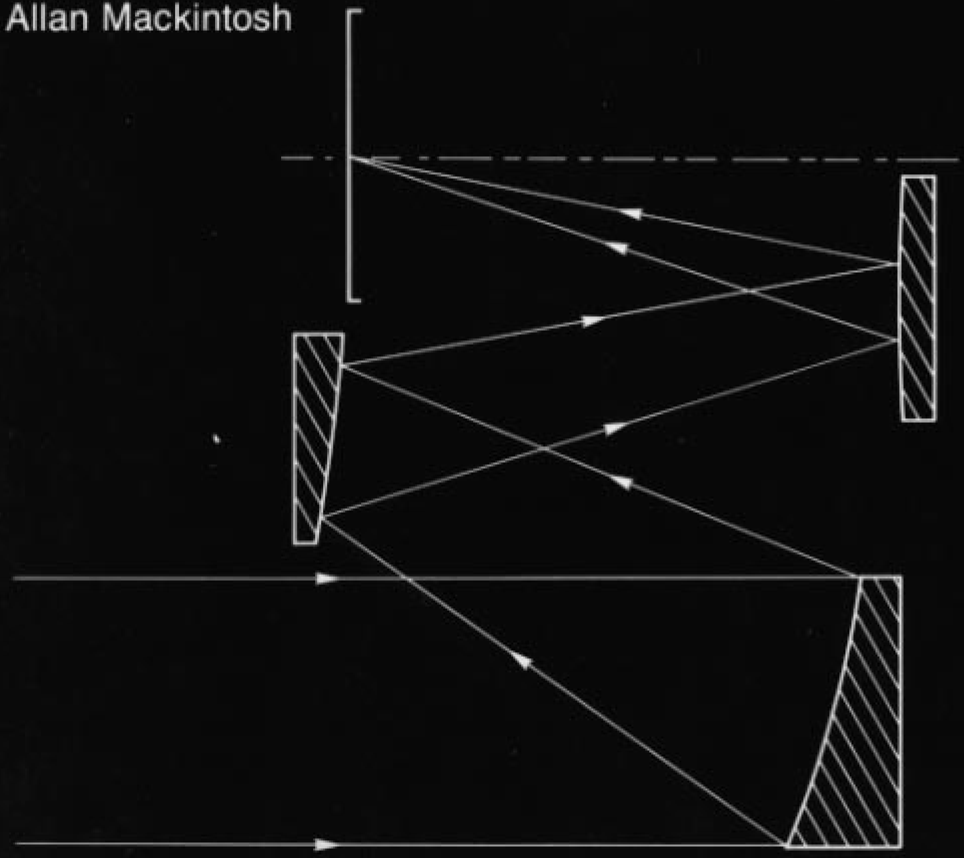
Advanced Telescope Making Techniques

Allan Mackintosh



Volume 1

Optics

Featuring Selected Articles from the Maksutov Circulars logically look for it in a certain section of the book. At the same time he must not miss items of important information which are not, at first sight, closely connected with any of the major divisions of the book.

Readers may get the impression that the book is excessively concerned with Maksutov telescopes. This was a natural development because, after all, the Maksutov Club was at the beginning formed for the production of Maksutovs. It was soon realized, however, that the extreme conditions met with in making a Mak (very short radii of curvature and very tight tolerances on thickness, etc.) made the techniques developed—or at least most of them—useful for tackling any other kind of telescope where precision construction is required. For the last 15 years the Maksutov Club has been interested in all kinds of telescopes and not only with Maksutovs.

The arrangement eventually decided upon for this book is as follows: it has been split into two volumes, "Optical" and "Mechanical," largely to reduce the cost of producing an oversized book which would contain all the relevant information.

Within the broad divisions of the two volumes, the order of information is that which appears to the editor to be logical. In this way, it is hoped that the book will be easy to read but at the same time the reader will be able to skip those parts of the book which are obviously for reference until he needs to go to them. Please extend your patience to the editor where he has failed in a rather difficult task.

—*Allan Mackintosh*

TABLE OF CONTENTS

VOLUME 1 — Optics

Chapter 1
FIGURING, ETC.

THE SPINNING METHOD FOR FIGURING
by E. G. Onions

I made all the curves on my Maksutov and also a 12½" f/4 by the spinning method and see nothing wrong with it. To start with, I altered my machine to give a turntable speed of approximately 75 r.p.m. and a stroke speed of 40. This *ratio* of table and stroke speeds (as recommended by Ferson, *A.T.M. III*) appears to facilitate a system of even wear (see Dévé). The spindles are far apart, the driving beam being nearly 6 feet long. This results in a practically straight stroke, the free end supported and sliding between fixed guides as the driving pin must "float" in its hole in the tool. Only two adjustments are possible—stroke length and fore-and-aft position of the driving pin.

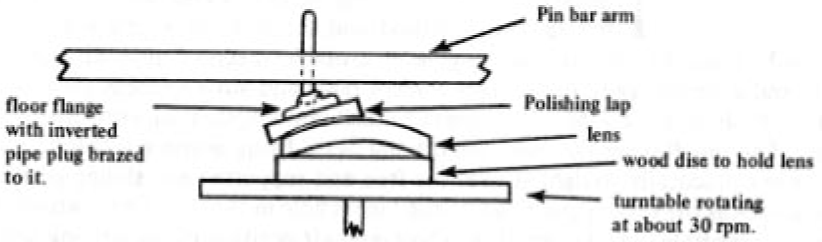
Rough grinding having been completed, I made up a tool in the ordinary way (tile tool) 5/6 the diameter of the mirror except that I did not facet; I ran the tiles straight across the tool in lines 1/8" or so apart (one-way channeling). Incidentally, making the polisher is very simple; I just lay pre-cast strips of pitch on the tiles—a very little molding will result in a perfect lap. The tool being ready, I centered the mirror on the table (to avoid wedge) and adjusted the machine for approximate position of S.E.W. (system of even wear); the driving pin was a little behind the center of the work when in the rearmost position ("rear" is the crank end of the machine) and stroke about 1/4 or 1/3 of diameter; grinding was continued with coarse carbo and adjusted until no change in radius was detected with the spherometer. This condition attained, I went straight through with the fining and polishing.

The first test of my 12½", done this way, showed a beautiful parabolic doughnut with a smooth curve and a delightfully clean edge. As I wanted a sphere, I moved the driving pin a little in front of center, with a 1/3 stroke to get the desired figure. With this method (contrary to hand working) it is much easier to bring a parabolic or hyperbolic figure up to a sphere than it is to get an oblate down. All the above applies to any curve, concave, flat or convex, and to avoid confusion it is best to consider the action in terms of wearing down center, wearing down edge and somewhere between the two—S.E.W.

