/or position of P_3 to shift the center of gravity of the assembly to the polar axis *c-c'*. A weight that is heavier but shorter and thicker is often better than one mounted at a distance on a long flexible rod. If the weight is in the form of a figure of revolution with respect to the declination axis, balancing in right ascension with the tube at a single position of declination, preferably at the meridian, is sufficient.

If the accessories on the telescope are changed, particularly as one changes from visual observation to photography, rebalancing may be necessary. It should be possible to do this rapidly without trial-and-error. In some cases, the weight P_1 may slide lengthwise on a rod supported on two stand-offs. This is not a good-looking arrangement, and we advise against it. It is better to make a one-time determination of the appropriate interchangeable weights P_1 and P'_1.

XIV-4. Siting of the Equatorial Telescope

We have seen in Section XII-4 how the polar axis may be adjusted approximately to the correct position in azimuth for the observer's geographic latitude. An approximate adjustment can also be made with a combination level and protractor applied, if possible, along a portion of the polar axis.

All that now remains is to refine these adjustments by astronomical observation. The following practical method is based in principle on a method described by Bigourdan (1893).

The telescope is fitted with a reticle eyepiece giving a magnification of about 200, and the instrument is pointed toward the south at an equatorial star *at a position near the meridian*. The eyepiece is turned to align one of the filaments of the reticle parallel to the diurnal movement, so that the star moving into the field remains on this filament. Lock the declination axis and follow the star for several minutes either manually or by engaging the drive. If the polar axis is poorly adjusted in azimuth the star veers away from the filament in declination. *If the star veers toward the northern half of the field, the error is corrected by shifting the upper end of the polar axis toward the east* (Fig. 139A). Note that, with the image inverted the north side of the field is at

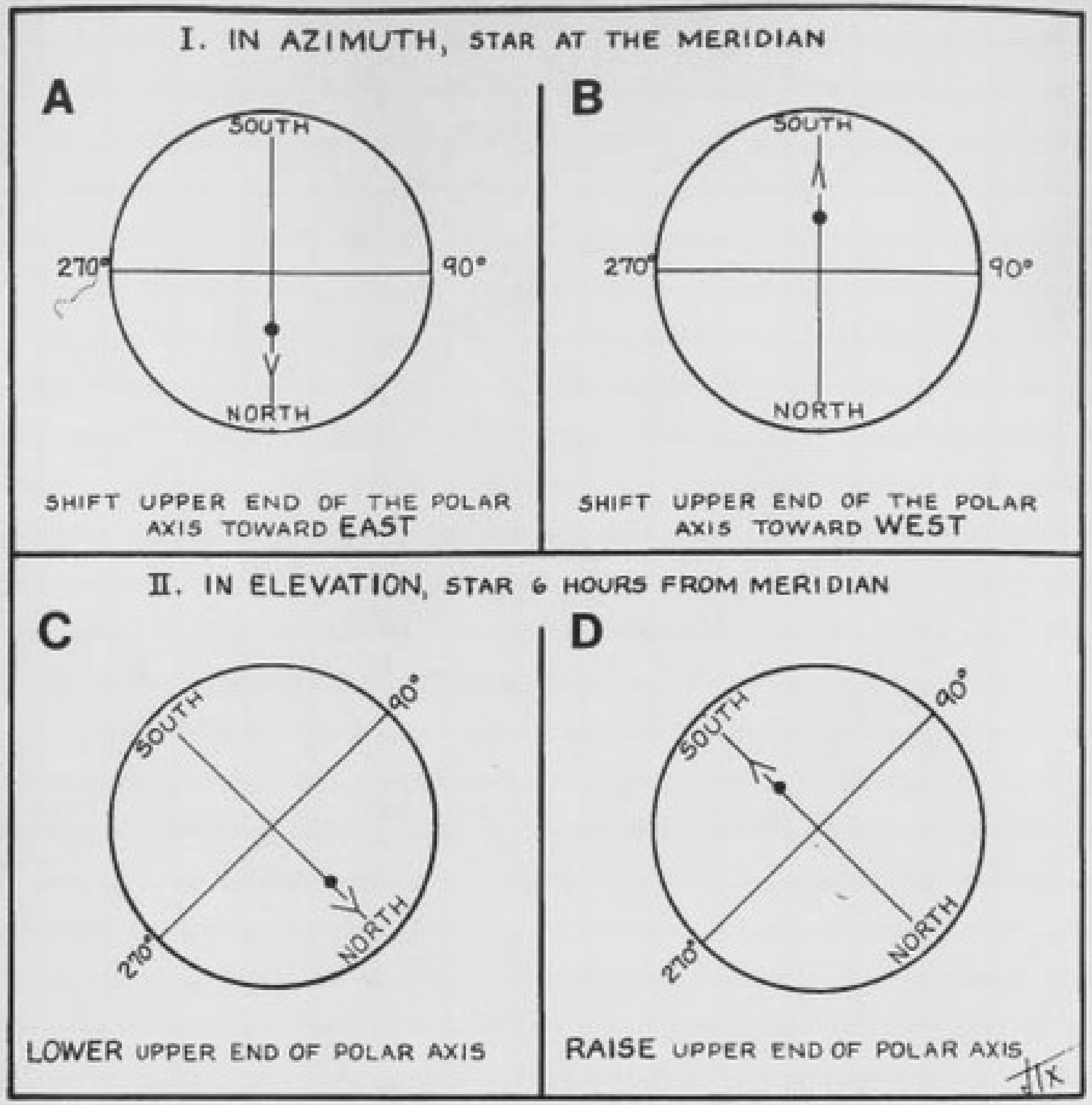


Fig. 139. Adjustment of an equatorial.

the bottom for an observer viewing a star in the south. Naturally, *if the star shifts toward the south part of the field, the upper end of the axis must be displaced toward the west* (Fig. 139B).

It is best at this time not to fuss too much over this adjustment, but first to complete the declination adjustment, then to return for a second, closer adjustment in azimuth.

The telescope is now pointed on a star at a declination of +40 or 50 degrees *and 6 hours away from its transit across the meridian, toward the east or the west.* This time, it is an error in the polar axis inclination which accounts for any drift of the star in declination. *If the star veers toward the north part of the field* (Fig. 139C), *the upper end of the polar axis must be lowered; it must be raised if the star drifts toward the south part of the field* (Fig. 139D). We now return to our equatorial star near the meridian, this now

being more immediately important for our present purpose. The adjustment to a second approximation is considered satisfactory if the star remains on the constant-declination filament for about a half hour. Note that the observed positions of the stars we selected included a refractive component inherent in ordinary conditions of observation. Whether we to choose to point our polar axis at a refracted or un-refracted pole is arbitrary; when we make long photographic exposures we shall in any event have to make many small corrections in declination.

XV

ATMOSPHERIC TURBULENCE

The atmosphere is the worst part of the instrument . . . André Couder

XV-1. Difficulties in the Use of a Medium-Power Telescope

Assume that we now posssess an optically perfect, properly adjusted telescope. Do we automatically obtain from it the performance promised by the size of its mirror? Not at all; the problems that remain may still be the most challenging, and the larger the telescope, the truer this will be.

The technique of the medium-power telescope could in itself justify a long treatise that unfortunately cannot be included in a short book of telescope making instructions. The owner of an 8-inch telescope has probably had some experience as an observer, perhaps on a smaller, more easily used refractor. He has probably acquired the simple skills that are mastered with a little practice: finding the object; focusing; avoiding vibration; selecting eyepieces; training the eye to observe; sketching the results of observations, etc.

If we consider the instrument merely as a light collector, we have no difficulty in obtaining the expected performance. For example, we can observe variable stars at relatively low power, and at the Newtonian focus we can take photographs of the faintest object accessible to the telescope. The surprises come as soon as we try to achieve a significant fraction of the theoretical *resolving power* of the mirror. In the study of close double stars and, to a greater extent, in observing weak planetary detail, the difficulties increase rapidly with increasing mirror aperture. Most of these have a common cause: *atmospheric turbulence*. Since performance under these conditions may reflect unfairly on the quality of the telescope, we have to consider the nature of these disturbances further. Whether we like it or not, the atmosphere and all of its defects are inseparable from the performance behavior of the instrument. Only by placing the telescope in space or on the Moon could we be free of them completely! Atmospheric disturbance is not a minor phenomenon; it introduces defects some ten-fold greater than those left by the optician. Forming a valid opinion of instrument quality by testing it on the sky takes long experience as an observer, and much waiting—often several weeks—for favorable conditions. We hope the following gives the reader the essentials needed to understand the observed image. Unfortunately, the phenomena involved are complex and interdependent, and turbulence is one of the most elusive adversaries we know.

XV-2. Atmospheric Defects

We have assumed up to now that the wavefront arriving at the objective from a star is perfectly plane (Section I-3). Actually, the wave must first traverse the atmosphere, and this is far from optically homogeneous. Since the refractivity of warm air is different from that of cold, air currents at different temperatures will deform the wavefront in a complex and variable manner. Assuming the telescope accepts a wide enough segment of the wavefront, the wave will appear quite irregular. Lord Rayleigh[1] has given us a convenient expression for the wavefront deformation δ produced by a body of air of path length l differing in temperature from the surrounding air by t °C.:

$$\delta = 1.1\ lt \times 10^{-6} \qquad (96)$$

Thus, a meter of air differing from the surroundings by 0.13° C. is enough to cause a quarter-wavelength deviation at 560 millimicrons. It is astonishing that at ground level one can obtain an image at all with a light beam 6 inches

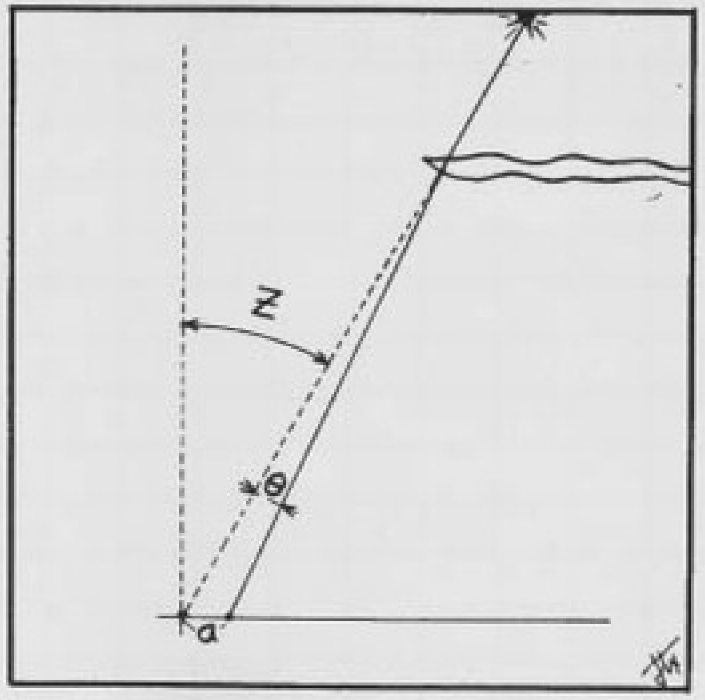


Fig. 140. Angle of turbulence, Θ.

or more in diameter. The phenomenon of wave surface deformation is complex. We can simplify it to a first approximation by characterizing the turbulence by a parameter θ, i.e. the angle of deviation of a light ray coming from a star after traversing a heterogenous layer of air (Fig. 140). Within the wavefront area defined by the objective, θ may have positive or negative values

[1] *Scientific Papers*, Vol. III, p. 102.

comparable in magnitude to the transverse aberrations we are already familiar with, and which to a certain extent characterize the seriousness of the phenomenon.

The naked eye receives a beam only a few millimeters in diameter. Since the deviations θ are of the order of a second of arc, heterogeneities near the observer have no perceptible effect, but those several kilometers away can produce displacements a of several centimeters. The energy received by the eye therefore varies constantly and we say that the star *twinkles*. If the star is low in the sky, we observe *chromatic scintillation* because the star's rays are incident at a large angle on the atmosphere and the various wavelengths are not equally refracted. There is fluctuation not only in brightness, but in the dominant color. A planetary disk, subtending for example 20 seconds of arc, does not scintillate except under unusual conditions; this angle is already large enough compared with the angle θ for the fluctuations to be small.

Scintillation as seen by the eye, or that is measured, for example, with a photosensitive receiver of small aperature, is not of much help in studying the turbulence that can effect a large astronomical instrument. A large enough area of the wave surface must be studied, and all the heterogeneities taken into account, not just those several miles distant in the atmosphere.

XV-3. Star Image Changes in the Small Instrument

When the objective aperture becomes as large as several inches wide, scintillation disappears because the collected light is more or less constant over a sufficiently large area. At a given instant, a large fraction of the incident wave surface approximates a plane inclined at some small angle. The image is not much changed, but momentarily shifted as a whole. The effect is that of *slow refraction*. With a spider cross-hair adjusted closely parallel to the diurnal motion, one can follow these shifts of the star image with a very high-power eyepiece.

As the telescope aperture increases, sensitivity to turbulence increases rapidly. Not only do the wave inclination angles θ become greater compared with the angular radius ρ of the diffraction spot, but on a wave surface 20 centimeters or more in diameter we see a veritable chaos of defects (as we show later) when we viewed the image by a Foucault test. For the moment, let us remove the eyepiece, and with our eye at the focal position, focus the eye on the mirror illuminated by a bright star. We see a pattern of alternating light and grey bands, the *flying shadows*, across the surface.

When the aperture is of modest diameter, under 20 inches as in the amateur instruments considered here, we have a simple way to relate the image quality to the parameter θ, the maximum inclination of any portion of the incident wave surface. The method is that of A. Danjon[2], which is interesting because it gives a quantitative estimate of the viewing quality on a particular night and viewing site by observing changes in the diffraction pattern. Using interferometric measurements, Danjon was able to construct

TABLE IX
CORRELATION OF IMAGE DEFECTS WITH WAVE-FRONT INCLINATION

Value θ	Description (see Figure 141)
V $\theta < 0.25\,\rho$	Perfect images; no noticeable defects and relatively stable
IV $\theta = 0.25\,\rho$	Complete rings with variable thickening in places
III $\theta = 0.50\,\rho$	Moderate agitation; broken diffraction rings; wavy edges on central spot
II $\theta = \rho$	Strong agitation; rings marginally visible or absent
I $\theta > 1.5\,\rho$	Image tending to appear like a planet

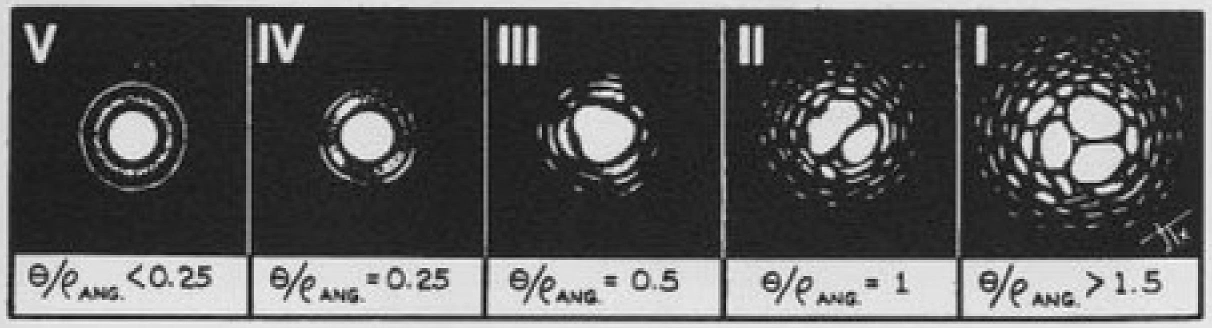


Fig. 141. Scale for quantitation of turbulence in a small instrument.

Table IX. It correlates image defects with the wave-front inclination θ. The scale is unavoidably very approximate, since the actual phenomenon is very complex and constantly changing. In addition, one should look for a possible systematic cause for a reinforced first diffraction ring, for example, residual spherical aberration corresponding to a transverse aberration of 1.5ρ. Also, in reflectors, the central obstruction makes the instrument somewhat more sensitive to turbulence. Only a reflector of high quality, enclosed by a window and having an obstruction of less than ⅙ D, would be comparable to a good refractor of $f/15$ in this respect.

[2] "Etude interfentielle de la scintillation"; *Reunions Institute d'optique*, 4th Year, p. 20, 1933, 2nd Meeting. See also *Lunettes et Télescopes*, p. 82.

The turbulence increases essentially as the secant of the angle z from the zenith (Fig. 140). Barring significant instrumental phenomena or local disturbance that we discuss later, we can tentatively accept this relationship and avoid testing stars less than 20 degrees above the horizon ($z = 70$ degrees; $\sec z = 2.9$) to avoid problems of atmospheric dispersion and local anomalies. A more complete evalution would evalute star images (of about third magnitude, assuming an 8-inch instrument) at different elevations on the scale of I to V. A protractor and plumb bob mounted on the tube can give the

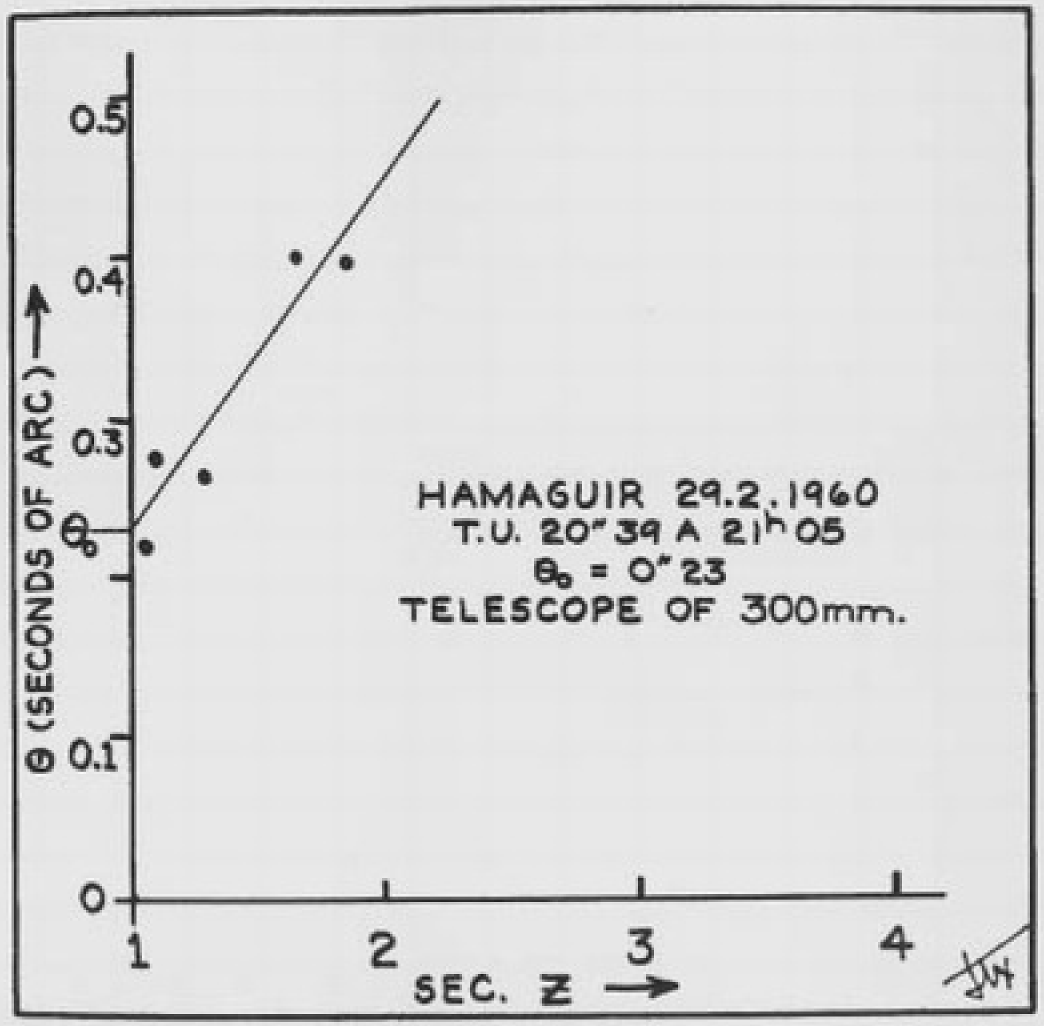


Fig. 142. Graph showing reduction of data on turbulence.

angle z. We know that the angular radius of the diffraction spot in seconds of arc is $\rho = 14.1/D$. The corresponding values, of θ are plotted on a graph (Fig. 142 as a function of the secant of z. The intersection of the plot with *sec* $z = 1$ gives us the particular value θ_0 for *turbulence at the zenith*. The graph shown in Figure 142, obtained on a 10-inch Newtonian at a desert station in the Hamada region of the Sahara, shows that a value of θ_0 equal to 0.23 arc seconds, still a moderate turbulance level that would be of little concern in a telescope of this aperture.