The use of a fixed speed machine will be criticized, but I maintain that the *effect* of any grinding and polishing operation is the *product* of two variables—speed and pressure, so that within reason we can use one speed and vary the pressure to suit diameters and stages of work. I am a firm believer in pressure and in all but the final stages of my 12½" I used 30 or 40 lbs. weight on the tool. In polishing, of course, weight adjustment is critical, for obvious reasons. My defense of the spinning method rests on the smoothness of curve attained and the freedom from turned edge. Considering that the free tool is rotating at a speed only slightly less than the work, you will see that the action is almost entirely rotary—the lap is not being dragged over the poor old edge!

POLISHING DEEP CURVES
by R. G. Hoffman

What I thought was going to be one of the most difficult tasks in making a Maksutov corrector turned out to be the easiest. This is all that was necessary.



In words, all that is necessary is to offset the tool or lens (whichever is on top), provide a moderate amount of pressure, fix the top element so that it will rotate and not slide off, change the offset from time to time so that zones do not form, and that's all there is to it. The pitch I used was very soft (softened by adding paraffin), so soft in fact that it only becomes brittle at room temperature.

Using Paul's test (*A.T.M. III,* page 327), I can detect absolutely nothing to indicate that the spheres obtained are short of perfect. No figuring was required on either side of the correcting lens. On the primary I used an ordinary alligator setup (Hindle, *A.T.M. I,* p. 324, 4th Ed. 1st printing) and had to polish a hump off the center, but even here the figure looked perfect and was not difficult to obtain. Testing these deep curves by any method that I have tried is not easy.

With regard to perforating a primary, I do NOT recommend drilling to within 1/16" of the surface from the back, then tapping on the plug lightly with a hammer after polishing and figuring. *Drill* that remaining 1/16" out when figuring is complete; this time going in from the face of the mirror. The edges of the hole will be much cleaner this way.

NOTES ON MAKING A MAKSUTOV CORRECTOR LENS
by A. J. Blackwood

Making a Maksutov corrector lens is getting to be old hat among amateur telescope makers and numerous articles have provided the ambitious lens maker with essentially all the details he needs to complete the job. However, in spite of the wealth of information available, there seemed to be many little problems and questions arising during the course of my work, the solutions to which I could not find in the published material. These notes are for those who are undertaking to make their first steeply curved lens.

I am a member of Amateur Astronomers Inc., of Cranford, N.J., and am indebted to a number of fellow members for suggestions and advice offered during the course of the work, particularly to Richard Ulmes, Kenneth Smith and Roger Tuthill. I decided to make a meniscus of 8" clear aperture with dimensions scaled up from the 6" Dall-Maksutov described in Feb. 1962 issue of *Sky & Telescope,* page 31. Incidentally, Mr. Horace Dall advised me of a typographical error therein—the R.C. of R_3 should be 32.20" instead of 32.80" and, correspondingly, the focal distance would be 16.10" instead of 16.40".

Tools. I decided to use metal tools with plate-glass squares (which I shall call facets) cemented to them with epoxy. I am generally familiar with the fabrication of high-pressure vessels and it seemed to me that it would be a relatively simple matter for one of the many fabricators to supply a pair of dished discs at a reasonable cost. My first approach provided two 8" discs for $18.00 (1966 prices), cut to diameter and dished to the specified radius of curvature. Two 2" lengths of 6" scrap iron pipe were spot welded to the discs to serve as "handles," one on the concave side of one disc and the other on the convex side of the other disc. The two tools were fitted with the glass facets.

Cementing of Glass Facets to Metal Tools. The metal tool surfaces were carefully cleaned with a grinding wheel and emery cloth. One face of each glass facet was roughly ground to "fit" the tool curvature and cemented to it with marine epoxy having a 6:1 ratio of resin to hardener. This was actually a batch operation done by placing the facets on the metal tool surface which had been coated with epoxy, with the result that on the concave tool there was some puddling of epoxy in the center and the facets had to be rearranged periodically until the epoxy hardened.

During the course of subsequent grinding with the several grades of abrasive, I encountered frequent loosening of facets, particularly on the convex tool where the surplus epoxy had drained off instead of puddling. When this occurred, the facet was cleaned with emery paper and the metal surface under the removed facet was scraped clean and serrated with the sharp edge of a file, following which the facet was recemented in place with 1:1 tube epoxy. Over 20 facets on the convex side and a few on the concave side were replaced in this way. I noted that the center facets on the concave tool, which had hardened in a pool of epoxy, never came loose. This loosening became quite a nuisance. I talked with other amateurs and they reported the same difficulty. As the finer grades of abrasive were approached, it became increasingly difficult to replace the loosened facets and get good cutting contact quickly, so I examined the situation more carefully. I came to the following conclusions:

1. The rough grinding of the facet faces when initially cementing them to the metal tool, and the thin layer of fluid epoxy (especially near the outer areas) combined to permit the entrance of water which, in due course, resulted in some rusting of the metal and weakening of the bond. When the facets loosened and were removed, a thin layer of hard epoxy, coated with rust, could be cut and stripped from the metal tool, and rusty "spots" were seen on the under side of the loosened facets.

2. K. D. Smith, a member of my amateur group, offered a solution. It will be recalled that the facets which were in a pool of epoxy in the concave center never became loose. K. D. suggested that a "pool" of epoxy be made around all of the facets by preparing a thick mixture of the 6:1 epoxy to which would be added some silica powder. (Cabosil, a thixotropic agent for fiberglass resins was used; it is available from Defender Supply Co. of New York and, no doubt, other suppliers). I promptly worked such a mixture around all of the facets with a spatula and after that not a single facet came loose. This treatment not only prevented water from seeping under the facets, but equally, or perhaps more important, it provided a lateral support for each facet so that they all reinforced one another. I might mention that I never had a facet, which had been epoxied to another facet to build up thickness, come loose and this gives further indication that rust was the probable culprit. Another useful thing that K. D. showed me was application, from time to time, of a circular sanding disc in a ½" drill to rebevel the edges of the facets to prevent glass slivers from breaking off the sharp edges and being a possible source of scratches during fine grinding.

Replacement of Facets. The convex surface of the corrector blank had to be changed from the original molded blank R. C. of 11.20" down to my design value of 9.33". This turned out to be a discouragingly slow process. Even with considerable overhang of the tool over the blank, the R. C. changed very slowly. But glass was being worn off the blank and I began to wonder if I would run out of center glass before the desired R. C. was reached. A half-sized tool was made up and used to grind the edge of the blank—while the R. C. changed somewhat, it took perhaps four or five times as much labor, due to reduced contact area. I later developed a wear rate theory which tended to explain, in part at least, why the curvature changed so slowly—a phenomenon which is mentioned quite often in articles about steeply curved surfaces (see later paragraphs on "A Theory about Wear Rate").