XV-4. Star Image Changes in a Large Instrument

A *planetary* type image I (Fig. 141) is hardly pleasing to astronomers, but worth examining because *it is the rule in a large instrument.* To ignore this phenomenon would not teach us much. We bring this up not only because curious amateurs wonder what can be seen in a large telescope, but because, alas, their simple 10-inch instrument will frequently show the same phenomenon.

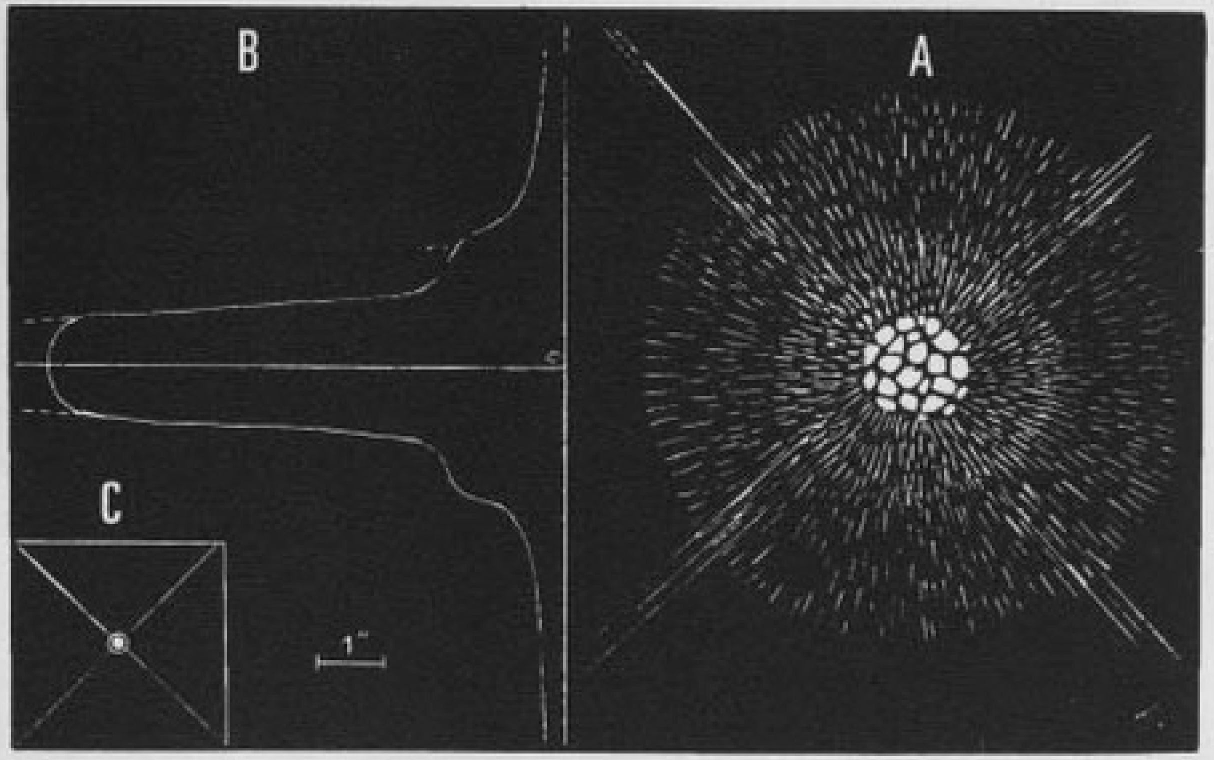
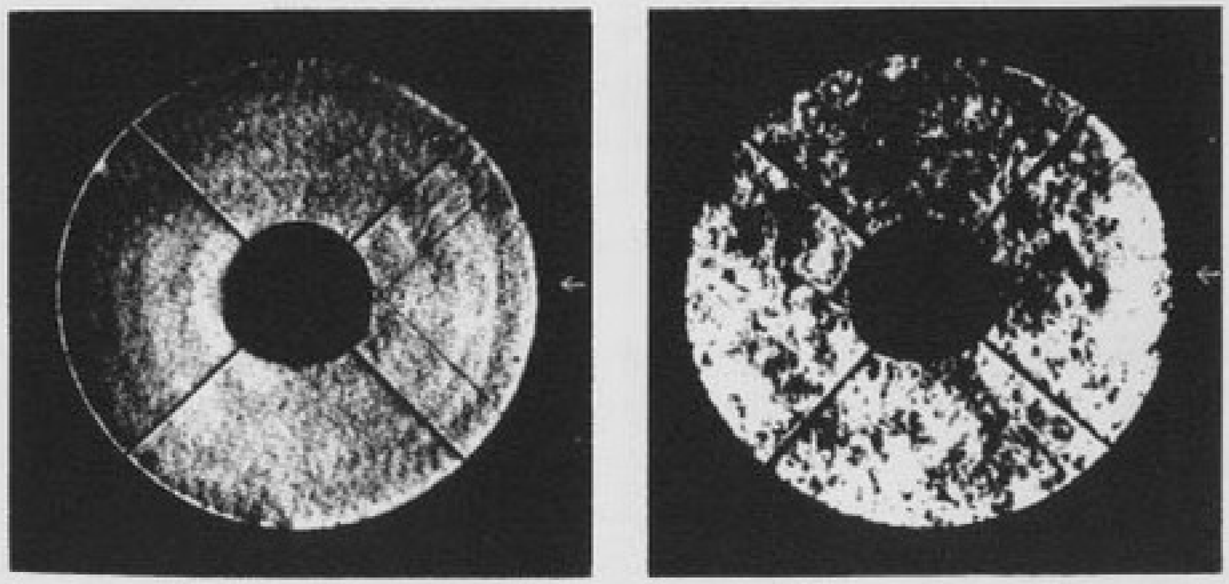


Fig. 143. Image of a bright star seen in a large telescope.

A star image will sometimes have a truly planetary appearance under particularly poor viewing conditions, as for example, when there is a cold wind like the *mistral.* One then sees a hazy disk with boiling edges, occasionally exploding from a diameter of 6 arc seconds up to 20 arc seconds! There is no clearly defined central area, but a true, more or less flat energy plateau. We shall also see another type of image change, much more frequently but fortunately less serious, observable in telescopes above 1-meter

aperture on nights when the θ value for a small instrument would be about 0.3 arc seconds. Figure 143 is an attempt to represent the image of a bright star, β Persei, $m_v = 2.3$, seen in the 76-inch telescope at the Observatory of Haute-Provence at a magnification of 960. It is an awesome turmoil of luminous, granular, worm-like forms in rapid motion of which only the easily visible central portions are shown here. The entire phenomenon extends out to several minutes of arc before it is lost in the black background of the sky. Let us look again at the middle of this central region. It is made up of very intense, mobile grains several hundredths to several tenths seconds of arc in width forming a *packet* subtending 0.2 to 2 arc seconds depending on the night in question and 1.5 arc seconds in the example shown. Outside the *central packet** is a zone that is still very bright, with smaller grains becoming progressively fainter and showing a powdery luminosity with two shoulders at diameters of 4 to 5 and 7 to 8 arc seconds. The diffraction flares caused by the supporting blades of the secondary flat mirror are themselves dulled in a variable manner. The curve B suggests, very approximately, the distribution of energy. We hope someday actually to measure this. For the present, we emphatically challenge the persistent, widespread notion that blames this broad energy spread on defects of the large mirror.[3]



A) 2 minute exposure B) 1/10 second exposure.

Fig. 144. Foucault test photographs made on the 193 cm (76-inch) telescope.

At least in the 76-inch reflector used in our example, which we know perfectly, not only are defects in the main and secondary mirrors very small, but the complete assembly in operation, corrected for flexure and temperature effects, gives a wavefront that is stigmatic to within $\lambda/8$ (Foucault pattern, Fig. 144*A*). We know *positively that* in the absence of an atmosphere the normal diffraction figure, 0.15 arc seconds in diameter (Figure 143*C*) would be

* This description was first made by the Author in 1959. Other observers re-discovered the phenomena which is now known as *Speckle*.

[3] J. Dommanget, "The Project for Creating a European Observatory in the Union of South Africa," *Ciel et Terre*, Vol. LXXIV, Nos. 7 and 8, p. 312.

obtained. Because of the limited brightness of the printed page, the drawing gives only a faint idea of the fantastic energy that is concentrated in this image. Such a result would be utopian; even the atmosphere in a large, fully enclosed air-conditioned laboratory would be too heterogeneous for such an image. To await the miraculous, ideal moment in a large telescope would be hopeless, but even partial dispersal of the turbulence can result in a startling improvement in definition.

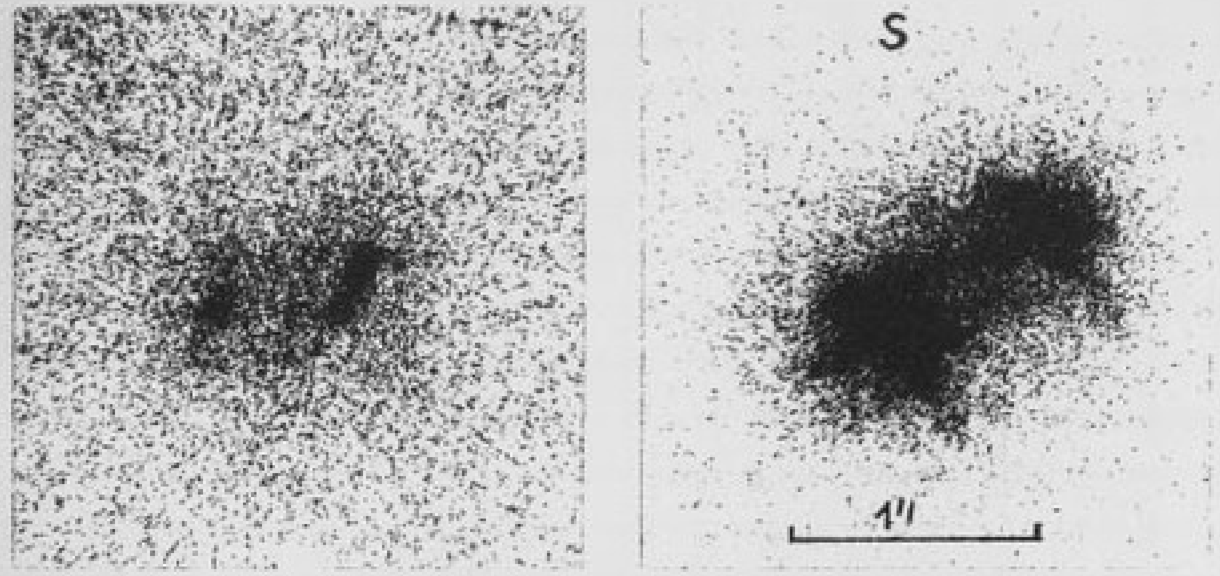


Fig. 144C Two exposures of a close double star which almost show the diffraction pattern. 0Σ359, m=5.76, p=0".49 taken with the 82-inch Mc Donald Telescope on September 24, 1964 (left 19h 54m, right 20h 25m) at the coude focus (f=153 meters) on Trix film 1/4 second (efl=4700 meters), scale is 1"=22.8 mm.

We caution against another error, namely the notion that a large telescope is inferior to a small one because of turbulence. The same destructive external phenomenon effects both, except that it is less noticeable in the small instrument because the image is not as bright, and the normal diffraction pattern is less conspicuous. The superior definition of the large telescope, which is impossible to exploit when image quality is poor, is indisputable when viewing conditions allow *better image quality*. Unfortunately, with a mirror 76 inches in diameter, one must sometimes wait two or three months for such conditions.

Do we have to emphasize that neither the angles of turbulence θ nor the magnitude of deviations on the wavefront (which tend toward the limit as the aperture approaches 20 inches) do not *in themselves* explain such a wide scattering of the energy? We have to look at some further consequences of the extremely complex wave surface received by the mirror. Such a wave surface acts as a *phase grating* whose defects are incomparably larger, more inclined and more heterogeneous than those represented in the photographs of Figures 41*C* and 131 taken by the Lyot phase contrast method. In the present case, the Foucault method is more than sensitive enough; the only difficulty is the extreme mobility of the disturbances. With the 76-inch telescope aimed at

Sirius, we succeeded in obtaining Foucault photographs with exposures of only 1/10 sec. (Fig. 144*B*). An exposure of the order of 1/1000 second would demonstrate the phenomenon faithfully only on a rather large image; however, in the present picture we can rather clearly distinguish the striae in the telescope tube itself, and the much more significant strata of external turbulence. A Foucault photograph on the same instrument, this time exposed 2 minutes (Fig. 144*A*), integrates all the changing atmospheric defects and reveals the true optical defects of the mirrors in the system, the amplitude of which, we note, does not exceed $\lambda/8$. The term *grating* is usually reserved for an optical element engraved with narrow, uniform parallel grooves that diffract the light according to a simple law into a central spectrum of zero order as well as an entire series of strongly deviated spectra of 1st, 2nd, 3rd, etc., order. But looking at the optical properties of the atmosphere, there is almost total anarchy: there are mixed defects of different magnitude, inclined in every direction, and in a constant, almost Brownian type of motion. Still, there are millions of them nearly the same size, and thousands of them at a given instant may have the zero slope that contributes to the high energy at the center. They diffract at a significant solid angle that easily attains several tens of seconds of arc according to some complex and variable law, but well enough defined statistically to maintain the image described above for several hours. If a gust of the *mistral* intervenes, introducing a layer of finely laminate striae parallel to the wind direction, the image immediately explodes and we note that its diameter is larger in a direction perpendicular to the wind because there is a distinct asymmetry in the angles of diffraction.

XV-5. Image Changes Due to Photographic Diffusion

The image of a point of light on a high-speed photographic emulsion has a minimum diameter of 20 to 25 microns (about 0.00078 to 0.00098 inch) caused by diffusion of light in the gelatin. Yet an $f/6$ mirror can give a diffraction spot about 1/3 this size (8 microns) in diameter. This resolving power, about equal to ρ, means that we must reconcile these relative values by using a focal extender to make F/D at least equal to 36, or much higher in practice. Turbulence will, of course, play its usual spoiling role. Subjective evaluation of the reuslts often leads to the view that photography cannot register all the *detail* visible to the eye because exposure times are necessarily long and refractive shifts during exposure spread the image. Actually, at least in large instruments, it is the optical properties of the eye that are more limiting than the mirror's capabilities. Taking the 200-inch telescope as an example, turbulence limits the useful magnification to about 1000. The corresponding instrumental pupil is then 5 mm in diameter, but it has a dark center about 2 mm in diameter due to the central obstruction.

Now, the pupil of the eye, dazzled by a planet or bright star in such an instrument, contracts to about 2 mm, so that if the eye is well-centered at the eye-ring it sees nothing. The eye must shift a little to one side to catch light passing along the secondary mirror about 6 feet away. On the question of short exposure times, experimental evidence is equally clear: a bright star at the focus of a one-meter diameter mirror, even with a focal extender, provides enough energy for a 1/500 sec. exposure, if desired, on ordinary high-speed emulsion. But it takes the eye 1/10 second to see a *detail.* Figure 145 shows a succession of images, exposed 1/100 second, of the double star, Castor, which is a beautiful object in even the smallest refractor, such as a 3-inch. At an acceptable turbulence level the resulting *central packet* had a diameter about one second of arc. Not only was shift due to turbulence not eliminated, but the effect of random deviation is especially shocking; we see *fine* detail, to be sure, but it is totally illusionary, as for example, flares, phantom separation, etc., while the separation of the two components (2.4 arc seconds) fluctuates by several tenth-seconds, and their relative orientation varies by about twenty degrees. An exposure of at least a second would be needed to give any seriously measurable image. Psychologically, the details seen by the eye appear to have better fidelity; but this is only because the eye is a very intelligent receiver.

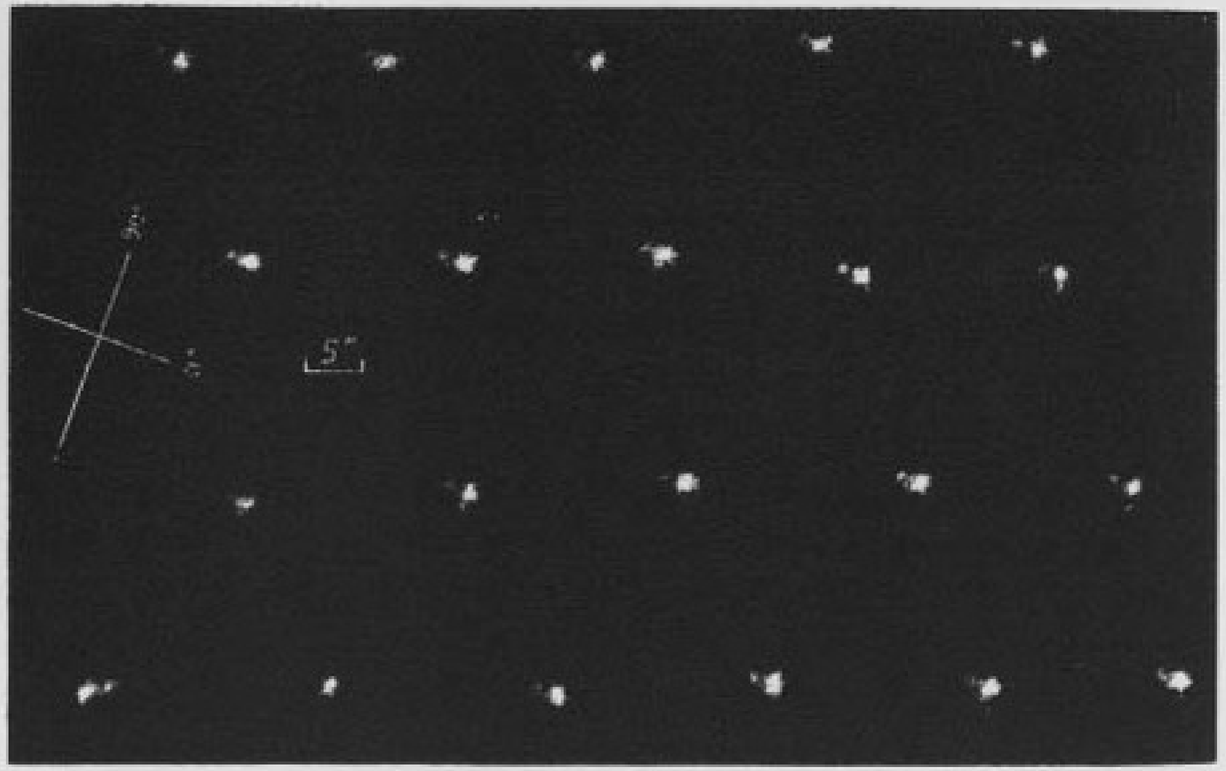


Fig. 145. Sequential photographs at 1/100 sec. of the double star α Gemini (Castor) April 8, 1955 telescope aperture 120 cm; 3.1 × Barlow amplification; magnification 10 equivalent focal length 219 meters.

We can therefore refute two strongly held beliefs, among others, namely that in a large or medium instrument:

1. Shortening the exposure time does not increase the amount of real detail obtained; and

2. It is turbulent shift, properly speaking, and not random refraction that is responsible for broading the photographic image.

Finally, let us consider long-exposure photography directly at the focus of mirrors of about $f/6$, where we no longer expect to approach the theoretical resolving power.

Offhand, it would appear that only photographic diffusion limits the resolution. Not at all! Even a modest telescope experiences this affliction of turbulence, as we shall see. A few words of explanation are necessary on the macro-photographic appearances of images of faint stars, whether made on a large or small telescope. Figure 146 is a ruthlessly enlarged very small part of the negative of an excellent photograph of the Andromeda Nebula (M31) taken at the focus of the 47-inch telescope at the Observatory of Haute-Provence. The background light of the night sky and the unresolved population II of the nebula form an irregular veil on the plate background consisting of *large,* very thinly scattered grains.

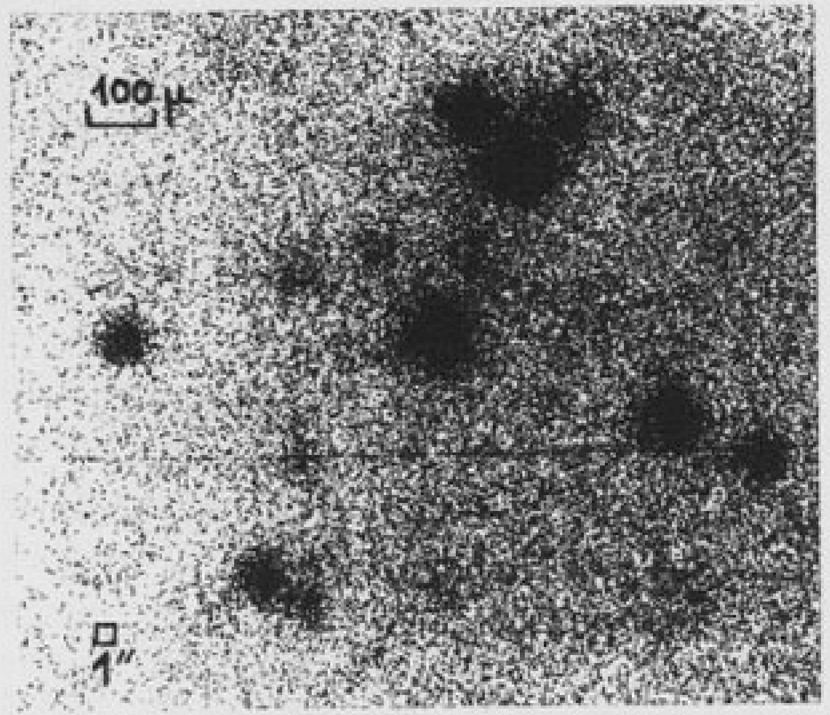


Fig. 146. Photographic negative of star images, highly magnified, 60X.

The images of weak but definite stars (in this case, of about $m_{pg} = 21$) are seen as faint disks of increased density where the grains are simply a little more numerous. If the star is brighter, the disk is denser and better defined by an accretion of finer grains. A central maximum appears, permitting the optimistic measurement-taker to announce good performance. On the other hand, cheating is not possible for a star at the extreme limit, where the image ceases to be significant because of a lack of grain density clearly exceeding background fluctuations *over an image area of sufficient diameter.* This diameter is that of the *central packet* described in Section XV-4 and Figure 143.

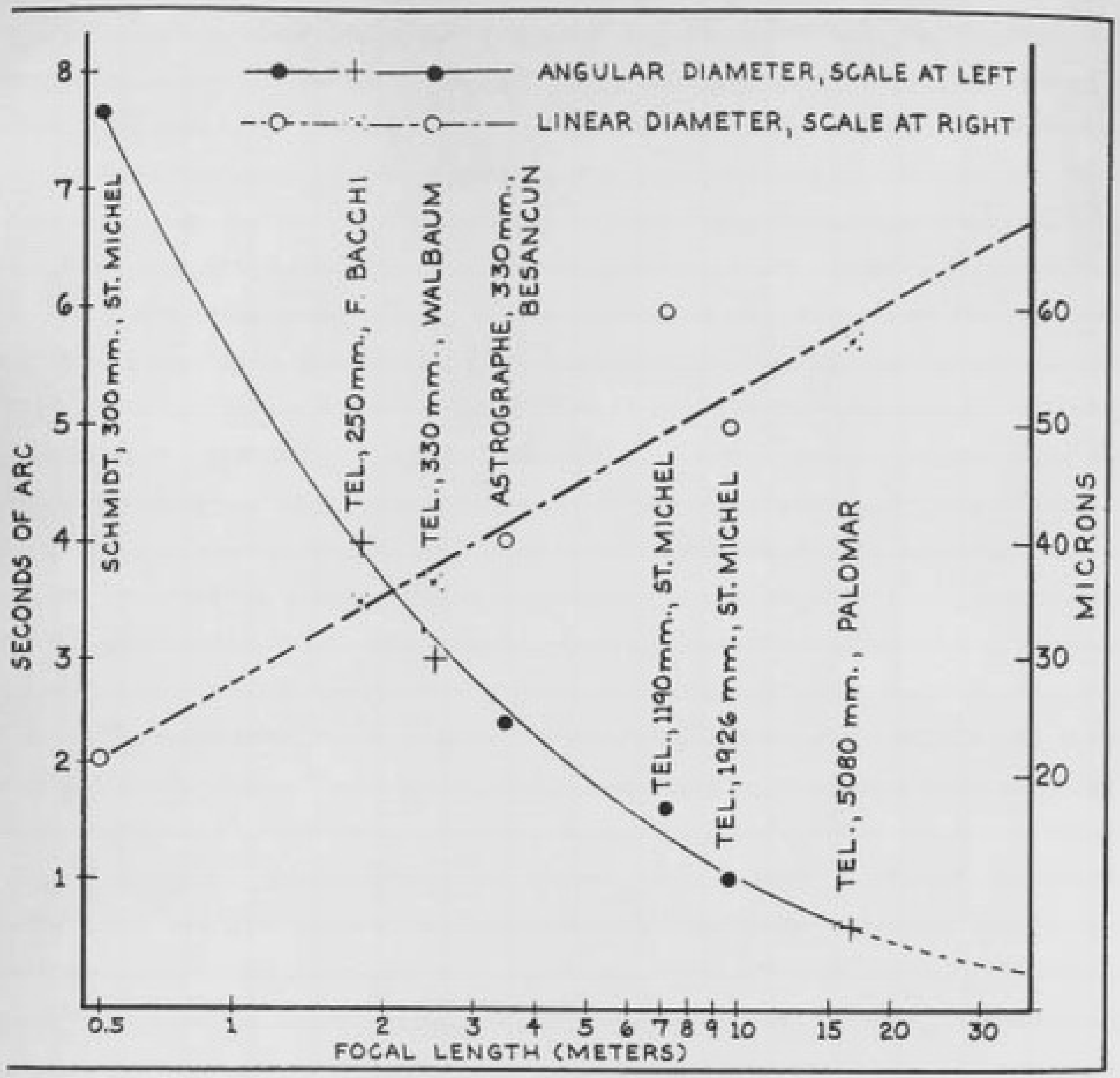


Fig. 147. Diameter of the smallest photographic star images as a function of instrument dimensions for long exposure times.

Only in this zone are enough photons received to make the large grain developable in the case of a faint star. The diameter of photographic image can be easily measured within 5 or 10 percent using a small measuring microscope with an optimum magnification of about 20. We find a diameter of about 60 μ on the photograph of Figure 146, or about 1.7 arc seconds, a value much greater than the 22 μ attributable to photographic diffuson alone on the emulsion used (IIaO, Eastman Kodak). On the basis of the best data obtained over several years of meticulous work, where we were fully confident about optical quality (tested before and after exposure), and sure of the precision and stability of focusing and of the carefully monitored and corrected drive rate, we know what the practical experimental limit, if not the absolute limit is, that is virtually impossible to exceed. This limit cannot be attributed to turbulent shift; *it is almost the same as we found on the instantaneous photographs blown up to much larger scale.*

Let us see how this varies with the dimensions of the instrument. For the comparison to be fully significant, we must be sure in each instance that the optimum conditions prevailed and that the data represents a practically perfect *textbook case*. The open circles on the graph of Figure 147 represent the author's best personal photographs, taken on emulsion 103aO or IIaO and under well-defined conditions. The crosses relate to two selected photographs borrowed from the collection of our colleagues F. Bacchi (10-inch telescope) and Walbaum (13-inch telescope). This data was supported in both cases by several years' work that appeared to us as sufficient assurance of validity. The last cross relates to a photograph, also of a quality difficult to surpass, taken by Baade on the 200-inch Hale Instrument at Mount Palomar showing the population II in the elliptical nebula NGC 205[4]. Naturally, the focal lengths, plotted on a logarithmic abscissa for convenience are associated with correspondingly increased apertures because the instruments, almost without exception, are about similarly proportioned.

The locations of the different instruments are not equivalent, when they are at even the same station. The micro-climate can cause very local anomalies affecting a single instrument. The abnormal point on the graph relating to the St. Michel 47-inch instrument is a good example. This illustrates the value of considering the various levels of turbulence, as we do later.

Acknowledging these reservations, the irrefutable fact remains that photographic resolution is improved in large telescopes. How then, do we reconcile this with our description of the wave surface as a *phase grating*, since the wave defects, which are external to the instruments, are the same and diffract in the same way? We must consider the overall result represented by the image, in which improvement is due to three causes:

1. The center of the energy dispersion, that is, the normal diffraction pattern, has a smaller diameter with a large mirror. This explains only a small

[4] See *L'Astronomie*, Cover of the December 1953 issue.

part of the improvement, and is not applicable to the 120-inch (Lick) and the 200-inch Hale, where the optical qualities are sufficient to give a good photographic image but not the theoretical diffraction disk.[5]

2. The wavefront corresponding to the large mirror contains more random fluctuations. The energy distribution curve (Fig. 143B) is better defined in its details. In particular, the *central packet* that forms the peak comprises more grains, and defines a higher and sharper apex (the beginning of which is shown by the broken lines on the left of the figure). *The diameter of this peak area, where the exposure is just able to cross the detection threshold of the emulsion, is smaller.*

3. Fluctuations in position of the central peak are rarer and of smaller amplitude when the wave surface is large compared with its elemental defects. This is easy to understand. When the objective is not much larger than the inclined elements of the wavefront, the probability that one of these elements will, at given instant, cover a substantial fraction of the pupil is high. The image is not destroyed, but is shifted or deformed. On the other hand, given the large number of inclination defects between zero and θ, their distribution is more or less Gaussian; the *stability of the central peak improves as the mirror becomes larger and the defects more numerous.*

If the wave surface has relatively wide defects, the corresponding image is more concentrated but subject as a whole to considerable refractive shifts, whereas if the defects are fine the image is broadened more, but the center is perfectly stable. In either case, the advantage lies with the large mirror.

The logarithmic scale on the graph of Figure 147 obscures the enormous effort invested in telescope design and construction to improve the definition by a fractional second of arc. Extrapolation of the curve—indicated by a broken line—to a hypothetical telescope about 400-inches in diameter suggests that photographic star images as small as 0.4 or 0.5 arc seconds might be possible. Such improvement compared with the 0.7 arc seconds of the 200-inch Hale Telescope may not appear worthwhile, but it is fundamental to progress in fathoming the universe. In effect, there is a second atmospheric effect, aside from turbulence, that limits the performance of a large instrument. This is the *background light of the night sky*, which according to Baum[6], corresponds to a parasitic source of magnitude 22 for each square second of sky area. Now, a square second is the area covered by the image of a faint star in a 200-inch when conditions are not exceptionally good. A star of magnitude 22 doubles the energy level compared with the background and gives a strong image, but a magnitude 23 star adds only 40 percent and one of magnitude 24 only 16 percent. This is the limit, not because the receiver lacks sensitivity, but because the useful energy has to be concentrated in a smaller area of the sky, and *only a larger mirror can do this.*

[5] Mayall, Vasilevskis, "Quantitative tests of the Lick Observatory 120-inch Mirror," *The Astronomical Journal*, Vol. 65, Number 5, June 1960, p. 304. and Bowen, "Final Adjustments and Tests of the Hale Telescope," *P.A.S.P.*, Vol. 62, Number 366, June 1950, p. 92.

[6] "Some Photoelectric Problems," Otto Struve, *Sky and Telescope*, Volume XIV, Number 5, March 1955, p. 188.

Our discussion has extended to massive instruments far removed from the amateur telescope, but the graph also provides some comfort for the amateur. The instruments of our two collegues fall very properly within the hierarchy of performance, and an unprejudiced observer would be astonished at their efficiency, given their extreme modesty. They can detect stars of 17 to 18 magnitude, and their images are only 3 or 4 times larger than those achieved by a 500 ton colossus! Obviously, the amateur has neither the desire nor means actually to advance our knowledge of the universe in many areas, but what he can achieve is still spectacular. If he is a reasonably methodical type, he can contribute to genuine research, for example, in the surveillance and discovery of supernovae in the galaxies, double stars, or even in photoelectric photometry. We are awed, of course, by the giant telescopes that alone can probe the farthest limits but, we should not on that account underestimate the enormous contributions that can still be made with medium and small telescopes used by many skilled observers.

XV-6. First Stage of Turbulence: The Instrument

Turbulence can be classified conveniently in three categories, though the lines of demarcation are not sharp.

Concerning turbulence inside the instrument, the reader will find it useful to review Section X-1 on the advantages of a telescope window.

Internal turbulence may be observed as follows: We aim telescope at a bright star, or better, at a planet of apparent diameter preferably between 10 and 20 arc seconds. Removing the eyepiece, we make a Foucault test (Section II-21 to 23) by holding a calling card against the eyepiece mount, and using its edge as a knife-edge. With a little practice, and adjustment of the edge forward and back according to the direction of shadow movement, we are able in a second or two, even with an altazimuth mounting, to intersect the image point. Instead of uniform darkening, such as one would see using a sphere tested at the center of curvature, we see boldly contrasted shadows moving across the mirror, caused by optically non-uniform veins of air lying across the light path. Figure 148 shows some of the effects that may be observed, as reproduced in the laboratory with a spherical reference mirror 12 inches in diameter with a radius of curvature of 217 inches corrected to one- or two-hundredths of a wave.

The Rayleigh formula makes clear that no instrument in actual use can be completely free of perturbation. Figure 148A shows the small, broad, very slowly changing disturbances (about 1/10 wave) that characterize the air in a basement. An exposure of several minutes would be needed to integrate such changes before one could see the defects of the mirror itself. Such perturbation hardly affects the diffraction image; the brightness of the first ring may change slightly and the central disk be momentarily deformed.

The reader may suppose, with good logic, that the air near the mirror could be made more homoegeneous by stirring it with a fan. Figure 148B shows the unhappy result. An 8-inch fan was placed 2 feet to the left of the mirror. We see a rapid agitation that breaks the wavefront into steep fragments about 2 inches across, corresponding to deviations of the order of a half wave. The image quality level (Figure 141) falls to II. The image of a star under the same conditions is markedly altered. Energy in the inner diffraction rings is scattered, breaking them up into a pattern of bright, shifting arcs. The central disk remains, but it would be quite difficult to detect a faint companion star close to the brighter star. Only when disturbances in the telescope are already worse than that shown in Fig. 148B could one expect improvement with a fan.