About this time, Roger Tuthill, also a member of my group, suggested that I knock out several of the center facets on the concave tool, which would then result in grinding the outer areas of the corrector blank without reducing the central area. This was done and it was while knocking out the facets that I realized how strong the pool of epoxy really was in the center and why K. D's suggestion to build up the epoxy in the channels around the facets worked so very well. At any rate, Roger's suggestion was the solution to my problem. The desired R.C. was quickly reached and the surface was not too far from being spherical. Then came the question—how to replace the facets which had been knocked out and at the same time get reasonably good contact with the convex corrector blank surface? Of necessity the facets would have to be thinner than the ones knocked out. I hit on a novel idea which worked out extremely well and may have application in other situations where facets have to be epoxied in place. First I cut facets from plate glass which was slightly too thin. One face was roughly ground to the corrector curvature with an emery wheel and the glaze taken off the other face. I then cut a piece, approximately 7/8" long and 1/4" wide, from a sheet of thin spring steel (a piece from an old clock spring would do very well). Cutting the piece from sheet with tin shears resulted in the pieces being slightly curved, but they could have been bent to the desired curvature with pliers. A piece of this slightly curved spring steel was then fastened to the roughened bottom of each facet being replaced, using a dob of epoxy. After the springs had hardened into place, the facets so prepared were placed against the metal tool with the spring prongs in contact with the metal. Thickened epoxy was then worked into the spaces between and under the facets. The convex side of the corrector blank was then given a coat of oil to prevent excess epoxy from sticking to it, pressed down against the facets being cemented in place, and weighted in place. This resulted in the springs pushing the facets up against the convex corrector blank surface during the period in which the epoxy was hardening. Several hours later, when grinding was resumed, the newly placed facets were in immediate contact with the mating surface and grinding resumed normally.

Spherometers. Two different spherometers were used. One, a rough-and-ready three footed type for following the early progress of the work is in common use during the mirror-grinding classes at our club. The feet are three machine screws equally spaced on a 5" circle on a piece of 1/4" aluminum plate (or ½" plywood, if preferred), and projecting beyond the lower face slightly more than the anticipated sagitta at 2½" from the center of the corrector blank. The ends of the machine screws are beveled against a grinding wheel to give essentially point contact. A ½" hole is drilled through the center of the 5" circle and a hardwood plug made to fit accurately into this hole. A 1/8" hole is then drilled through the center of the plug and a long machine screw having 32 threads per inch is threaded into the hole. The metal screw cuts its own thread and should subsequently be tight enough to stay put in any position. A large metal washer is fitted to the top of the machine screw to serve as a means for turning it by hand. A wire "pointer" is fastened to the machine screw between the head and the washer. A piece of paper 5" diameter is marked off from 0 to 360 in five-degree intervals and is glued to the top of the spherometer plate. The length of the machine screw should be slightly more than twice the length of the sagitta so that it can be used to measure both concave and convex sides without removing it from the center hole.

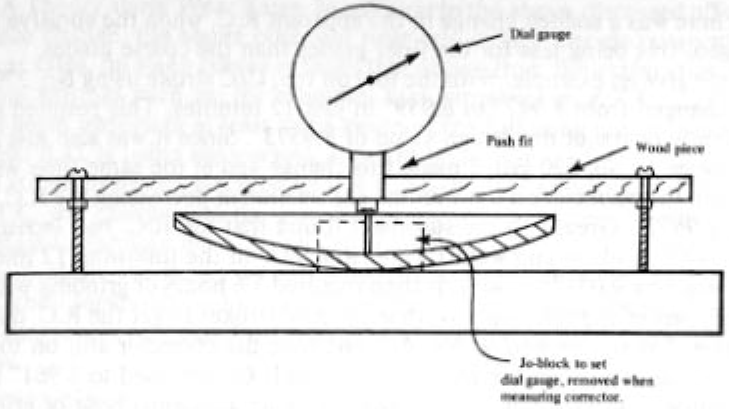
In operation, the zero reading is taken by placing the three feet on a flat plate glass surface and noting the degrees on the scale as indicated by the pointer when the center point just touches the flat surface. At the instant of contact, the spherometer becomes slightly wobbly, or can be rotated bodily around the center point since the three feet have been slightly lifted from the surface. The spherometer is then placed on the curved surface to be measured and the machine screw threaded in or out as the case may be until the tip again touches the surface and the plate becomes wobbly. By counting the number of complete turns and the fractional turn in degrees, the sagitta can be measured and the R.C. determined in the usual way. By making the machine screw tips essentially pointed, no correction for ball foot diameter is necessary. Readings on the degree scale can easily be repeated to within plus or minus 5°, or .0004". This simple instrument is remarkably sensitive and accurate, and it was only during the late stages of grinding that a 2-ball spherometer was used to get more precise results.

My precision 2-ball spherometer was made as follows: a 26" length of Brown and Sharpe square oiled steel bar was purchased, and a local machine shop which had a reputation for doing precision work agreed to cut, drill, tap and supply all set screws, ball bearings (for the feet) and fit two rods for the feet for less than $20. The 1" square bar was first precision cut and the ends ground flat into one 13" length, one 9½" length, two 3/4" lengths and two ½" lengths. The four short pieces were individually measured with a micrometer for thickness and squareness and subsequently served as "Jo-blocks" of nominal ½", 3/4" and 1" sizes in making basic measurements. The 13" long piece simply served as a "flat" for establishing zero readings on the dial gauge in the center of the 2-ball spherometer and in making center thickness measurements. My dial gauge is a Starrett No. 25-131 with a maximum range of 0.125" and .001" divisions on the dial scale—one complete turn being .050". By using a series of extensions for the dial gauge, plus the above-mentioned "Jo-blocks," it was possible to measure all corrector and primary mirror sagittas with the same pair of feet, thus minimizing all sources of error which might result from using a dial gauge with a long travel, or from changing or disturbing the positioning of the spherometer ball feet.

I soon became sold on the ease, precision and reproducibility of this type of spherometer and in making sagitta measurements to approximately .0001" by interpolating within the dial scale 1/1000 divisions. The spherometer was rigid and heavy and rested firmly on the surface being measured due to its own weight. My procedure was as follows: first a paper cone was made having the same diameter as the surface being measured, and a small hole cut in the center. When a sagitta measurement was to be made, this mask was placed over the glass surface and a pencil dot was put on the glass surface through the hole in the mask. This was to ensure that when the spherometer was placed on the glass surface the dial pin would be centered on this dot. For truly spherical surfaces this is an unnecessary refinement but it is recommended nevertheless as the surface is quasi-conical until the late stages of fine grinding. The spherometer was then rocked slowly back and forth over this central dot. The dial reading would reach a null point and recede from dead center, and could repeatedly be read to 1/10th of the dial division just as one reads a slide rule. The radius of curvature is determined in the usual way, making due correction for the diameter of the balls on the spherometer foot.