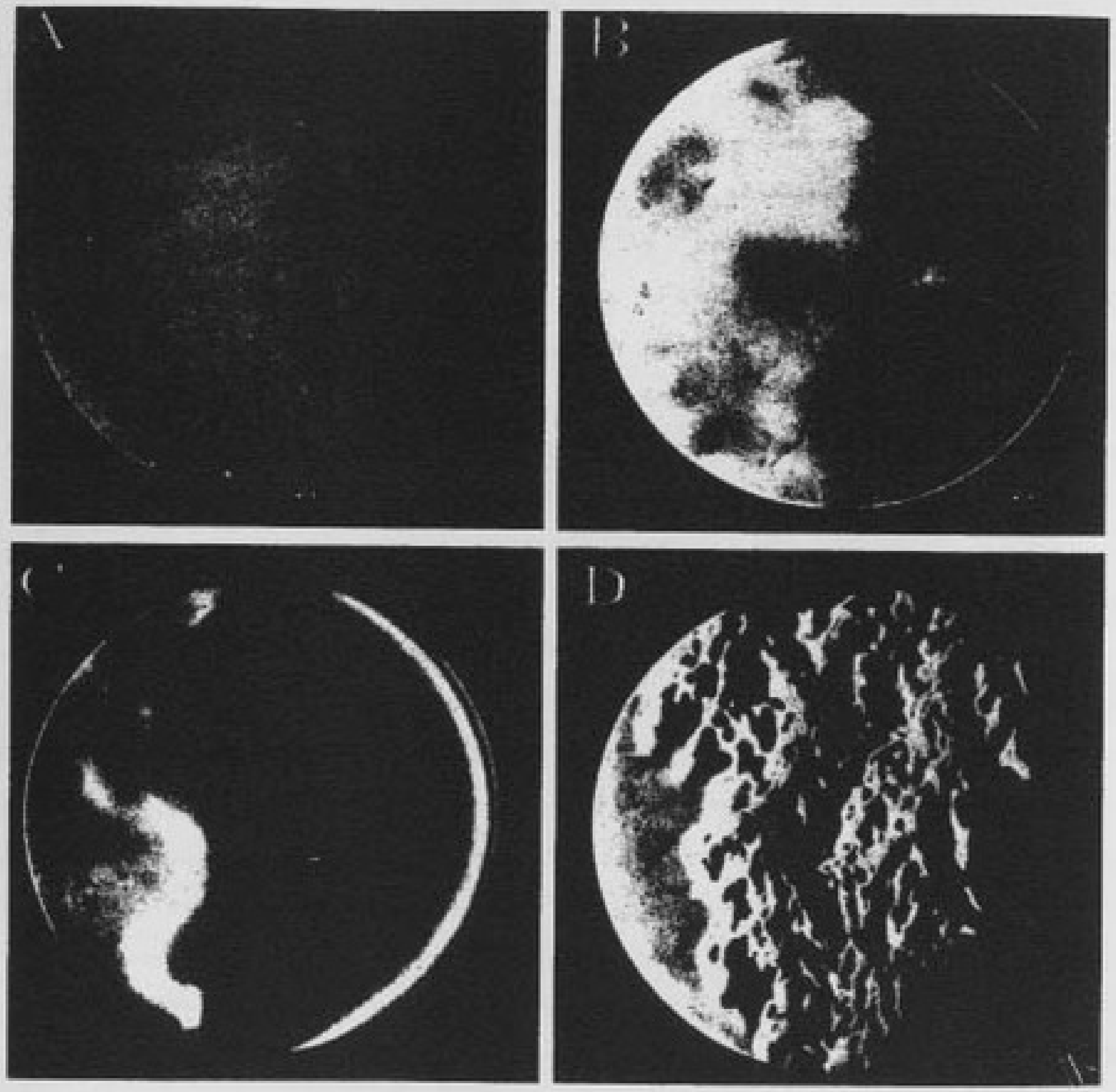


Fig. 148. Turbulence originating in the instrument as revealed in Foucault test photographs (spherical mirror, 300 mm. diameter. Knife edge at the right in all cases). (A) Quiet atmosphere, very slow air movement. Slit width 5 μ. Exposure 1 sec. (B) Air rapidly agitated with fan. Slit width 15 μ. Exposure 1/50 sec. (C) Slow air movement; sheath of warm air adjoining tube wall. Slit width 15 μ. Exposure 1/25 sec. (D) Rapid, intense turbulence (candle flame positioned 20 in. below light path). Slit width 45 μ. Exposure 1/250 sec.

The telescope walls' being in a position to affect a long portion of the optical path, may be a source of particularly troublesome convection currents. The effects in Figure 148C resulted merely from inserting into the telescope a short (4-inch) section of tubing only ½-inch larger in diameter than the mirror and 40° F above ambient temperature. The broad, slow-changing, and disturbances affect large portions of the wavefront. In addition, there is an air layer an inch or more thick, bordering the walls of the tube, which produces a visible wavefront error well over a fringe in magnitude at the right edge of the mirror. A star image under these conditions would still be useful, but it would undulate and of course would show appreciable aberration caused by the zonal layer.

Much more destructive to image quality is the use of a metal telescope tube that is too narrow for the diameter of the mirror. Fluctuations are then numerous and rapid, and a permanent air sheath hugging the metal wall, intrudes into the beam. To avoid these effects the tube must be at least 4 inches larger in diameter than the mirror. The poor performance of metal-tube telescopes has led many, mistakenly, to adopt an open tubular framework. This is equally objectionable from other points of view. On the other hand, the wooden tube of our standard telescope performs well even when it is rather close-fitting. This is due partly to its square cross-section but mainly it is because the plywood panels are poor heat radiators.

Convection effects are often seen at the edges of metal parts that unavoidably lie within the beam, such as the secondary mirror mount and the spider arms, but these are not serious. Andre Couder has devoted a special article to these effects.[7] Figure 148D shows the rapid, narrow, and very steep wavefront dislocations that occur 20 inches above a candle flame. Not surprisingly, the diffraction pattern of a point source under these conditions breaks up into 50-fold wider area of churning, glistening image fragments. The image hardly needs to be affected this much before useful observations are completely impossible. Almost as bad are the eddies of air that can arise from the metal parts of an equatorial mounting, or from the ground; or from that excellent heat radiator which is the observer's own body. Anyone who has performed the Foucault test has been charmed by watching the convection currents rising from a hand placed in front of the mirror.

Steps can and should be taken to minimize internal turbulence in instruments of 10-inch or larger aperture. How to accomplished this was the subject of Section X-1.

XV-7. Second Stage: Local Turbulence

There are external disturbances also, of course, at distances ranging from close to the instrument to several hundred yards beyond. The observer's breath

[7] *L'Astronomie*, 63, p. 253 (Sep.–Oct., 1949).

may itself be disturbing, but can be deflected by a lightweight telescope tube extension about 1-½ feet long. When the instrument is pointed high enough above the horizon, disturbances arising from the ground diminish abruptly. But if a wind sweeps obliquely across the telescope opening, it creates serious eddies, especially if the air has been streaming across a warm rooftop.

Local atmospheric conditions are at their worst when the telescope looks out the open window of a house. Even when the room is allowed to equilibrate approximately to the outside temperature, there is still an irregular but permanent turbulence, leaving little hope for useful magnification beyond 100 or 150X. It would be a mistake, though, for the amateur with no other alternative to be discouraged. With a little perseverance, he can still find favorable conditions, especially at certain times of the year (often in the spring), and in the hours before sunrise. When the temperature conditions are reversed, the air outside being warmer than that inside, the images can be excellent. If this were not so, nearly every astronomical instrument mounted under a dome would be useless for performance at high resolution.

Out-of-doors, conditions are usually better. However, broad, concrete-covered areas exposed to the sun must be avoided, as well as nearby walls and other radiating structures having high heat-storage capacity. The shape of the terrain is equally important. Warm air tends to ascend along the hollows, and locations on a hillside or near a hillock that partially obscures the view will *a priori* be unfavorable. Still, there are no hard and fast rules; experience must be the deciding factor in every case. Convective circulation of warm or cool air originating from a distant source is easily confused with high-altitude disturbances. The Foucault test in this case no longer shows sharp, slow-moving shadows, but broad fluctuations that change too rapidly to been seen directly. Using an eyepiece, we cannot focus on these disturbance as we can on high-altitude perturbation (see below).

For our purposes, an *ideal* observing site (aside from geographical locations, which is another question) can be described as follows: the immediate locale is level and grass-covered; the telescope is mounted on a pillar several yards high, with a light, open wood framework supporting the observer's platform and a shelter for the telescope that is substantially larger and higher than the instrument. The sides and roof of the shelter are of double-wall construction, and the roof is designed to roll away from the instrument to the north. Figure 123 shows a practical and economical shelter of this type, assuming the amateur accepts the thought of a high framework supporting everything several meters above the ground level. The best domes are also insulated enclosures of very large diameter, compared with the overall size of the instrument. They also have a wide hatch that is, hopefully, free of serious turbulence along the middle half of its length.

XV-8. Third Stage: High-Altitude Turbulence

Let us point the telescope at the limb of the Moon. We mount a medium-power eyepiece, M = 200, on our standard telescope. Focusing carefully on the lunar details, we use a ruler to measure precisely the position of the eyepiece in the drawtube. The waviness of the limb is due to turbulence. Drawing the eyepiece back slightly, we note that the undulations become sharper and the contrast is greater; it appears in fact that we are now focusing on the turbulence. The first eyepiece setting corresponded to the focal length of the mirror F; the second setting $F + a$ is the conjugate distance, which we shall call p, corresponding to a turbulent object whose real distance is p', according to:

$$p' = \frac{Fp}{p - F} \quad \text{and in practice} \quad p' = \frac{F^2}{a} \qquad (97) \quad (98)$$

We find that p' is sometimes only a few hundred yards from the telescope if there is a cold wind, such as the *mistral* at ground level. The effect of local turbulence is then combined with that at higher altitudes. Most often, however, we detect a rather high well-defined layer at an altitude of about 11,000 feet. Of course, this is not very easily done. An amateur colleague, Boyee, made an extensive study of about 5,000 soundings with a 7½-inch telescope. When values on the Danjon scale of turbulence were related statistically to the wind direction at all altitudes, the data revealed not only the classic layer at 11,000 feet, but a second, very well defined layer of disturbance at 18,000 feet. When Blamont conducted experiments in the creation of sodium-vapor clouds, formed by ejection from a Veronica rocket at high altitude, we were able, with a 10-inch telescope, to photograph cloud tufts of less than 2 minutes of arc formed at an altitude of 80 kilometers in a cross-wind of 36 meters per second!

We should not, then, expect that an elevated site will give a decisive reduction in overall turbulence. Local turbulence, which is often predominant, will still persist. And so far as internal turbulence is concerned, Foucault tests on a sealed telescope, fitted with a window and evacuated, show significant improvement only when the residual pressure goes down to a fraction of a millimeter of mercury or less. High-definition photographs of the solar granulation, taken from a balloon with a telescope aperture of only about 12 inches, gave results significantly better only at about 114,000 feet. High observatory locations are valued primarily for greater atmospheric transparency. Sometimes, by happy convergence of circumstances, a telescope at a high location also has better than average image quality. This is the case on some isolated peaks such as Mount Hamilton, Pic du Midi, Mauna Kea, and some high plateaus such as Mt. Palomar.

The search for an ideal terrestrial site for a large telescope is Utopian; it would seem that nothing less than abandoning the Earth and setting up our telescope on the Moon will do! Nevertheless, surveying and testing for a least objectionable site is valuable if done realistically and without too much compromise for non-technical reasons. The surveying instrument should be moveable from place to place and have a diameter of at least 20 inches so as to provide visual and, more importantly, photographic data that can be extrapolated to a telescope of large dimensions. More specifically, technically perfect long-exposure photographs would immediately rate the location on the graph of Figure 147. Once a general site is selected, after a systematic study covering a full year at least, the buildings should be positioned and designed to reduce local turbulance to a minimum, i.e., they will be domes well isolated within the surrounding vegetation and as high as possible.

We have once again digressed from the amateur's usual territory, but with the feeling that the reader should fully appreciate a subject that dominates everything that is possible in ground-based astronomy. Besides, we know amateurs who have decided where to retire or spend their vacations on the basis of the image quality they could enjoy in various places. The majority accept conditions as they find them where they happen to live. Given the complexity of the atmosphere, as we have shown, they evidently feel that regardless where on Earth they may be, they must wait for miracles. They also know that places which at first glance would appear the least favorable sometimes enjoy better than average conditions. For example, the dirty haze over the crowded center of Paris, so destructive of transparency, is *excellent with respect to turbulence.* It acts as a huge lid under which air exchange is suppressed and often much less violent.

XV-9. Conclusion

It has been our hope, before leaving the amateur to his own study of the sky's curiosities, to equip him or her with as much knowledge as possible; to provide not only facts, but understanding. Many will apply only a small part of what we have presented here. Certainly, neither the complex data sheets nor the telescope windows, equatorials and analyses of turbulence are indispensable to those who want simply to admire lunar detail or the nebulae. Others, however, will now want to go beyond the scope of this book, to learn about Schmidt telescopes, Maksutovs and Brachytes, about refractors, coronagraphs, polarizing monochromatic filters, and so on. The amateur's zeal, once set in motion, is insatiable; it is restrained only by his available leisure time—if even then! We leave these hardy souls to their own devices; the possibilities open to them are in any event, quite inexhaustible. Those who have mastered the basics can now move on independently to make their own original and often valuable contributions. Some notable examples of such phenomena are discussed and illustrated in Appendix K.

APPENDIX A

LIST OF SUPPLIERS

For the most current information concerning suppliers the reader should consult *Sky and Telescope*, *ASTRONOMY*, and *Telescope Making* magazines. Suppliers are constantly entering or leaving the market and therefore any list stands a high probability of becoming dated rather rapidly. The list presented below is representative and generally reflects businesses which have served the amateur telescope maker for a number of years. Neither the inclusion of those listed below or the exclusion of others should be considered approval or disapproval by the author, translator or the publisher.

TELESCOPE PARTS

Economy Telescope Co.
11721 Easthill Dr.
Chesterland, OH 44026
(Fiberglass Tubes)

North Star Telescope Co.
3542 Elm St.
Toledo, OH 43608

Edmund Scientific
101 E. Gloucester Pike
Barrington, NJ 08007

University Optics
Box 1205
2122 E. Delhi Rd.
Ann Arbor, MI 48106

Kenneth F. Novak & Co.
Box 69
Ladysmith, WI 54848

Meade Instruments Co.
1675 Toronto Way
Costa Mesa, CA 92626

Celestron International
Box 3578
2835 Columbia St.
Torrance, CA 90503

FINISHED DIAGONAL MIRRORS

E & W Optical Inc.
2420 East Hennepin Ave.
Minneapolis, MN 55413

Coulter Optical Co.
Box K
Idyllwild, CA 92349

COATINGS

Morvac Optical Coating
2085 Placentia Ave., Unit 2
Costa Mesa, CA 92627

P.A. Clausing
8038 Monticello Ave.
Skokie, IL 60076

Evaporated Metal Films
706 Spencer Rd.
Ithaca, NY 14850

P.A.B. Coating Services
1112 Chateau Ave.
Anaheim, CA 92802

MIRROR MAKING KITS

N. Remer Optics
Box 306
Southampton, PA 18966

Willmann-Bell, Inc.
Box 35025
Richmond, VA 23235

A. Jaegers
6915 Merrick Rd.
Lynbrook, NY 11563

Optica b/c
4100 MacArthur Blvd.
Oakland, CA 94619

```
 For a Pressmann-Camichel"
 B1= 0
 B2= 7.045

Diameter of axial secondary= 3.667
       Diameter for field U= 4.539
Epsilon 0.707 of:
                      primary= 0
                    secondary= 1.626E-04
Slope at edge of:
                      primary= 0
                    secondary= 5.731E-04
Schwarzschild Coefficients:
                         Coma= 5.614
                 Astigmatism=-1.359
          Petzval Curvature=-3.545
         Curvature of field=-.828
        Coma in arc seconds= 93.56
 Astigmatism in arc seconds=-4.743
   Radius of field curvature
 in the unit used for input=-130.463
(If <=0, curvature is toward sky)"

External coma has a positive coefficient B

For a different combination enter    0 to stop
                                     1 Ritchey-Chretien
                                     2 Dall-Kirkham
                                     3 Pressmann-Camichel
                                     4 stigmatic combination
Enter choice? 4


Enter: B1,9999 or 9999,B2
? -1.5,9999
 For stigmatic combination
 B1=-1.5
 B2=-9.523

Diameter of axial secondary= 3.667
       Diameter for field U= 4.539
Epsilon 0.707 of:
                      primary=-1.628E-04
                    secondary=-2.197E-04
Slope at edge of:
                      primary=-2.17E-04
                    secondary=-7.745E-04
Schwarzschild Coefficients:
                         Coma=-2.057
                 Astigmatism= 4.452
          Petzval Curvature=-3.545
         Curvature of field=-12.45
        Coma in arc seconds=-34.28
 Astigmatism in arc seconds= 15.541
   Radius of field curvature
 in the unit used for input=-8.675
(If <=0, curvature is toward sky)"

External coma has a positive coefficient B

For a different combination enter    0 to stop
                                     1 Ritchey-Chretien
                                     2 Dall-Kirkham
                                     3 Pressmann-Camichel
                                     4 stigmatic combinati
Enter choice? 0
```

APPENDIX D

"GLEANINGS FOR ATM'S" FROM SKY AND TELESCOPE MAGAZINE NOVEMBER 1941–DECEMBER 1983

"Gleanings for ATM's" is a monthly column in Sky and Telescope magazine. It appeared with the first issue—November 1941 and has continued ever since. The first editor was Earl B. Brown who conducted the column through October 1956. Starting with the November 1956 issue, Robert E. Cox managed it for the next 11 years, until December 1977. Roger W. Sinnott then became the editor, a position he holds to the present (1984).

Authors and editors who appear frequently are identified by their initials. Therefore, Earl B. Brown (E.B.B.), Allyn J. Thompson (A. J. T.), Robert E. Cox (R.E.C.) and Roger W. Sinnott (R.W.S.). The page numbers are for the beginning of the column and follow the month.

Most large libraries maintain either a collection of the actual magazine or a photocopy. Microform editions from 1941 and xerographic copies are available from University Microfilms International, 300 Zeeb Rd., Ann Arbor, MI 48106. Sky and Telescope magazine is published by Sky Publishing Corporation, 49 Bay State Rd., Cambridge, MA 02238.