I will digress here to mention that the span on the spherometer was measured both with an inside micrometer and with a French vernier caliper and estimated to within plus or minus 0.0005". This precision was hardly necessary, as a matter of fact, since for measurements and dimensions, it can be calculated that an error in the measurement of the span of three mils would produce an error of only 1/15th the permissible error in the measured R.C. Furthermore, any slight error in measuring the span on the instrument might be considered to be unknowingly scaling the basic design slightly up or down, except that the theoretical center thickness would be very slightly in error on the finished lens—but far less than the permissible error limits.

Thickness Measurements. Center thickness was measured in a very simple way using the same technique as was used with the 2-ball spherometer. The corrector blank was placed, convex side down, on the 13" long flat bar with the pencil dot, previously mentioned, in the approximate center of the bar. A piece of wood 1" x ½" x 10" was center drilled to take the dial gauge stem (push fit), and two rounded end machine screws were located equidistant from the center and about 9" apart, so as to straddle the corrector blank. Using the flat bar and the Jo-blocks, along with the proper dial extension, permitted a direct measurement of center thickness. This dimension was checked very frequently, as might be expected. The Figure shows the arrangement employed.



Edge thickness was measured using the technique described by R. E. Cox in the July 1961 *Sky & Telescope.* Usually 8 equally spaced measurements were made, reading the micrometer to approx. 1/10th division. The thick areas were then reduced by letting the tool overhang on the corrector and applying extra pressure in that area. Results before and after were plotted on x-section paper and the smoothness of the curve through the points was an indication of the accuracy of the individual measurements as well as a guide to the success of the corrective procedure. This check was made after each change in grade of abrasive used in finishing the convex side (the concave side having already been polished) to make sure that the edge thickness never got out of bounds, and to have it close to a uniform value when the finest grades of abrasive were reached. My formula, applicable to my particular dimensions and arrived at by simple geometry, indicated that my final edge thickness was what it should be for my design center thickness and two R. C. values.

Achieving Precision Radius of Curvature. The accepted way of deepening the curvature of a concave lens or mirror surface is to stroke with the blank on top, using overhang to accelerate the process; conversely, to flatten a concave surface, the strokes are made with the tool on top. The reverse is necessary when stroking to change a convex surface. Furthermore, the book will tell you that as the desired curvature is approached closely, repeated reversals as abrasive changes are made, will result in your surface reaching the exact desired curvature.

This is only partly true, and for steeply curved surfaces it may not be true at all, depending on such factors as are discussed below:

Take the case of finishing the R_1 (concave surface). If this is the first surface finished, neither center nor edge thickness are critical considerations and one need only arrive at the desired R.C. Fortunately, I completed R_1 through polishing first and discovered the pitfalls; if I had completed both sides up to grade No. 400 or No. 600, and then worked toward the design R.C. and thickness, I might have been in trouble—perhaps not to the extent of ruining my lens, but I would probably only have been within the permissible range rather than right on the target. I found out two things while I still had plenty of glass to work with:

a) The R.C. decreased (curve deepened) very, very slowly with the corrector on top, *but* it increased (curve flattened) very rapidly when the tool was on top.

b) There was a sudden change in the apparent R.C. when the abrasive grade was changed, this being less for the finer grades than the coarse grades.

Let me give an example. With the tool on top, C/C stroke using No. 220 grit, the R.C. changed from 8.947" to 8.959" in just 12 minutes. This resulted in my having slightly overshot my design value of 8.9573". Since it was also just about time to change to No. 320 grit, I made this change and at the same time went to stroking with the corrector on top with the expectation of decreasing the R.C. from 8.959" to 8.9573". Greatly to my surprise I found that the R.C. had *increased* to 8.971" in just 6 minutes and went further to 8.983" in the following 12 minutes. The R.C. was now 0.026" too long. It then required 1½ hours of grinding with No. 320, a large part of the time with overhang and W strokes to get the R.C. down to 8.959" again. I then changed to No. 400 grit with the corrector still on top and found the same thing, but less pronounced. The R.C. increased to 8.961" in the first 15 minutes, stroking C/C. It required almost an additional hour of grinding, some with overhang, to reduce the R.C. by 0.003" down to design value. Somewhat later, I found that I was slightly shorter than my target value while still grinding with No. 400 grit, and changed to tool on top to get it back again. The R.C. went from 8.955" to 8.9625" in 15 minutes, following which it required another 1½ hours with the corrector on top to get the R.C. back down to 8.9573". Note that in this case a change of abrasive was not involved, and this should be kept in mind when reading the subsequent section on a theory about wear rates.

The conclusion reached from the above is that a change from a coarser to a finer abrasive results in an unexpectedly large and sudden change in R.C.; and that it is a very slow process indeed, even with overhang, to deepen the corrector curvature with the corrector on top—but a very fast process to flatten the curve with the tool on top.

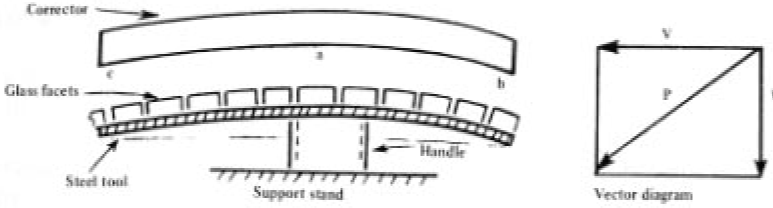
The effect of grit size is probably due to the larger size of particles cutting more glass in the center than the edge, thus making a quasi-conical surface rather than a spherical surface. Then the next smaller size grit doesn't grind at all in the center at the beginning, but rather averages out the curvature. It might be mentioned that with ¼" balls on the spherometer feet, it is hardly likely that the measurements would be affected much by the pit size with the change in abrasive grade. It is also of interest that during the unexpectedly long time grinding with the corrector on top, and to balance out the effect of having overshot the mark when the tool was on top, and to balance out the effect of grit size changes, the center thickness changed from 0.7460" to 0.7120", or 0.034". This could be very important wherever thickness is a critical measurement, and luckily I had another 0.054" of thickness remaining for finishing the convex which had already been rough ground down to No. 220 grit and to approximate design R.C.

Take the case of finishing the convex. Generally similar experience resulted during the fine grinding. With the convex corrector on top the R.C. increased very rapidly indeed, whereas with the tool on top the R.C. decreased very slowly. It is estimated that on a given grade of abrasive in this general range of grades, the ratio in rates of change of R.C. was approximately 5 to 6 times greater when the corrector was on top. I also noted that, just as in the case of grinding the concave, changing from a finer to a coarser abrasive (as was done a couple of times to accelerate the wear) the R.C. decreased abruptly, while in making the change from coarse to fine, the R. C. increased abruptly. It will be understood that in all three cases the R. C. is the apparent curvature as measured from the surface of the corrector blank.