1941	Nov	18	Henry Fitz—Early American Telescope Maker, R.S. Bates
			Twenty-Inch Operations, C.F. Alsing
			Collimating, E.B.B.
	Dec	22	Paradoxical Parabolas, E.B.B.
1942	Jan	22	The Gaviola or "Caustic" Test, E.B.B.
	Feb	22	The Gaviola or "Caustic" Test, E.B.B.
	Mar	20	The Gaviola or "Caustic" Test, E.B.B.
	Apr	20	The A.T.M. and the War, E.B.B.
			Wooden Cell, R.S. Luce
			Report on a Schupmann, E.B.B.
	May	22	Further Note on Diagonals, E.B.B.
			Correction to April 1942.
	Jun	22	Objective-Grating Plates, J.G. Baker
	Jul	16	Refractor Versus Reflector, E.B.B.
	Aug	18	Designing an Achromatic Objective—I, E.B.B.
	Aug	18	Make Your Own Spectroscope, E.B.B.
	Oct	18	Designing an Achromatic Objective—II, E.B.B.
	Nov	18	A Simple Filar Micrometer, E.B.B.
	Dec	18	Designing an Achromatic Objective—III, E.B.B.
1943	Jan	17	The A.T.M. and the Future, E.B.B.
	Feb	18	Designing an Achromatic Objective—IV, E.B.B.
	Mar	18	An 8-Inch F/1.5 Schmidt Camera, N.J. Waitkus

Oct 300 How to Build a Quartz Monochromator—VII, R.B. Dunn
Nov 16 A Small Observatory and its 5.5-Inch Refractor, H. Pfleumer
Dec 43 The Gremlins and My Photometer, J.J. Ruiz
1952 Jan 66 A Portable Reflector With Unusual Features (6-Inch), C.P. Custer
Feb 95 Telephotography For Amateurs, A.J.T.
Mar 122 A Sturdy Mount and a Sandblasted Mirror, W.A. Rhodes
Apr 148 A Inexpensive Refractor (4.25-Inch), E. Nussbaum,
Crosshairs For A Finding Telescope, K.L. Walko
May 175 A Lightweight Portable for Group Observation (6-Inch Refl.), F.L. Rose
Stops for Solar Observing, F.L. Goodwin
Jun 201 A Well-Constructed Portable Reflector (6-Inch), C.H. Coles
Jul 228 How to Mold and Pour Your Own Castings—I, C. Raible
Aug 257 How to Mold and Pour Your Own Castings—II, C. Raible
Sep 283 The Haggart Observatory at Oregon City (20.25-Inch), H.P. Haggart
Oct 308 Turning a Wooden Telescope Tube, George Andrus
A Home-Made Telescope (6-Inch Refl.), R.E. Pendergraft
Nov 19 A Large Portable Cassegrainian (20-Inch), F.W. Manning
A Clock-Drive Mounting for Camera and Telescope, L. Mussgnug
A Grinding Machine for Amateurs, William A. Ervin
Dec 48 Balancing Equatorially Mounted Telescopes, J.C. Boyle
1953 Jan 78 A Simple Spectroscope For Solar Prominence Observations, H. Leinbach
Feb 107 A Improved Herschelian Telescope, J. S. Hindle,
Still Lunar Photography, R.G. Knittel/A.J.T.
An Open-Tube Reflector (6-Inch), F. Salomon
Mar 136 Two Atlanta Telescopes (12- and 16-Inch Refl.) W. C. Close
Apr 137 A Versatile Portable Mounting, H. I. Smith
May 138 Notes on Basic Optics—I, E.B.B.
Dewing Prevention for Refractor Elements, F.L. Goodwin
Jun 219 Inexpensive Portable Planetary Telescopes (3-, 4-, 5- or 6-Inch Ref.), J.V. Lawrence
Jul 244 Notes on Basic Optics—II, E.B.B.
A English Reflector (8-Inch), H.B. Buie
Aug 271 Limiting Visual Magnitudes for Small Telescopes, F.J. Kelly
Sep 293 Notes on Basic Optics—III, E.B.B.
Dec 58 A Large, Inexpensive Springfield Telescope (12-Inch), M. Collin
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Feb 130 Making a Double-Ring Spider and Elliptical Diagonal, L.N. Schoenig
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Mar 166 Notes on Basic Optics—VI, E.B.B.
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Apr 201 An Economical Lumber and Pipe Reflector (8-Inch), W.E. Simpson, Jr.
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May 237 Notes on Basic Optics—VIII, E.B.B.
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Jul 311 Notes on Basic Optics—VIII, E.B.B.
Aug 347 Field of View and Image Size, R.E.C.
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Sep 389 Notes on Basic Optics—IX, E.B.B.
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Oct 433 A Telescope Drive with a Right-Ascension Circle, O. Gingerich
Nov 29 Notes on Basic Optics—X, E.B.B.
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Dec 71 A 6-inch F/10 Springfield Refector, O.R. Knab (see 000 039 of manuscript)
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1955 Jan 113 Notes on Basic Optics—XI, E.B.B.
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Feb 159 The Doreddie Observatory (12-Inch Newt.-Cass.) E.D. Onstott
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Mar 199 Notes on Basic Optics—XII, E.B.B.
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Apr 247 A Second Telescope (5-Inch Refl.) W.M. Black
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May 295 Notes on Basic Optics—XIII, E.B.B.
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Jun 345 An Electric Portable Reflector (6-Inch), M. Shapiro
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Jul 385 Notes on Basic Optics, E.B.B.
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Aug 427 A Simple German Mounting, H. Pfleumer
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Oct 513 A Experience with the Dall Null Test, S.J. Warkoczewski
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Nov 35 Notes on Basic Optics—XVI, E.B.B.
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Dec 87 A 6-Inch Newtonian with Hydraulic Drive, B.A. Stevens
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1956 Jan 133 Notes on Basic Optics, E.B.B.
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Feb 181 A Grinding Machine and Some Telescopes, E.B.B.
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Mar 236 A Cassegrainian-Maksutov Telescope Design for the Amateur, J. Gregory
Apr 289 An Antidiffraction Mask for Reflectors, W.A. Rhodes
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A Vibration-Proof Mounting Support, E.R. Bunker
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May 341 A Split-Ring Mounting for a 12-Inch Reflector, N. Herrett
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Jun 390 A Portable Instrument for Astrophotography, F.N. Veio
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			How Little Abrasive, K. Masson
	Oct	600	Some Amateur Mountings of Special Interest, R.E.C.
	Nov	38	A New Test for Cassegrainian Secondaries, B.A. Norman
			A Versatile Observing Setup with an 8-Inch Reflector, D. Parker
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	Feb	201	A Prime-Focus Camera for a Large Reflector—II, C.P. Custer
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			An Inexpensive Observatory in Texas, P. Hudlow
			An Easily Built Adjustable Slit, K. Masson
	Apr	309	More Maksutov Notes—Radius Testing, R.E.C.
	May	368	Construction of a Solar Telescope, W.J. Semerau
	Jun	423	Notes and New Data on Maksutov Telescopes, R.E.C.
			A 10-Inch Reflector with a Pasadena Mounting, G.L. McFarland
	Jul	473	Using Spherometers in Maksutov Radius Testing, R.E.C.
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	Sep	589	Herschelian Telescopes for Amateur Use, R.E.C.
			A New Solar Observatory in the Northwest, B.C. Parmenter
	Oct	651	Newtonian Focus Position and Parfocal Eyepieces, R.E.C.
			A Rigid Pier, J.A.E. Eyster
			Correction to August 1958, A. Kutter
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			Suggestions for Mirror Makers, J. Cokor
1959	Jan	166	The Fieldston School Observatory, G. Kada
			A 12.5-Inch Fork-Mounted Newtonian-Cassegrainian, S. Lutz
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			Maksutov Telescope Notes, R.E.C.
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			Grinding a Maksutov Lens, J. Youdale
			A Roll-off Roof Observatory for a 12.5-Inch Reflector, W. Davey
	May	406	A Large Amateur Observatory of Unusual Design, J.J. Knuijt
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	Jul	526	A Low-Cost Furnace to Melt Metal for Castings—II, W. Cheney
	Aug	582	A Herschelian Telescope for Lunar and Planetary Observing, A.W. Lilge
			Making Long-Focus Mirrors, B.C. Parmenter
			Penta-Prism Diagonal for Finder Scopes, E. Everhart
	Sep	643	A Heavy-Duty Mounting with Friction Control, W.J. Semerau
	Oct	703	A Simplified Schmidt Camera for Amateurs, B.W. Pocock
			Microscope Objectives for Radius Testing, R.E.C.
	Nov	51	A Low-Power Microscope System for High Magnifications, S.W. Schultz, Jr.
			Some Advantages of a Transfer Lens, R.E.C.
			Telescope Camera Holder, G.D. Carter Jr.
	Dec	123	An English Catadioptric Telescope, J. Youdale
			A Flat-Roof Observatory, W.E. Harris
			Proper Location for a Newtonian Diagonal, K. Masson
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			An All-Purpose Telescope Assembly, J.A. Wells
			The Twyman Effect in Diagonals, R.E.C.
			A Simple Mounting Made of Thick-Walled Tubing, R.V. James
	Feb	246	A 20-Inch Reflector Built in Brazil—I, B.H. Young
	Mar	310	A 20-Inch Reflector Built in Brazil—II, B.H. Young
			Correction to February 1960.
	Apr	374	A Silo-Domed Observatory for a 12.5-Inch Telescope, N.R. Ross
			Concerning Spherical-Mirror Telescopes, R.E.C.
	May	438	The Memphis Astronomical Society Observatory, M.S. Showden
			Designing a Finder, R.E.C.
	Jun	502	A Portable 6-Inch Catadioptric Telescope, G. Konstanzer
			Glass Removal in Parabolizing, A Mackintosh
	Jul	47	Measuring the Magnification of a Telescope, R.E.C.
			A Portable Observatory for Small Telescopes, M.F. Wells

	Aug	107	A Solar-Prominence Telescope Using an Interference Filter, A.K. Presnell
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	Oct	232	A Mounting Made of Automobile Front-Wheel Assemblies, J.D. Eoff
			An Australian Amateur's Grinding Machine, B. Watson
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			Correction to December 1960.
	Nov	302	A Precision-Mounted Small Refractor, R.E.C.
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			An Altazimuth Reflector with a Drive, W.T. Thomas, Jr.
			Some Rules of Thumb (tube size, diagonal position, diagonal size), R.E.C.
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1961	Jan	52	An 9-Inch Fork-Mounted Reflector, R.H. Field Sr.
	Feb	116	An 8-Inch Catadioptric of Superb Observing Qualities, S. Saul
			An Attachment for Eyepiece-Projection Photography, G. Konstanzer
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			The Vista Del Cielo Observatory in Alberta, W.A. Knox
	Apr	236	Multiple Extrafocal Images of Extended Objects, R.E.C.
			Clock Drive on a Pier, R.V. James
			Mounting Diagonal Mirrors with Cement, M. Kiefer, Jr.
			An Aid to Figuring Perforated Mirrors, R. Zussman
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			A Novel Arrangement for a Finder, R.E.C.
			A Maksutov Convertible to a Schmidt Camera, R.E.C.
	Jun	358	An 8-Inch Reflector with a Transistor-Controlled Drive, J.E. Gunn
			An Amateur Society's Low-Cost Roll-Off-Roof Observatory, A. Nieuwenhoff
	Jul	47	An 8-Inch "Beavertail" Dall-Kirkham Reflector, A. & G. Doschek
			Checking Concentricity of Maksutov Correcting Lenses, R.E.C.
	Aug	106	Cleaning the Lens of a 12.25-Inch Refractor, R.E.C.
			Pineview Observatory, A.L. Crowley
			A Chicago Amateur's Garage-Top Palomar, H.G. Raddatz
	Sep	166	A Simple Aluminum Camera Support, R.E.C.
			A Pole Finder for Portable Telescopes, G. Konstanzer
			A Foucault Light Source from a Flashlight Bulb, R.E.C.
	Oct	232	An Improved 4.25-Inch Unobstructed Oblique Reflector, O.R.Knab
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			Figuring a Paraboloid with the Ronchi Test, E. Lumley
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1962	Jan	48	Why Not an Erecting System? H.E. Dall
	Feb	109	A Dall-Maksutov Telescope with an Erecting Lens, H.E. Dall
			A Two-Pier Equatorial Mounting, D.R. Fichtl
	Mar	168	Further Notes on Multiple Extrafocal Images, R.E.C.
			Windows for Reflectors, R.E.C.
			An Indicator Light for Electric Drives, J. Randi
	Apr	226	Characteristics and Testing of Cassegrain-Type Telescopes, R.R. Willey, Jr.
			Anodizing Aluminum, R.E.C.
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	Jun	347	Two Reflectors with Simple Mountings of Pipe, R.E.C.
			The M-17 Elbow Telescope as a Finder, R.K. Leavitt
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	Jul	48	A Large Reflector on a Cross-Axis Mounting, C.G. Scarborough
			Using Wide-Band Interference Filters for Solar Observing, G. Klaus
	Aug	106	A Precision Caustic-Curve Tester, R.P. Reedy
			A Rugged Inexpensive Telescope Mounting, R.G. Hoffmann
	Sep	168	A Rich-Field Telescope with a Transfer Lens, D.M. Clement
			A Portable Telescope for Astrophotography, P.J. Peters
	Oct	231	A 10-Inch Spherical Reflector with a Negative Correcting Lens, S.M. Heumann
	Nov	300	Making Low-Power Eyepieces for Amateur Use, C.C. Chinzi
			An Orthoscopic Eyepiece from Stock Parts, R.E.C.
	Dec	368	Placing and Aligning the Newtonian Diagonal, R.K. Dakin
			"A Practical Heated Observatory", R.E.C.
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			The Hot-Wire Foucault Test, R.E.C.
			Correction to December 1962.
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Apr 232 Eliminating Stray Light in Cassegrain Telescopes, R.R. Willey Jr.
May 292 A Wall-Mounted Schiefspiegler for Lunar and Planetary Work. O.R. Knab
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Jun 355 Simple Equipment for Precisely Timing Observations, H.A. Bowman
Jul 49 A Polar Adjustment Device for Portable Mountings, H. Pfleumer
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A Cream-Separator Mounting with Manual Drive, R.O. Thomas
Aug 103 An Altazimuth Mounting with Slow Motions, H.L. Cleaveland
Masking Stray Light in a Large Reflector, I. King
A Solar Telescope-Spectroscope Combination, E.G. Carlen
Sep 167 A Polar Telescope for Visual Solar Work, B.C. Parmenter
Oct 231 A New Zealand Amateur's Well-Equipped Observatory, J.B. Orr
Nov 292 A 12.5-Inch Newtonian for Planetary Observing, R.C. Maag
A Wye Mount for a 6-Inch Reflector, L. Acker
A Simple Solar Telescope, D.R.P. Coats
Dec 355 Two Folded Refractors with Fixed Eyepieces, D.F. Sklar
A Method of Checking Focal Length While Grinding, G.E. Patston
1964 Jan 46 Fixed Telescopes with Clock-Driven Mirrors, R.E.C.
A Heated Observatory for a 24-Inch Reflector, R.E.C.
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Feb 117 A Portable Mounting for a 35-mm Camera, W.C. Lovell
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An English Observatory with a 12-Inch Reflector, R.H. Chambers
Mar 180 A Maksutov 11-Inch of Newtonian Form, R.W. Tuthill
Apr 242 Null Testing Telescope Mirror by Immersion, R.T. Holleran
May 308 A Simple but Accurate Foucault Tester, H.F. DaBoll
A Grinding Machine for Mirrors up to 16-Inch Diameter, R.E.C.
Jun 369 A Transistor Oscillator-Amplifier for Sidereal Drives, C.N. Fallier, Jr.
Jul 40 An 8-Inch Newtonian-Cassegrain Telescope, R.G. Coutchie
Aug 97 The Problem of Focusing in Amateur Instruments, R.E.C.
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Sep 168 Maksutov Camera for Astronomical Photography, R.E.C.
Oct 235 Prize-Winning 8-Inch Reflector, E.P. Sejud
Nov 305 Experiments with Cemented Mirrors, E.G.H. Mobsby
Dec 377 More Reports on Sandwiched Glass Mirror Blanks, B.H.J. Waters
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Lightweight Mirror Blanks of Fused-Silica Elements, R.E.C.
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1965 Jan 44 An 8-Inch Reflector with Remote-Reading Circles, C.C. Simpson
Feb 112 A Novel Dual-Field 8-Inch Telescope, W.N. Lindsay
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Mar 176 A Straight-Stroke Grinding Machine, W. Drohomer
An M-17 Elbow Telecope Modified to 25 Power, R.F. Flathman
Rapid Polar Adjustment of an Equatorial Mounting, W.F. Davis, Jr.
Apr 242 A Massive, Well-Equipped 16-Inch Reflector, F.L. Aime
Detailed Instructions for an Oblique Reflector, R.E.C.
May 318 A Schmidt-Cassegrain Optical System with a Flat Field—I, A.S. DeVany
Jun 380 A Schmidt-Cassegrain Optical System with a Flat Field—II, A.S. DeVany
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Jul 41 The Training of Optical Technicians, R.E.C.
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A Homemade Telescope and Mountings for a 6-Inch Lens, W.A. Kuhn
Aug 104 Verniers for Setting Circles, R.E.C.
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Sep 172 A New Observatory at King College in Tennessee, E.W. Burke, Jr., & W.W. Rolland
Oct 243 A Battery-Powered Transistor Oscillator Drive, J. Hers
A Very Rigid Pier, S.M. Shartle
Nov 308 The Silvertooth Method of Working a Cassegrain Secondary, J.W. Gagan
Dec 375 Notes on the Cassegrain Secondary, R.E.C.
A Camera Adapter for Eyepiece Projection Photography, B. Bennett
1966 Jan 44 A One-Man 25-Year Observatory Project, J. Smolen
Feb 106 A Giant Binocular of Off-Axis Gregorian Design, R.E.C.
Mar 170 Notes on Newtonian Reflector Alignment, R.E.C.
An Observatory Over a Peaked Roof, G. Lombardi
Apr 231 A Diffraction-Limited Schmidt-Cassegrain Telescope, R.E.C.
A Junior's Inexpensive Clock Drive, C. Collier

May 300 Mounting a 12.5-Inch Long-Focus Mirror, B.F. Shinn
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Jun 366 Oregon Amateur's Simple Equipment for Astrophotography, A. Harris & J.D. Wiseman, Jr.
Jul 40 Notes on Constructing a 5.5-Inch Cassegrainian-Maksutov, H. Louth
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Aug 100 A Canadian Amateur's Observatory, R. Doucet
A Rich-Field Refractor, S. Pauley Jr.
Barlow Lens Design for a Spherical Primary Mirror, B. Brixner
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Sep 159 Working a Mirror Blank of "Zero" Expansion Coefficient, R.E.C.
Oct 228 An Engineering Student Builds a Mounting, V. Nikolashin
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Nov 300 A Connecticut Observatory with Roll-Off Roof, C.R. Hammond
A Rigid Mounting That Required Little Machining, C.R. Willingham
Dec 373 A Simple Comparator for Star Photographs, R.E.C.
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A Junior's Telescope, N. Sauer
A Variety of Instruments by a California Amateur, K.W. Landon
1967 Jan 45 An Improved Foucault Testing Device, R.K. Dakin
A Portable Newtonian with Temporary Mounting (6-Inch), H. Hyde
Feb 112 An Unusual 12.5-Inch Rich-Field Reflector and Comet Seeker, B. Leifer
An Easily Transported 16-Inch Newtonian, S.S. Germany
A Simple Telescope Drive Corrector, R.B. Minton Jr.
Mar 175 A Telescope in a Bowling Ball, B.C. Willard
Some Remarks on Eyepieces, D.S. Evans and A. T. Young
Extending the Uses of a Rich-Field Telescope, B. Froehly
Apr 244 A Well-Built Roof-Off-Roof Observatory in North Carolina, F.G. McInnis
Furthr Improvements on a Slitless Foucault Tester, R.E.C.
May 312 A Cooke Triplet Astrographic Lens for the Amateur, R.J. Donnel
Jun 382 An Observatory in Israel with an 8-Inch Oblique Reflector, M. Horowitz
A 3.5-Inch Terrestrial Reflector, M.R. Walsh
Neutralizing Atmospheric Dispersion, R.E.C.
Jul 44 A Special Portable Refractor for Women (3.5-Inch), W.H. Fisher
Some Three-Gear Sidereal Drive Arrangements, E.A. Fagen
Aug 108 A Twin-Telescope Observatory on Wheels (12.5-Inch Refl.), N.G. Oberle
A Hungarian Amateur's Rich-Field Telescope, B. Szentmartoni
Sep 176 A Plywood German-Type Equatorial Mounting, E. Pfannenschmidt
A Plywood Mounting and Fork for Reflectors, H.L. Yeagley & D.B. Firebaugh
Oct 258 A First Telescope of Large Aperture (10-Inch *f*/5.6 Newtonian), W. Basiewicz
An Electric Sidereal Clock, H.E. May
Nov 329 A Remotely Controlled Backyard Solar Observatory, W. Basiewicz
Dec 400 Swiss Amateur's Cooled-Emulsion Camera, H. Eggeling
An Italian Observatory and 14-Inch Reflector, R. Toledano
1968 Jan 48 Two Well-Equipped Observatories in Australia, R.E.C.
Feb 116 Elementary Aberrations in Telescope Objective Lenses, H.H. Coburn
A College Student's Telescope and Solar Spectroscope (4-Inch Refr.), R.E. Crumrine
Mar 182 A Pocketable 6-Inch Multipurpose Cassegrain Telescope, H.E. Dall
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Apr 249 A New Catadioptric Telescope Design Suitable for ATM's, R.A. Buchroeder
May 319 Notes on Telescope Making from Here and There (Alignment, Maksutov lens Thickness, Submerged Cold-Pressing, Calibrating Barlow Lenses), R.E.C.
Jun 390 Notes on the Buchroeder Catadioptric Telescope, R.E.C.
Jul 46 An Inexpensive Declination Slow-Motion Control, C.L. Kussner
A Portable Telescope and Camera, H. Michalewski
Aug 115 An Inexpensive Oscillator-Inverter Clock Drive, T.R. Galloway
Sep 183 A New Amateur Observatory in Central Arizona, R. & H. Lines
A Telescope Mounting Made from a Lathe Head, A. Boyles
Oct 256 A Toledo Amateur's Methods in Astrophotography, H.F. Zeh
Nov 336 An Improved Buchroeder Catadioptric Design, R.A. Buchroeder
Dec 406 A Sturdy Transportable Mounting for a 12.5-Inch Reflector, J.B. Thurmond
A Slew-and-Drive Unit for Amateur Telescopes, B.C. Parmenter
1969 Jan 45 An Inexpensive Spectrohelioscope by a California Amateur, F. Veio
Feb 112 A 10-Inch Refractor Fashioned in Wood, R.C. Ludden
A Split Ring 10-Inch Equatorial of Low Cost, A.C. Haven Jr.

Mar 182 An Amateur's 12-Inch Long-Focus Refractor, O.E. Shipp
A 5-Inch Binocular with Wide-Angle Eyepieces, B.L. Fitzgerald
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Apr 247 A 6-Inch Springfield Telescope with Remote Reading Dials, J.K. Newell
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May 316 A Combination Wide-Field Telescope and Astrocamera, H. Pfleumer
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Jun 386 A Photo-Chronograph for Timing Observations, A.S. Clarke
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Jul 46 A Semipermanent Telescope Pedestal, A.J. Blackwood
An Inexpensive Slide-off Roof Observatory, W.D. Williams Jr.
A Simple Recording Foucault Tester, A.C. Haven Jr.
Aug 112 Fabrication of a Wright Telescope, T.J. Waineo
A Small Domed Observatory, M.D. Scott
Sep 186 A Homebuilt Machine for Scanning Plates, H. Vehrenberg
A Very Sturdy 10-Inch Newtonian Reflector, N. Condoluci
A Sturdily Built Roll-off Roof Observatory, J.C. Baize
Oct 258 An Amateur's Torque-Tube Mount, H. Link
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Nov 342 Some Fine Telescopes are Exhibited at Stellafane, D. Milon
Dec 418 A New Three-Mirror Off-Axis Amateur Telescope, R.A. Buchroeder
1970 Jn 49 A Test for Figuring Cassegrain Secondary Mirrors, J.L. Richter
Feb 120 A Spectroscope Attachment for Viewing Solar Prominences, J.B. Newton
Hints on Eclipse Instrumentation for Photography, R.E.C.
Mar 186 On Making A Channeled Pitch Lap, J.T. Carle
A Folded Herschelian Off-Axis Reflector (8-Inch), J.R. Pawlick
An Inexpensive Pipe Mounting, G.A. Wimer
Apr 254 A Phoenix Amateur's 12.5-Inch Schmidt Cassegrain, M. Kufman
May 318 A Slitless Spectograph for the Flash Spectrum, W.C. Atkinson
Jun 389 An Amateur-Built Precision Mirror Tester, J.J. Woerner
A Portable 6-Inch Dall-Kirkham and Celestial Camera, K. Moll
Jul 46 Making a 6-Inch Air-Spaced Visual Objective, O.R. Knab
Aug 110 A Chinese 9-Inch Semiportable Reflector, K.L. Liu
Improving the Performance of a Large Instrument, J.D. Eoff
A Novel Solar Image Screen, M.B. Schwartz
Sep 169 A 10-Inch Newtonian with Counterposed Canopy, E.K. Owen
Oct 235 The Flexure of a Concrete Telescope Pier, G. Kessler
Notes on Clock-Drive Speed Controls, R.E.C.
Remote Declination Readout, R.C. Gebhardt
Nov 313 Fork-Mounted Telescopes with Dual Eyepiece Positioning, R.P. Jensen
A Short-Focus 12.5-Inch Newtonian Telescope, D. Watts
Dec 382 A Versatile Overarm Mirror-Grinding Machine, P.R. Zurakowski
1971 Jan 46 CHT: A Catadioptric Herschelian Telescope with Tilted Components, R.E.C.
Feb 109 A 35-mm Camera for Astrophotography, S.R.B. Cooke
A Simple Yoke Mounting for a 12-Inch Reflector, L. Secretan
Mar 175 A Guided Camera for a 16.375-Inch Newtonian Telescope, S.J. Warkoczewski
Apr 243 Making an 8-Inch Refractor Objective, R.G. Quade
The Wedge Problem, R.E.C.
May 310 A Fixed-Eyepiece Refractor with Heated Observatory, W. Fellows
Fiber Optics for a Tester, B.D. Hurt
Jun 379 A German Amateur's 12-Inch Newtonian Reflector, M. Lammerer
A Collapsible Lightweight Cassegrain Telescope, V.G. Nikolashin
A Meccano Telescope (6-Inch), C.D. Rorke
Jul 42 A Double-Field Finder and Guide Telescope, F.L. Johns
Putting Together a 12.5-Inch Telescope, M. Herbstritt
Aug 107 Apollo Rendezvous and Telescope Fair in Ohio, D.M.
Sep 170 A Working Model of a 70-Inch Telescope, M. Kaufman
Stock Removal in Mirror Making, R.E.C.
Oct 235 A Simple Knife-Edge Focusing Attachment, R.C. Dickinson
A Compact Prizewinning Spectrohelioscope, C. Horne
Nov 302 An Australian 12.5-Inch Buchroeder Relay Telescope, A.E. Coombs
Dec 374 Two Amateur's Set up an Observatory-Telescope Cooperative, A.E. Morton
An Amateur-Built Chain Drive for a 12.5-Inch Reflector, C. Nash

1972 Jan 47 A 4.5-Inch Unobstructed Maksutov Telescope, A.E. Crowe Jr.
Feb 114 An 18.5-Inch Telescope in Memphis, D.H. Bratton
Telescope with Unobstructed Light Paths, R.E.C.
Mar 183 A Quickly Aligned Foucault Testing Apparatus, G.L. Wilson
Notes on Spherometers and Wedge Testers, R.E.C.
Apr 252 Don't Belittle That Small Telescope!, C.L. Kussner
Attaching A Large Setting Circle to a Clock Drive, B.D. Morrison
May 320 An Australian 11.5-Inch Wright Telescope, D.H. Whitehead
Jun 388 The Vacuum Method of Making Corrector Plates, R.E.C.
Jul 47 A Novel Drive on a 20-Inch Telescope, R. Tuthill
A Simple Dew-Preventive Device, M. Seslar
Aug 120 The Newton Observatory in Manitoba, J.B. Newton
Sep 189 Some Items from the Gleanings Mailbag (8-Inch F/5 Newtonian, A Swiss Unobstructed Reflector), R.E.C.
An Observatory and a Telescope Base for Field Use, J. Hers
Oct 258 A Wisconsin Amateur's 20-Inch Newtonian Reflector, R. Parmentier
An Inexpensive Mounting with Fixed Eyepiece, J.L. Pfann
Nov 327 A Compact 16-Inch Cassegain Reflector, J. McClure
Dec 400 An "Old-Fashioned" 6-Inch Telescope (refl.), M.J. Kenney
A Portable Telescope with a Wooden Fork, R. Grodinsky
1973 Jan 51 An Observatory Built as a Retirement Project, W.C. Allen
Feb 115 A Dual-Power Cassegrain with a Relay Lens, E.L. Jones
A Motor-Driven Eyepiece Focuser, C.W. Bowen Jr.
Mar 183 An Arc Lamp for Optical Testing, R.E.C.
Apr 250 Making a 16-Inch Telescope, J.R. Smith
May 315 An Easily Constructed Caustic Tester, J.F. Kielkopf
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Jun 389 A California Amateur's 12.5-Inch Newtonian-Cassegrain, H.O. Leitner
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Jul 46 Casting a Pitch Lap in a Mold, W.K. McLaughlin
A Large Portable Knockdown Telescope (12.5-Inch Cassegrain), R.P. Walker
Aug 117 Construction of a 10-Inch Cassegrain, R. Sigler
A Driven Pointer for Setting Circles, C.R. Bishop Jr.
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Sep 184 A Dutch Clock Drive Made from Meccano Parts, J. Van Raalten
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Oct 254 Construction of a Blink Comparator, L.F. Mahon
Temperature Effects on Mirror Cells, R.E.C.
Nov 329 Photographic Polar Alignment of an Equatorial Mountings, C.P. Custer
Dec 405 The Focal Reducer as a Telescope Accessory, P.A. Valleli
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Feb 122 A Norwegian Observatory with Sliding Roof Sections, C.A. Deberitz
Mar 191 An Automatic Guider for Astrophotography, F. Covitz
Apr 259 More About an Automatic Telescope Guider, F. Covitz
May 333 The Lensless Schmidt Camera for Astrophotography, C. Ashcraft
An Observatory Made from a Prefabricated Toolhouse, M. Reynolds
Jun 408 Russell W. Porter's Folded Refractor, A.S. Leonard
A Telescope Drive with a Homemade Worm Gear, W.W. Kendall
Jul 49 A Large Reflector with an Unusual Pipe Mounting, B. Kimmel
A Self-Operating Meteor Camera, B. Mayer
Aug 114 A Retired Engineer's 12.5-Inch Newtonian-Cassegrain, W.J. Sheehan
Sep 182 The Crawford Eyepiece Mounting, R.W.S.
Pinhole and Knife-Edge—How Far Apart?, R.J. Magee
Oct 251 A 10-Inch Newtonian with a Stream-Pipe Pier, A. Pirera
Clock Drive for Department-Store Telescopes, R.E.C. & R.W.S.
An Eight-Legged Spider, J.W. Davison
Nov 325 A Ronchi Null Test for Paraboloids, E.G.H. Mobsby
Dec 401 A California Amateur's Dall-Kirkham Telescope, A.W. Daggit
Experiences in Figuring a 24-Inch Mirror, S. Dunlop
Correction to October 1974.
1975 Jan 46 A New Three-Mirror Unobstructed Reflector, A. Kutter
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Feb 115 More About the Tri-Schiefspiegler, A. Kutter
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Mar 183 Some New Illuminated Finders, R.E.C.
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Apr 255 The Large Reflector of a California Amateur (14.25-Inch Newtonian), R.A. Nye
May 323 A Folded Refractor Exclusively for the Sun, J. Dragesco
Crayford Manor Revisited, J. Wall
A Nomogram That Tells Eyepiece Travel, R.W.S.
Jun 399 A Northwesterner and His Astrophotography Equipment, H.R. Dittmer
Jul 50 Making a Pitch Lap with the Mirror Underneath, P.E. Moniot
Lap Making Techniques at Macalester College, S.W. Schultz, Jr.
Aug 122 A Cold Camera That Needs No Vacuum, E.L. Jones
A Crystal-Controlled Oscillator for Telescope Drives, J.B. West & R.S. Bradford, Jr.
Sep 190 A High-Performance Maksutov Telescope, R.D. Sigler
Oct 255 Stellafane: A Year for the Newtonian, R.W.S.
Nov 332 Old Telescopes at Hartness House, R.W.S.
How to Beautify and Protect Telescopes, W.H. Pierce
Dec 413 A Compact Mirror Grinding Machine, A.W. Daggit
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Making a Projection Blink Comparator, B. Mayer
Feb 127 A Graphical Approach to the Foucault Test, A. Millies-Lacroix
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Mar 199 Miscellaneous Items from our Mailbag (Pitch-lap making, fused silica, from a New Hampshire old-timer, assembling a refractor, more on fired-clay mirrors, protecting aluminum parts, the Sigler Maksutov telescope, electronic drive controls, R.E.C. & R.W.S.
Apr 278 A 12.25-Inch Folded Newtonian Reflector, E.S. Danilovicz
The Light Gathering Efficiency of Telescopes, R.E.C.
May 349 A Pillow-Block Mounting for a 12.5-Inch Cassegrain, A. Schug
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Further Notes on Exposure Times, R.W.S.
Jun 423 Structural Considerations for Telescope Makers, J.J. Brooks
Jul 59 A Digital Clock for Sidereal Time, F. Reid & K. Honeycutt
A Visual Photometer for Small Telescopes, W.S. Houston
Aug 135 Ideas from Resourceful Readers (A homemade toothed sector, a temporary telescope, a 5-Inch binocular, a mounting from the past, plastic threads), R.E.C. & R.W.S.
Correction to July 1976.
Sep 210 Extensions of the Dall Null Test, D.E. Stoltzmann & M. Hatch
Additional Notes on Null Testing, R.E.C.
Oct 193 A Split-Ring Mount from Aluminum Extrusions, B. Shutt
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Dec 471 A Well-Equipped 8-Inch Newtonian Reflector, E.W. Piini
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Making a Vinyl Dust Cap, T. Moon
Feb 139 A Large Maksutov with Newtonian and Casegrain Foci, H. Louth
Mar 220 The Size of the Newtonian Diagonal, W.T. Peters & R. Pike
An Easily Transported 20-Inch Telescope, A. Grebner
Apr 306 W.A. Bradfield and His Comet Seeker, R.W.S.
May 391 A Homemade Filar Micrometer, J. Polman
Jun 475 A "Porter's Folly" Mounting in Europe, R. Schlafke
A Foucault Tester for Short-Focus Mirrors, J.T. Carl
Jul 60 What is a Fabry Lens?, J. Africano and R. Quigley
A Camera Mount for Projection Photography, D.A. Harbour
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Aug 140 A Foucault Tester with Digital Readout, R.J. McKeon
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Sep 233 The New 24-Inch Reflector at Crayford, J. Wall
Some Very Large Amateur Telescopes, R.E.C. & R.W.S.
Oct 328 Some Highlights of Stellafane, R.W.S.
Nov 425 A New Catadioptric Telescope—I, D.C. Dilworth
Dec 521 A New Catadioptric Telescope—II, D.C. Dilworth
1978 Jan 78 The Precise Adjustment of an Equatorial Mounting, B.L. Souther
Feb 173 Further Notes on Adjusting a Telescope, B.L. Souther
More About the Thumbwheel-Controlled Oscillator, J.B. West

Mar 257 A California Amateur's 11-Inch Refractor, J.R. Schroeder
Apr 347 Star Images in the Presence of Aberrations, H.W.J. Blote
May 433 Sidereal Conversion of a Heathkit Digital Clock, R.E. Gilbert
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Correcting Periodic Error in a Clock Drive, L.J. Faix
Jun 530 A Tangent Arm with a Specially Cut Cam, A. Hamon
A Reusable Pitch Mold, A. Raycraft
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Jul 65 A Telescope with Variable Eyepiece Height, J. Cline
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Correction to May 1978.
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Aug 155 Channeling Pitch Laps, B. Drohomer
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Sep 249 Mirror Making at Macalester College, S.W. Schultz Jr.
Oct 345 New Directions for an Old Hobby?, D. di Cicco
Nov 455 Notes on a 16-Inch Astrometric Reflector, W.S. Penhallow
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A New Way to Make Pinhole Light Sources, R.W.S.
More on Contact Lenses, K.P. Bowen
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A "Hairbrush" Telescope Mirror, E.G.H. Mobsby
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Feb 185 Report of a Belgian Telescope Maker, D. Cardoen
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Mar 294 The Hastings-Byrne 6.25-Inch Refractor, J.A. Church
Apr 392 Driving a Telescope with a Wood Putty, M.L. Bartels
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May 487 An Altazimuth Observatory Chair for Binoculars, B. Leifer
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Aug 175 A 16.5-Inch Reflector with a Porthole-Glass Mirror, R.Y. Schwaar
A Simple Polishing Test, J.T. Carl
Sep 270 Mounting a 6-Inch Tri-Schiefspiegler, H.M. Benson
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Oct 367 A Hindle-Type Grinding Machine for Large Mirrors, S.S. Germany
Nov 473 Making an Aplanatic 4-Inch Telescope, E. Turco
Dec 582 A 6-Inch Binocular with Tilted Primary Mirrors, A.H. Hale
1980 Jan 71 The Volume Method for Finding Radius of Curvature, P.D. McGrath
A Sturdy Junkyard Pier, C. Callahan
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Hugh Pipe Fittings for An 8-Inch Catadioptric, G. Tagliati
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Caution When Casting Lead, B. Lipofsky
Feb 163 Spin-offs of the Poncet Mountings, R.W.S.
Mar 294 The Hastings-Byrne 6.25-Inch Refractor, J.A. Church
Apr 338 Have Telescopes, Will Travel, J.L. Dobson
May 425 A Collapsible Telescope Stand of Plywood, G. Stacey
Perforating a 22-Inch Mirror Blank, W.N. Goff
Jun 519 Measuring Double Stars with a Grating Micrometer, C.M. Pither
Jul 64 Optical Configurations for Astronomical Photography, M. Simmons
Aug 158 Telescope Makers Gather for Riverside 1980, D. di Cicco
Sep 245 A White-Light Solar Telescope, R. Pike
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Oct 330 A Short, Movable Foucault Pendulum, H. Kruglak, R. Pittet, & S. Steele
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Nov 432 The Stellafane Experience, D. di Cicco
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A Tap For Large Sectors, H.M. Benson
Dec 530 The Plastic Astrocamera, B. Anderson and K. Sikes
Climb a Mountain with Your Telescope, J.R. Patrick
1981 Jan 71 Running a Telescope with a Microcomputer, D.R. Skillman
Feb 162 Comfort for Astronomers: An Observing Chair, J. Riggs
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Mar 256 The Large Reflector of a Texas Society, A. Ciampi & T. Williams
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Apr 356 Optical Ray-Tracing on a Microcomputer, L. Larks
Scopes with Wooden Tubes, B. Gunnerson
May 448 Microprocessor Control of an Eclipse Camera, G.H. East
How to Make Precision Pinholes, R.W.S.
Jun 545 A "Folded Newtonian" with Dual Focal Lengths, N. Loveday
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Balancing a Telescope, P. Drisdelle
Jul 70 Decentering a Lens for Comet Photography, L. Panecchi
The Saga of a 24-Inch Reflector, P. Drisdelle
Aug 166 Maksutovs with Subaperature Correctors, R.W. Field
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Sep 272 A 10-Inch Reflector and Unusual Dome in Surrey, D.K. Northrop
Image Orientation at a Coude or Springfield Focus, A.T. Young
Oct 376 An Apochromatic Triplet Objective, R. Christen
Nov 496 Arizona Amateur's Photoelectric Photometer, R.A. Nye
Dec 610 Modifying a Reflector for Planetary Observations, L.S.Najman
1982 Jan 85 The Alvan Clark 48-Inch Optical Flat, B.L. Fitzgerald
Contact Lenses and Testing, K.P. Bowen
Notes about Equal-Radius Schmidt-Cassegrains, J. Gregory
More on Pinhole Light Sources, R.P. Smith
Biscuit Cutters from Steel Water Pipe, R. Harger
Feb 198 A Steel-Ball Drive for Small Cameras, P.U. Lind
Driving a Telescope With a Wire Cable, A. Zeljko
A Guiding Reticle Illuminated by Starlight, T. Britton
More on the Christen Lens, P. Weissman
To Tighten a Mounting, R.W.S.
Mar 302 Optical Designs of Some Famous Refractors, J.A. Church
Apr 407 The Advantages of a Slow Worm, P. Fountain
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Revised Triplet Design, R. Christen
An Observer Comments, F. Szczepanski
May 519 Surface Profiles from the Foucault Test, R.T. Holleran
Evolution of an 8-Inch Newtonian, D.S. Wile
Jun 621 Experiments with All-Sky Photography, C. Schur
Restoring Old Tubes, J. Mayenschein.
Night Viewer for Star Charts, R.L. Tanner
Jul 86 A Sundial That Tells Standard Time, C.P. Hamkins
Stands for Binoculars, R. Mandler
Telescope Parameters from a Handy Graph, J.W. Dobbin Jr.
Aug 183 Riverside '82: A Year for Big Telescopes, D. di Cicco
A Null Test for Cassegrain Secondaries, M.V. Spooner
Sep 279 Constructing a Measuring Engine, E. Everhart
How to Reduce Plate Measurements, B.G. Marsden
Oct 375 Peoria's New 24-Inch Telescope, A. Grebner
Optics and the "Golden Ratio", R.W.S.
Nov 486 An Analemmatic Sundial at Union College, H.C. Ohanian
A Simple Mirror System for Binoculars, T. Matsumoto
6-Inch Cassegrain Binoculars, N.P. Butler
Dec 598 The Acme Telescope, J.L. Richter
A Vote from Spokane: Make It Yourself!, W.K. Martin
1983 Jan 81 An Amateur Solar Telescope, G. Gottschalk
Equatorial Tracking with a Dobsonian, C. Baetens & F. Kinnet
Feb 176 Resolution Criteria for Diffraction-Limited Telescopes, D.E. Stoltzmann
Mar 273 Gleanings for ATM's, C. Wolterand R. Merz
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Apr 366 A Portable Platform for Astrophotography, R. Mandler
Making a Simple Chronograph, D.L. Boulet