A Theory about Wear Rates. In addition to the above-discussed effect of particle size change, the above observed wear rate differences also suggest a theory for wear rates, on steep curves at least, that differs from the explanation advanced in some writings such as, for example, that appearing in *A.T.M. I,* page 347. It would seem important at least to be aware of the following presentation since, as the final R.C. is being approached, it might be unwise, and even risky, to use an offset stroke to hasten reaching final R.C. So the lens grinder should be aware of how R.C. will change with the corrector on top vs. the corrector below during the final stages, planning the work so that thickness will not turn out to be too thin.

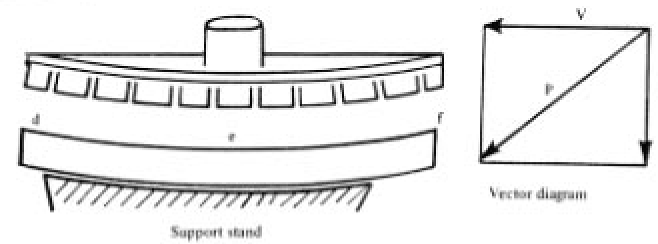
I illustrate the theory by two schematic sketches showing the corrector and tool slightly separated, and a vector diagram showing the direction of vertical and horizontal forces resulting from pushing the material by hand during the grinding process.

Corrector on Top



Corrector shown separated from facets for the sake of clarity.
P = direction of push by hands.
W = weight of corrector plus hands.
V = horizontal force resulting from hands' push.

Tool on Top



Notes same as above except that W = weight of tool plus hands.

Note that the effect of the horizontal vector gets greater, and the vertical vector less, the flatter the push from the hands, viz. a high barrel to walk around versus a low barrel. In the upper diagram, the vertical force will result in wear over the entire area from *c* to *a* to *b* with somewhat more wear at the center area *a;* but the horizontal force will result in wear at the edge area, none whatever at the center where it would be tangent to the curvature. Thus the vertical force tends to deepen the curve and the horizontal force tends to flatten it, *and they offset each other.* The net effect will depend on which of the two forces is greater. On a steep curvature the horizontal force could result in more flattening than deepening even with the corrector on top, and may explain why it is difficult to deepen a steeply curved lens with C/C strokes.

With the tool on top and applying the same reasoning, the vertical force will flatten the curvature and the effect will be somewhat more rapid than the deepening with the corrector on top, due to the greater weight of the tool. But again the horizontal force will have no effect on center wear where the vector is tangent to the curvature, and will have its greatest effect in the outer areas. Thus in this case the two forces *complement* each other and result in rapid flattening of the curvature.

Considering both of the above cases, it is clear that it becomes very difficult indeed to deepen the corrector on the concave side with C/C strokes, and my experience indicates that it is quite difficult even with overhang, particularly when pushing the strokes at a flat angle on a high barrel.

In the case of the convex side of the corrector, a similar argument can be advanced to show how the horizontal force always tends to flatten the curvature. With the tool on top, its deepening effect is being offset by the flattening effect of the horizontal force; but with the corrector on top, the two forces both tend to flatten the curvature.

Scratches. Many amateurs grinding Maksutov correctors apparently have had trouble with scratches developing during fine grinding and polishing. In my experience this is due to one, or two, or all of three causes. These are:

a) Fine chips of glass breaking from feather sharp edges of the glass facets on the tool (or from failing to keep a bevel on the edges of the corrector itself). Grinding bevels on all facets periodically with a sanding disc in a hand drill as previously mentioned should minimize scratches from this cause.

b) Impurities in the fine grades of abrasive or in the polishing agent. Three times I ground through No. 600 grit without any trace of a scratch, and subsequently in two of the three cases a multitude of scratches followed the use of No. 305 emery (Edmund Scientific). The first of the two times I ground for an hour before looking at the surface and I attributed the scratches perhaps to incomplete clean up at the start, or to carelessness. So I scrubbed very meticulously, reverted to No. 400, followed by No. 600 (without scratches) and repeated the No. 305 emery. This time I examined after 10 minutes and again there were scratches! Then I made a preliminary examination of the suspect No. 305 by putting a small amount in a glass phial with water, shaking it up and decanting the surplus water. Then I shook it up again and slowly rotated the phial at a steep angle. I immediately noted larger particles adhering to the sides of the glass, indicating contamination. The visible particles might have been agglomerates, but K. D. Smith took a sample for microscopic examination and reported that there definitely was contamination with an abrasive of about No. 400 grit size.

c) I have heard of folks who had scratches occur while removing the corrector from the tool or from the lap when it was slid completely off. I successfully avoided scratches from this source in the following ways. When working on the concave side, I placed a waxed piece of board at the proper elevation alongside the tool, and then the corrector was slid off the tool in such a fashion that the edge of the corrector touched the waxed board when the opposite edge was about 1½" from the edge of the tool, with the *beveled* edge of the corrector riding on one of the facets of the tool at the breakaway point.

On the convex side I slid the corrector off the tool to about the same relative position, and then lifted quickly. As above, this caused the beveled edge of the corrector to pivot on one of the outer facets, making a clean breakaway instead of a sliding one.

Employing these three anti-scratch techniques, I was fortunate in completing my corrector without any visible scratches on either side.

Miscellaneous.

1. The wear rates using different abrasives may be of interest, and the results compared with what others have reported. Keep in mind that these data depend on various factors peculiar to the individual case, such as length of stroke, strokes per minute, degree and extent of time with overhang, weight of tool when on top, amount of hand pressure, etc., etc., and probably height of barrel or table on which the work is mounted. Here is what my data show (values picked from a smooth curve drawn through the results with the various abrasives):

Grit size	Change in center thickness *mils per hour.*
No. 60	37.0
No. 120	10.5
No. 220	7.5
No. 320	5.2
No. 400	3.3
No. 600	2.0
No. 305 emery	less than 1.0

2. Hard water ring. One evening when I was washing my fully polished concave surface with tap water prior to drying it and taping it for protection while the convex surface was being finished, the phone rang while the lens was still wet. I put it down concave side up and forgot it for perhaps 20 minutes. I then noticed that there had been a pool of water collected in the center 1½" in diameter and that it had dried, leaving a deposit of hard water salts. I tried soap and water, vinegar, extended thumb rubbing with distilled water, the same with vinegar, an ammonia solution, gasolene, toluene, iso-octane and acetone. In reflected light the ring could still be seen! A chemist friend said that it was probably etched into the glass and that it was probably calcium sulphate rather than the vinegar-soluble calcium carbonate. However, I decided that if it was really etched into the glass, it would have to be ground or polished out. It turned out that ¼-hour polishing with cerium oxide completely cleared up the situation. Actually it would not have mattered since the "spot" to be aluminized in due course on the opposite side would have been of larger size than the deposit, but aesthetically I wanted the ring removed.

3. Viewing the surface for pits or scratches. The concave surface was first fine ground and polished while the convex was at the No. 220 stage. Surface blemishes on the concave could readily be seen both by reflected and transmitted light. Then the concave was taped with Mystic tape, a well-known product. This tape wasn't very satisfactory for two reasons,—it tended to come loose when in water; but more importantly, the backing on the tape was white, making it impossible to see any blemishes on the convex surface. I then tried "Stix-on" tape, available in many hardware stores, and found it more resistant to water, and since it has a dark backing surface, blemishes could readily be seen.

4. Polishing. There is nothing particularly significant to report on the polishing. The laps were make by heating pitch squares, made with an Edmunds rubber mat, to a molded thermal cement surface poured into a circular tin can of slightly sub-normal diameter. Both surfaces of the corrector polished out evenly to the edge in less than 30 minutes, using cerium oxide with short C/C strokes—this indicated that the final stages of fine grinding had produced a good spherical surface free from pits. When the channels on the convex lap began to close up, I found that a 3/16" rat tail wood saw, carefully used, cleaned them out beautifully. On the concave lap the rat tail saw couldn't be used, but a knife blade, heated in a butane torch, was used to cut the channels wider, and the lap was then warm pressed to reduce the ridges left by the cutting. This was quite satisfactory.

In conclusion. I am almost ashamed to admit how long it took me to finish my corrector lens, and my consolation is to know that I have a lens exactly to specification and with no visible imperfections under a magnifying glass. Both R.C. values are within 5 units in the fourth decimal place; thickness is only 6 thousandths below design value and wedge variation around the circumference is plus or minus 1½ ten thousandths. But for those interested, here it is:

Concave.	Grinding 35½ hours,	Convex.	Grinding 46½ hours,
	Polishing 9 hours,		Polishing 7 hours,
	Total 44½ hours.		Total 53½ hours.
			Grand total, 98 hours.

This is actual work time on the lens and does not include an untold number of hours spent in thinking and planning as I went along; preparation of spherometer charts and running off innumerable square roots to the fifth decimal place on an electric computer; writing up my notes (I doubt if anyone made a more detailed set of step-by-step notes on their Mak corrector—an offshoot of my research background!); charting results; and drawing graphs to see visually the progress being made. My wife insists now that I can't do the simplest chore around the house without making a graph to show the progress of the work! I would estimate that all of this fringe work, to say nothing of the time making auxiliary rigs and taking measurements, would be at least another 100 hours—perhaps another 200 hours. But how does one measure time against the pleasure and satisfaction of a job that you know is well done?

PARABOLIZING LARGE MIRRORS

by A. Mackintosh

Anybody who has made an f/4 or f/5 telescope knows the difficulty in parabolizing the mirror. In the case of a 4" or 6" mirror the job has to be done on a full-sized lap because sub-diameter laps are likely to be too small to handle easily; using a full-sized lap with the mirror on top, the TN finds that he has to use absurdly exaggerated strokes even to get the mirror to depart from a sphere, and has to continue to use those strokes to get full correction. In the case of an 8" mirror, sub-diameter laps are possible to handle, and 10" or larger are almost invariably parabolized with sub-diameter laps. In the latter case, the TN is likely to find himself scrubbing away at the sphere for hours without any appreciable change taking place in the appearance of the mirror under the Foucault test.

A.T.M. I is mostly concerned with mirrors of around f/8 and it is surprising that the technique of handling large mirrors of short focus is not dealt with in greater detail in *A.T.M. II* or *III*. A 12" or 16" f/8 Newtonian is little short of a monstrosity and almost all amateurs who plan a large telescope go for a shorter focal length in order to have a better chance for a steady mounting for these large telescopes; this applies also to both Newtonian, compound and catadioptric telescopes. Those who do make large instruments of long focal length must be prepared to make a mounting for them which weighs a couple of tons or more. Apart from good engineering design, sheer weight of metal plays quite a large part in steadiness for large instruments, and nowadays weight of metal is likely to result in a light bank balance.

Most of us have made a 6" f/8 or thereabouts and well remember that parabolizing took a comparatively short time—anything from half an hour to two hours, depending on our experience and skill. Why should the large short focus jobs take such a long time?

Comparatively few people have any idea of the amount of glass to be removed in parabolizing. *A.T.M. I* states that we have only to remove a few millionths of an inch in turning a sphere into a paraboloid and leaves it at that; this is perfectly true for a 6" f/8, but short focus telescopes are a different tale. I was talking to a fairly experienced amateur a short while ago who was working on a 12½" f/5 and he was happy to think that only a few millionths of an inch of glass would have to be removed, until I showed him that he would have to get off very nearly 1/10,000th of an inch for full correction.

We all know that $r^2/2R$ is an approximate formula for the sagitta of a sphere and some of us know that the accurate formula for the sagitta of a sphere is $S = R - \sqrt{R^2 - r^2}$, and that the accurate formula for the sagitta of a paraboloid is our old friend $r^2/2R$. The difference in the results of using these gives us the amount of glass to be removed in parabolizing.

The tables at the end of this article are worked to one millionth of an inch for all the usual sizes of amateur telescopes. Table I gives the sagitta for the sphere, Table II for the paraboloid, and Table III the difference between the two.

It will be noticed that the paraboloid is shallower than the sphere and this is contrary to our usual ideas as we generally deepen the sphere to a paraboloid for convenience in working—it simply means that the sphere and paraboloid are tangent at the edges of the mirror. If we move the paraboloid down by the amount of the difference, we shall have the sphere and paraboloid tangent at the center, and if we move it a little further, we shall have it tangent somewhere between the center and the edge—the condition where we wear away the sphere to the paraboloid with the least removal of glass. As this shift only amounts to approximately .0003", even in the case of a 16" f/4, it will make no significant difference to the mathematics and will merely move the center of curvature of the mirror by .0003", an amount which is negligible.

Table I. Sphere $S = R - \sqrt{R^2 - r^2}$

f/	4	5	6	7	8	10	12	15
6"	.093842	.075047	.062527	.053589	.046886	.037506	.031253	.025002
8"	.125122	.100063	.083370	.071451	.062515	.050008	.041671	.033336
10"	.156403	.125078	.104212	.089314	.078144	.062510	.052089	.041670
12"	.187683	.150094	.125054	.107177	.093773	.075012	.062507	.050003
16"	.250245	.200125	.166739	.142903	.125031	.100016	.083342	.066671

Table II. Paraboloid $S = r^2/2R$

f/	4	5	6	7	8	10	12	15
6"	.093750	.075000	.062500	.053571	.046875	.037500	.031250	.025000
8"	.125000	.100000	.083333	.071429	.062500	.050000	.041667	.033333
10"	.156250	.125000	.104167	.089286	.078125	.062500	.052083	.041667
12"	.187500	.150000	.125000	.107143	.093750	.075000	.062500	.050000
16"	.250000	.200000	.166667	.142857	.125000	.100000	.083333	.066667

If we examine the tables, we find that the amount to be removed in parabolizing a 6" f/8 is 11" x 10^{-6}; at f/10 it is only half this amount, and at f/12 to f/15 the mirror may be left spherical. Let us take the case of a 12" f/5, though; here we find that the amount to be removed is 94" x 10^{-6}, or very nearly .0001". This means that the depth of removal is very nearly 8 times that of the 6" f/8, and when we consider that the 12" has 4 times the area of the 6", we begin to think. Of course, the maximum difference does not exist all over the mirror and, without going into complicated integration to find out the exact ratio, let us assume that the area increases the amount twice; this gives 16 times the amount we have to remove for a 6" f/8. In the case of a 16" f/4, the amount is approximately 40 times that of a 6" f/8.