May 460 An Objective-Prism Spectrograph, B. Sorensen
Correcting the Eye's Astigmatism, J. Van Ellinckhuysen
Jun 548 An Observatory with a Voice, M.G. Otis
Telescope Making and Robotics—A Look Back, R.W.S.
Jul 67 A Simple Coma Corrector for Newtonians, D. Mikesic
More on All-Sky Photography, J. Sloan
Resolution of the Craig 24-Inch Refractor, R. Rainge
Aug 159 Riverside 1983, J.W. Briggs
Sep 255 A Polar-Disk Mounting for Astrophotography, M.D. Hooley
A Drive-Control Frequency Monitor, M. Harner
Refractor Design: Clairaut's Forgotten Legacy, J.A. Church
Oct 351 A Cross-Axis Mount in a Box, B. Simon
An Easy-Viewing Newtonian Finderscope, M. Lahiri
Viewing Diffraction Patterns, F.L. Redburn
When is a Spherical Mirror Good Enough? J.P. Cannon
Nov 453 An Easy, Inexpensive Sidereal Clock, R.J. Newton
A Silicone-Rubber Pitch-Lap Mold, M.J. Harlow
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A Lightweight 8-Inch Newtonian, R.E. Condit
Charting Telescope Attributes, O.S. Correa
Dec 557 A Featherweight 24-Inch Equatorial-I, R.A. Sanders

APPENDIX E

BIBLIOGRAPHY OF TELESCOPE MAKING MAGAZINE, VOLUMES 1 THROUGH 20

Telescope Making magazine began publication in Fall 1978. This quarterly quickly grew to 48 pages per issue, though issues after 20 are frequently larger. The editor is Richard Berry and the associate editor is Robert E. Cox. Two collections of *Telescope Making* articles have been republished: *How to Build a Dobsonian Telescope*, and *How to Build Your Own Observatory*. The publisher is AstroMedia Corporation, 625 E. St. Paul Ave., Milwaukee, WI 53202.

TELESCOPE MAKING 1, FALL 1978
- Cassegrain Optical Systems, R. Buchroeder
- A Light, Portable Wooden Yoke Mounting, F. Sanders
- An Inexpensive 4" f/10 Reflector, R. Berry
- MakingPitch Laps, S. Shultz, Jr.
- Making a 3" Schiefspiegler, O. Knab

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- A Compact 6" Folded Refractor, S. Smith
- Tularcitos Observatory, B. Ashurst
- A Handsome Fork-Mounted 10" Newtonian, B. Wyant
- Accurate Focusing, B. Mayer
- Zonal Test Tolerances, D. McGuire
- Eye Safety and Drugs, R. Hill
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- A Tripod Carry Case for a Compact 4.4" Refractor, A. Daggit
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- An All-Spherical Relay Telescope, R. Sigler
- Permanent Piers for Backyard Observatories, E. Dodds
- Amateur Astronomy in Milwaukee, R. Zit

TELESCOPE MAKING 3, SPRING 1979
- Design of a "Small" 20" Telescope, J. Stull
- A 10" Portable Open Tube Newtonian, R. Lasher
- A Compact All-Spherical Catadioptric Newtonian Telescope, T. Bird and A. Bowen
- Build Your Own Telescope House, J. Tkash
- A Three Weekend Observatory, J.W.H. Simpson
- Apollo Observatory's 19 3/8" Dall-Kirkham Telescope, R. Hoefer
- Description of a Forty-Feet Reflecting Telescope, Sir W. Herschel
- How to Make a Lens, J. Wilson
- An R.A. Slow Motion for Small Telescopes, G. Papazian

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- It's Stability That Counts, B. Kestner
- Constructing a 10" Kutter Schiefspiegelr, R. Schmidt
- An Amateur-Built 32" Reflector, J. Perry, Jr.
- Scuppernog Observatory, T. Renner

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Contrast and Resolving Power for Visual Telescopes, Van Venrooij and Rutten
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The 1983 Texas Star Party, R. Cox
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Marshal Martz's 76-cm Telescope, N. Sperling
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A Glass Fiber Observatory, D. Ratledge
A Solid-State TV Camera, P. Manly

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The Amateur Space Telescope: ISRG Update, R. Pfeiffer
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Dobson and Dobsonians, J. Dobson
Riverside 1983, R. Cox
Baffling Cassegrain and Schmidt-Cassegrain Telescope, F. Melsheimer

APPENDIX F

INDEX TO SELECTED TELESCOPE MAKING ARTICLES IN SCIENTIFIC AMERICAN 1925–1959

The November 1925 issue of *Scientific American*, carried a story entitled *The Heavens Declare the Glory of God* which launched telescope making in America. This article, inspired by Russell W. Porter and written by Albert G. Ingalls, is the story of Stellafane.

For the next 35 years practically every issue contained something on telescopes and telescope making. Most appeared in the monthly column *The Backyard Astronomer*, then *Telescoptics* and finally, *The Amateur Scientist*. For over 20 years this column was edited by Albert G. Ingalls. These articles formed the basis for the three volume work *Amateur Telescope Making*. However, not all the articles appearing in the magazine were re-printed in the book series—many interesting stories now lie hidden on the shelves of libraries. Most large libraries have this magazine so the material is accessible, the problem is knowing where to begin!

Edgar Everhart compiled and published the original version of this index for *The Maksutov Club Circular, No. 59*. However, this version of the index has been substantially re-structured. The index is selective in that not all the articles which appeared have been included. Although practically every issue contained pictures of amateur instruments, club meetings and similar material, articles had to be of permanent interest. Instruments under 12 inches have been generally excluded unless they are unique or illustrate an interesting principle. Dates of publication are coded; 1.48.45 should be read January, 1948, page 45.

EXACT FORMULAE FOR CALCULATING SIZE AND OFFSET FOR NEWTONIAN DIAGONAL MIRRORS

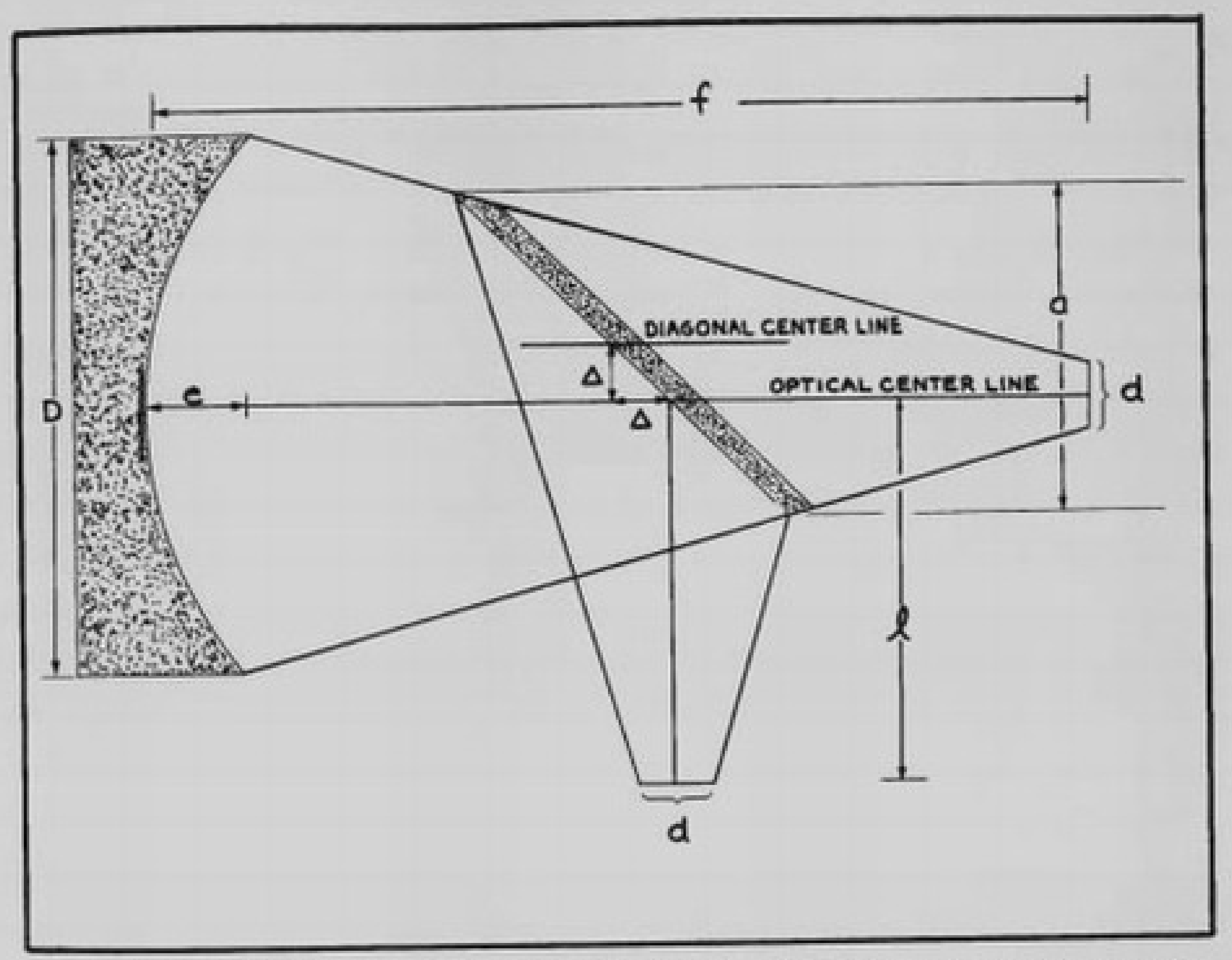

Fig. 149. Relationship between the optical centerline of a Newtonian telescope and the centerline of the diagonal mirror. For a uniform illumination of the focal plane the diagonal must be displaced away from the eyepiece and toward the primary mirror by equal amounts.

To achieve uniform illumination of the focal plane, the Newtonian diagonal mirror should be slightly decentered from the primary's optical axis. Figure 149 shows a fast mirror which exaggerates this displacement which is both toward the mirror and away from the eyepiece by equal amounts. For instruments of moderate aperature and focal ratio this displacement can (and should be) ignored. The offset for the standard 8-inch *f*/6 described in this book is about 0.052 inch and is not worth the added effort to accommodate. Large aperature, short focal length systems do require this off-set. A 12-inch,

$f/4$ primary requires the diagonal to be off-set by nearly 0.15 inch. Dakin[1] has derived formulae to precisely calculate this offset value Δ and the exact size of the diagonal's minor axis a:

$$a = \frac{L}{M} + \frac{L}{N} \qquad (99)$$

$$\Delta = \frac{\frac{L}{M} - \frac{L}{N}}{2} \qquad (100)$$

where L, M and N are calculated:

$$L = d(f-e) + l(D-d) \qquad (101)$$
$$M = 2(f-e)-(D-d) \qquad (102)$$
$$N = 2(f-e) + (D-d) \qquad (103)$$

and were e is the mirror's maximum depth (sagitta) from formula (19):

$$R = \frac{r^2}{2e} \text{ or } e = \frac{r^2}{2R} \qquad (104)$$

Re-working example 1, in Section III-2 gives:

Formula (104) $e = \frac{4^2}{2(96)} = 0.083$

Formula (101) $L = 0.43(48-0.083) + 6.3(8-0.43) = 68.60$

Formula (102) $M = 2(48-0.083)-(8-0.43) = 88.26$

Formula (103) $N = 2(48-0.83) + (8-0.43) = 101.91$

Formula (99) $a = \frac{68.60}{88.26} + \frac{68.60}{101.91} = 1.45$

Formula (100) $\Delta = \frac{\frac{68.60}{88.26} - \frac{68.60}{101.91}}{2} = 0.052$

[1] R. K. Dakin, *Sky and Telescope*, December 1962, pp. 368-69. See also *Sky and Telescope*, February 1963 p. 114 for corrections to Dec. 1962 article.

APPENDIX H

ELECTRONIC DRIVE CONTROLS FOR DECLINATION AND RIGHT ASCENSION AXES

Electronic telescope controls have become simpler and more reliable. In this section three circuits (AC and DC motor Declination switches and a variable rate AC motor driver for Right ascension) are described with schematics, photographs and printed circuit art work with and without parts layout. Detailed, step-by-step instructions are not given. Individuals who are familiar with electronics will have no trouble assembling these units. Those who lack this experience should find a knowledgeable individual to help them.

Both the DC and AC Declination switches must be mounted with insulated stand-offs. Voltage is present on the transistor/SCR mounting hardware used on these circuits and it must not have a direct chassis ground. Sound safety practices dictate that both the electronic chassis, motor case(s) and metal telescope parts should be connected to a common ground. To do this use three conductor wire: Black (hot), White (electrical ground) and Green (common or chassis ground). Do not underestimate the shock hazard that potentially exists with any electrical device. If fuses blow or you feel current, discontinue use and determine the cause before resuming use.

Fig. 161. Richard Berry's 20-inch Dobsonian

APPENDIX J

PITCH TESTING

For the novice, the fingernail test for pitch hardness is not very precise; the nail may be hard or soft and pliable, the amount of pressure and the time it is applied can vary from person to person and even from day to day. Little wonder then that a certain amount of mystery surrounds the subject for the beginner.

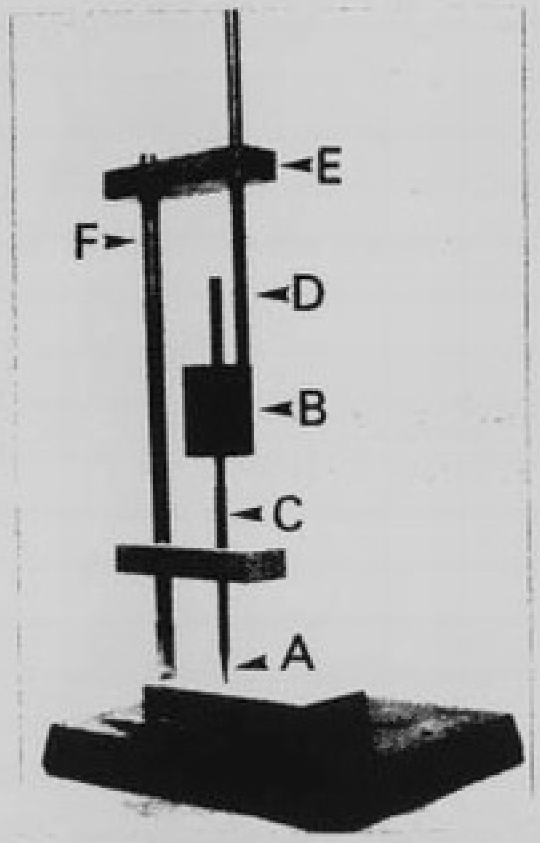

Fig. 162. A simple polishing pitch viscosity tester.

Figure 162 illustrates a device generally described as a Twyman[1] viscosity tester. In principle the tester is very simple. A pointed steel rod weighted to 1 Kg (2.2 Lbs.) is allowed to penetrate a pitch sample for 5 minutes. The depth of

[1] Twyman, F. *Prism and Lens Making*, Hilger Watts, 1952. See also: Brown, N. *Optical Polishing Pitch*, Preprint UCRL-80301, Lawrence Livermore Laboratory. This paper was submitted to Optical Society of America Workshop on Optical Fabrication and Testing, Nov. 10–12, 1977, San Mateo, CA.

penetration is then compared with a standard that considers the temperature of the pitch. The steel rod is tapered at a 14° angle and the tip is flattened (to about 0.04 inch).

There is little reason for complicating the tester—micrometers and dial indicators do not significantly increase accuracy. The depth of penetration is then compared with Figure 164 to determine if it is within acceptable limits. Figure 162 shows a simple, but effective tester. The pointed steel shaft (A) is weighted (2.2 Lbs.) with a 2-inch diameter steel rod (B) and is loosely supported by a thin walled brass tubing mounted in a wooden support block (C). A second length of brass tubing (D) is friction fitted into another wooden support block (E). Support block E is also friction fitted to the support shaft F and allows the entire assembly to be moved up and down or rotated out of the way so that the pointed steel shaft (A) can be raised and lowered onto the pitch sample.