Table III. Difference $D = [R - \sqrt{R^2 - r^2}] - r^2/2R$

f/	4	5	6	7	8	10	12	15
6"	.000092	.000047	.000027	.000017	.000011	.000006	.000003	.000001
8"	.000122	.000063	.000036	.000023	.000015	.000008	.000005	.000002
10"	.000153	.000078	.000045	.000028	.000019	.000010	.000006	.000003
12"	.000183	.000094	.000054	.000034	.000023	.000012	.000007	.000003
16"	.000245	.000125	.000072	.000045	.000031	.000016	.000009	.000005

We are now beginning to see why the big fellas take so much longer to deal with than a 6" f/8, and it appears that we shall spend a very long time on them if we tackle the parabolizing with pitch laps and rouge. The situation is not quite so bad as it appears because sub-diameter laps have a strong local action if they are used with considerable weight on top of them; even so, we shall do well to use every technique at our disposal to shorten the time of working, because pitch laps have a nasty habit of deteriorating after prolonged use.

What to do? Well, we can begin parabolizing at the end of fine grinding, but this requires exceptionally good judgment of when to stop, otherwise we shall land up with a hyperboloid which will be even more difficult to deal with than the sphere. In this respect, Mr. K. D. Smith's and Mr. A. J. Blackwood's tables of wear rates should be helpful.

However, the best way to tackle the problem is probably to use coarser abrasive than the usual polishing agents when beginning polishing after fine grinding. These can be used either on pitch or plastic laps and will bring up sufficient polish to read a figure under the Foucault test. Most of the parabolizing should be done in this way and only the final stages should be done with rouge on a pitch lap. In this way, a good optical finish will be obtained in a reasonable time, provided that care is taken to work all the surface of the mirror at the end while bringing the final touches of the parabola to book on a new pitch lap.

The spinning method of figuring, as written up by Mr. Onions in this chapter, can also be used effectively. In this case, the edge zone should be concentrated on because maximum action will result in this area while action will be minimized at the center of the glass. Of course, this also means that a great deal more glass will have to be removed and this may offset the advantage gained in speed of action.

REMOVAL OF OVERCOATING
by H. J. Watson

To remove overcoating, the method I use is to pour a caustic solution on the surface and let it set until the caustic penetrates the quartz overcoating which is porous. The amount of time will vary from surface to surface due to differences in the coating. I do it in the sink, face up, and as soon as the aluminum is dissolved, quickly rinse the surface with water. A vinegar rinse can also be used to quickly neutralize the caustic. If care is taken to rinse all the caustic away, no harm will come to the optical surface. Due to the porous nature of the overcoating, any solvent of aluminum can be used—I have tried HCL and it works, but it is a bad acid to have around the shop where you have good tools, etc. As far as I am concerned, quartz overcoating has value only in industrial applications where mirrors in certain instruments and setups are out in the open and have to be cleaned from time to time. In a telescope there is no need for it and aluminized mirrors can be cleaned if some care is used. One fairly safe method is to soak the dirty mirror in a detergent and water solution for a half hour or so and so to loosen any corruption, then rinse under the tap and finish with a distilled water rinse—if warm to hot (about 180° F.) distilled water is used, the drying is speeded up. The mirror should be air-dried, face down, on a clean cloth or towel (not a bath towel) with one edge blocked up about a quarter of an inch or so to allow air circulation. The distilled water should prevent any water marks in the drying. If there is still dirt or stains on the mirror, it can be dunked again in detergent and water solution and gently dabbed at with a wet cotton ball under water. To find out how much pressure you can use without damaging the mirror requires some experimentation. For a regular Newtonian primary, try the dabbing first in the center area of the mirror where it is masked by the diagonal—not the edge—thus if too much pressure is used, the damage is in a relatively unimportant area of the mirror. If any rubbing is done, cleaning a mirror is a risky job. Cleaning mirrors should be kept to a minimum and never attempted until the coating is at least two months old.

TURNED EDGE
by A. J. Blackwood

Writers on telescope making discuss "turned edge" as the bane of the amateur telescope maker, and offer some precautions for minimizing the chance of getting it. *A.T.M. I,* page 291, quotes Ritchie as forestalling turned down edge by "diminishing the area of the squares around the edge of the tool by trimming their edges." Porter supports this by saying, "It is O.K. Have done it frequently to advantage." This is a correct statement but little explanation is offered to support it. The question arises that if any trimming of the edges of the outer squares is done, why not eliminate the outer squares entirely? In my opinion this is desirable, and it is successful then only if the mirror or lens is in the upper position. Many people apparently hold to the opinion that if sub-diameter or over-diameter tools are used, the smaller (tool or mirror) should be worked in the upper position. My experience does not support this view.

On page 370 of *A.T.M. I* a plausible explanation for turned edge is given, blaming it on the push-and-pull being applied too high above the plane of the work during grinding and polishing, such as would occur with a long handle on the tool. The paragraph reads as though the mirror is on the bottom in all cases being discussed. I would agree with this, but *only* if the mirror is in the bottom position. It should have little, if any, effect with the mirror on top.

Texereau passes off turned edge with a simple statement (page 130 of the American paper-back edition of 1963), "A defective edge often results from unconsciously applying pressure at the edge of the tool, or from too long a stroke, or too soft a lap." The implication is that one must avoid these situations. The second and third precautions are controllable, viz. always use a short stroke, center over center, while striving for a spherical surface, and test your pitch for proper hardness such as Texereau describes on page 68. But if turned edge is due to the first factor, how does one avoid this "unconscious application of force at the edge of the tool"? A good question.

Some time ago I worked four successive surfaces, the last one being a 9″ spherical mirror for my Maksutov, and achieved a high degree of polish without any evidence whatever of turned edge on any of the four. The Ronchi lines were sharp and parallel right to the very edge, even when focusing down to three lines over the entire surface of the mirror. My system, and an accompanying theory to explain the results, are as follows:

Procedure. Do all fine grinding, No. 600 and finer, and all subsequent polishing, with a sub-diameter tool in the ratio of about 9:8, and work with the mirror or lens in the *upper* position—never in the lower position. The mirror surface must be really spherical and free from turned edge before polishing is begun, and this is assured if extra time, say double the usual recommended time, is given to the last two stages of fine grinding. I like No. 600 followed by No. 305 emery, applied with an artist's brush, without stopping the push-and-pull strokes. To assure a good spherical surface, use short, center-over-center strokes in all of the above, always with the mirror on top.