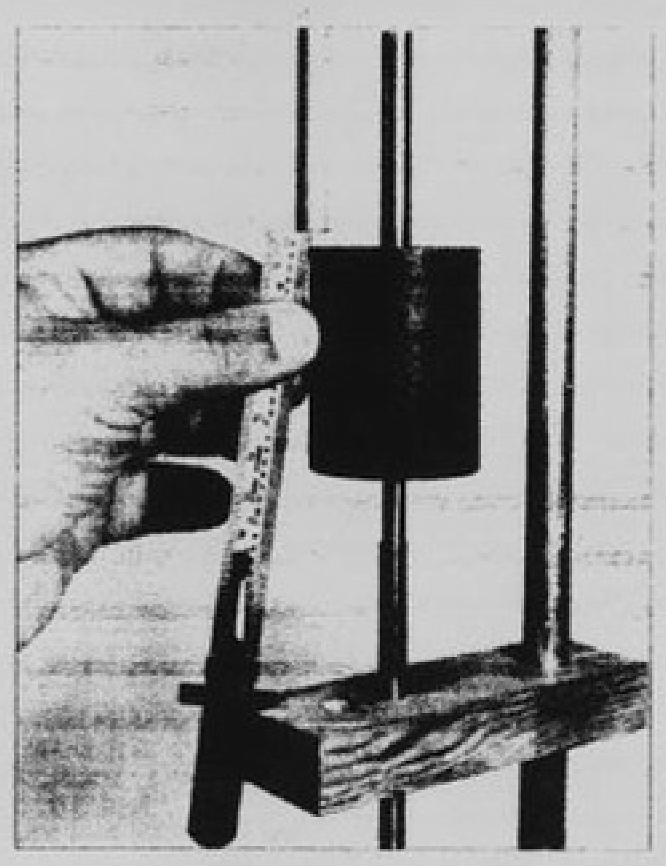

Fig. 163. Method of measuring depth of penetration into pitch sample after 5 minutes.

Once the weighted rod is placed on the pitch sample the brass tubing (D) is positioned over the weight and brought into light contact. After 5 minutes, the pointed rod will have penetrated the pitch and a gap will appear between the brass rod and the top of the weight. This is illustrated in Figure 163. The gap is measured with an ordinary steel scale.

Once penetration has been measured it can be compared with the diagram in Figure 164. Note that the vertical axis is titled Fall Rate and is logarithmic from 0.001 to 1.000 inch. The acceptable limits are fall rates of

0.02 to 0.24 inches for mirrors in the $f/6$ to $f/12$ range. This means that pitch which has a fall rate below 0.02 is too hard; that which has a fall rate in excess of 0.24 inch will be too soft. A fall rate of 0.07 will work over a temperature range of ±3°C or about ±5°F.

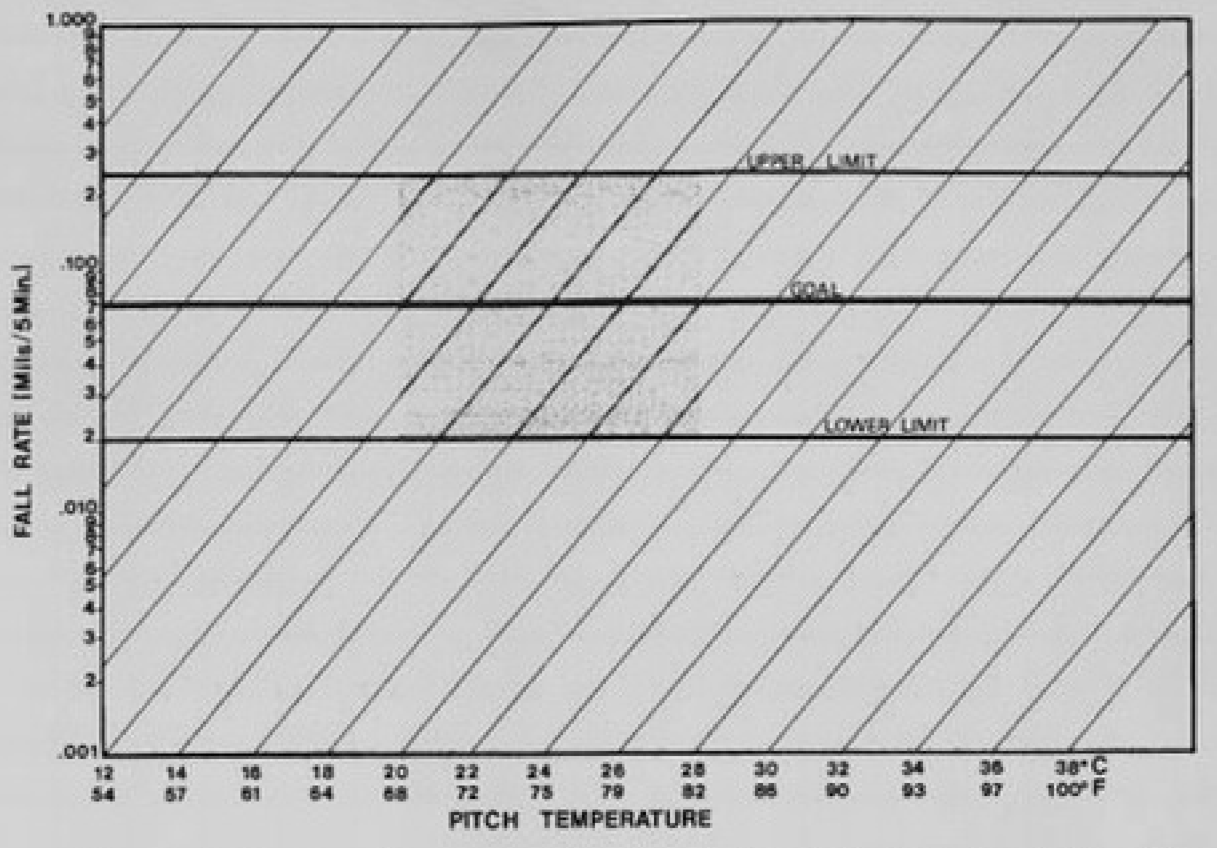

Fig. 164. Fall rate (mills/5 min.) of a 14° pointed steel rod weighted to 1 Kg. Diagonal lines display this fall rate in relation to temperature. Shaded area represents working range most suitable for amateurs—Five minute fall rates between 0.02- and 0.25-inch for temperatures between 68° and 82°F. This table is based upon work done by J.P. Prideaux.

The shaded area of Figure 164 highlights the temperature range (20 to 28°C) that most experienced amateurs prefer. It is good practice to work with a temperature of about 24°C and a pitch fall rate of about 0.07, then moderate changes in temperature or pitch hardness do not significantly change the action of the lap.

Once the rate of fall for pitch is known appropriate action can be taken to correct it. The workroom temperature can be raised or lowered, or the pitch can be modified, adding turpentine to soften it or cooking to harden.

Several factors can cause pitch that tests well to work poorly. If the lap is too thin, it will behave as if it is too hard. Conversely, a thick lap (more than 0.25 inch) will behave as if it is too soft. A lap that starts off at the desired thickness and hardness becomes thinner as the pitch flows and is trimmed, so effectively hardens. Finally, laps harden by prolonged exposure to air—plastic covers will slow this down between polishing spells.

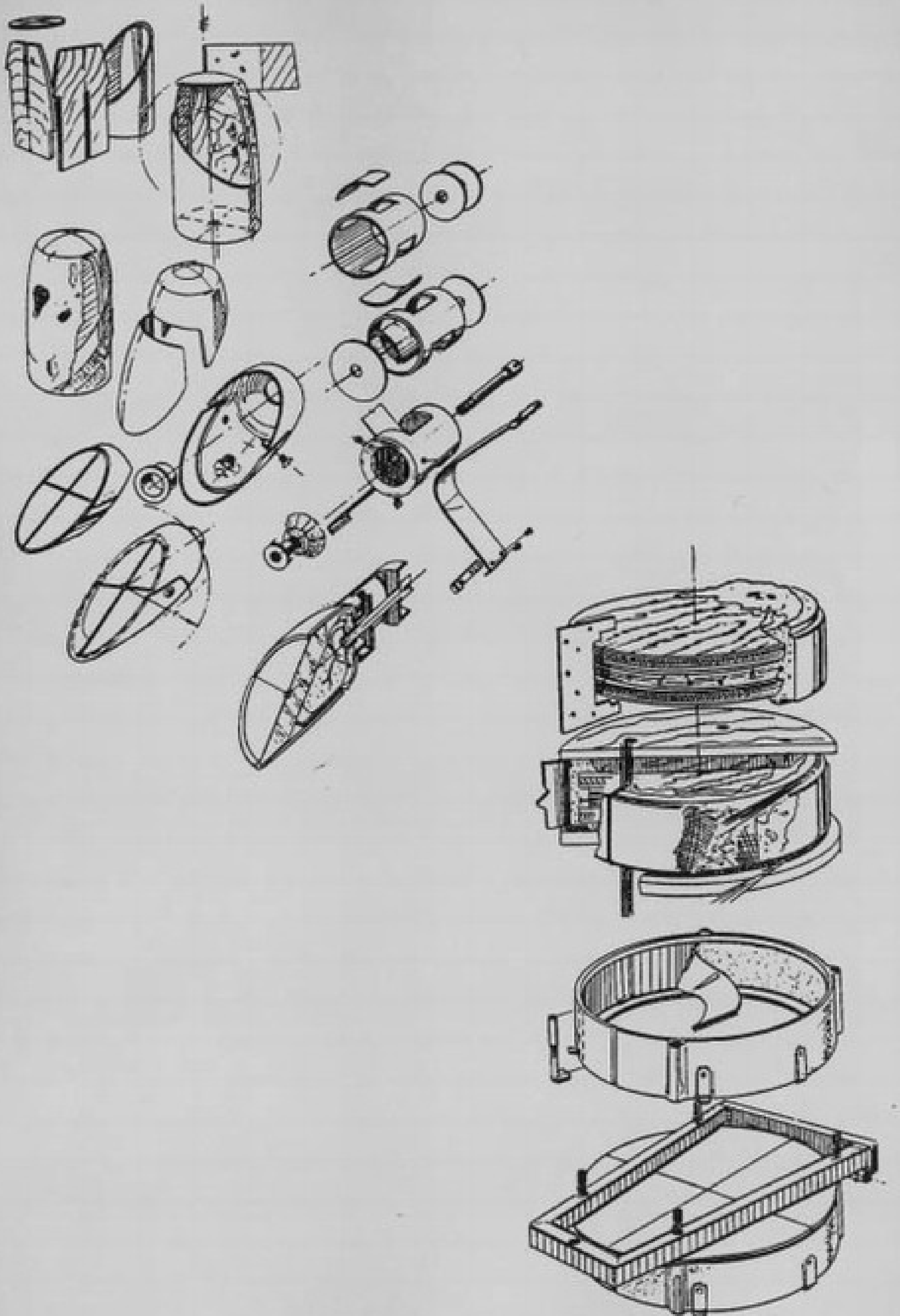

Fig. 174. These two diagrams show the general method Norman James used to make the secondary and primary mirror cells with fiberglass.

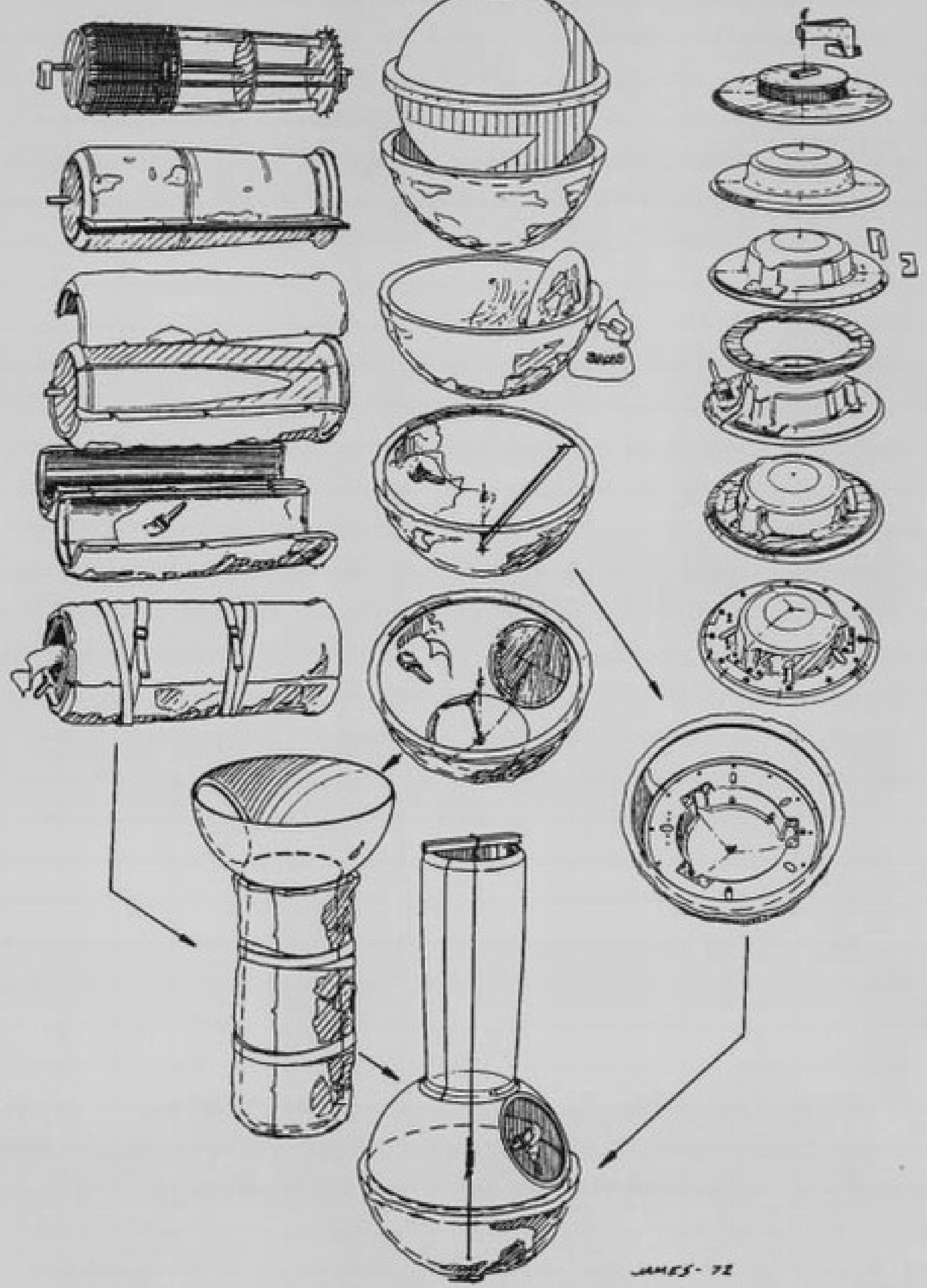

Fig. 175. Shown here is the method Norman James used to make the telescope tube and spherical base from fiberglass.

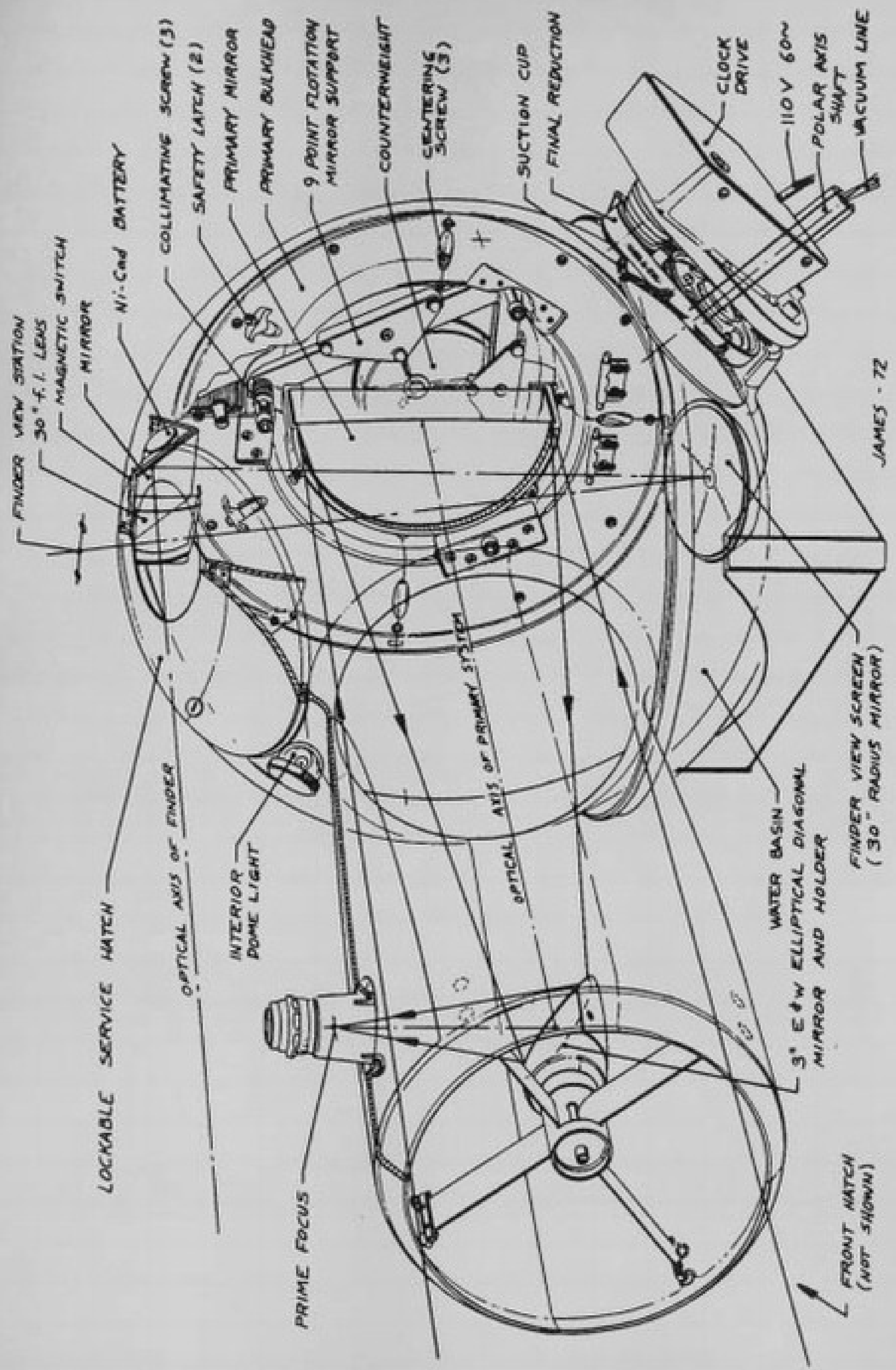

Fig. 176. This diagram shows the general layout for the James spheremount telescope.

Fig. 177. Robert E. Cox demonstrates his version of Horace E. Dall's pocket telescope (shown in *Telescope Making Book III*, and described in the December 1947, *Scientific American*). Box Cox, former editor of *Gleanings for ATM*'s and now associate editor of *Telescope Making* magazine, is a frequent speaker at amateur conventions and never fails to delight audiences when he shows this highly portable instrument.