Use fairly hard pitch, tested as described by Texereau, or during the melting let a drop fall in cold water and press it between the teeth. If steady slow pressure for, say, 5 seconds results in appreciable penetration without breaking, it is all right. Thin sparingly with turps if the pitch is too hard; continue heating to evaporate the natural solvents if it is too soft.

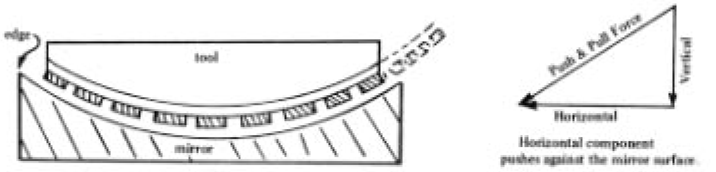
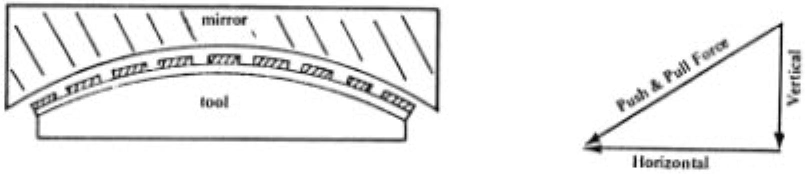


Fig. 1 Tool on top of mirror (tool sub- or over-diameter)

Theory. Fig. 1 shows a situation with a sub-diameter (or over-diameter) tool on top during the final stages of fine grinding or polishing. A vector diagram is shown at the right, indicating the forces at work and the direction of these forces (resolved into vertical and horizontal components), during the push-and-pull strokes. By definition, so to speak, the vertical forces, consisting of the weight of the tool plus the vertical component of the push-and-pull by the hands, are evenly distributed over the working area, and no surface is subject to "unconscious pressure." Therefore these vertical forces do not contribute to any tendency to turned edge.

However, the horizontal component of the push-and-pull force as indicated by the vector diagram tells another story. At the center of the mirror the horizontal force is tangent to the surface and is producing no rubbing pressure or wear at this point. Progressing from the center to the edge of the mirror, the horizontal force is applying increasing pressure on the mirror surface and reaches a maximum at the very edge. Here indeed is the application of "unconscious pressure" at the edge of the mirror! The edge of the mirror tends to wear more rapidly and results in the familiar "turned down edge." If this occurs during fine grinding, it is unlikely that any amount of subsequent polishing, even with the mirror on top, would completely eliminate the condition.



Horizontal component tends to lift the mirror off the lap and hence does not cause undue wear at the edge.

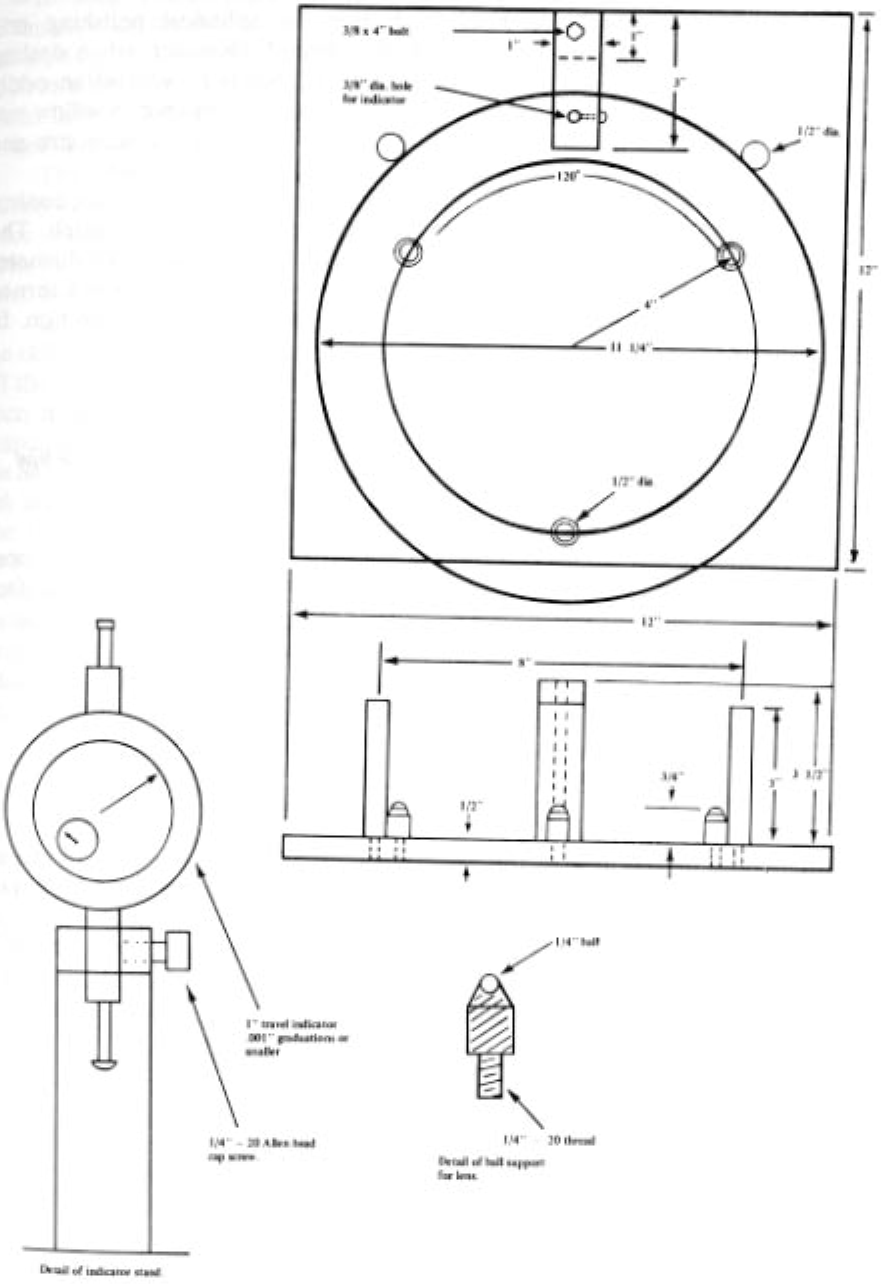
Fig. 2 Mirror face down on sub-diameter lap

Fig. 2 shows the mirror in the upper position, and has the force vector diagram at the right. The vertical forces, as in the above-described case, do not contribute to any turned edge tendency. But note what has happened to the horizontal component of the push-and-pull force. Again, at the center of the mirror this component is tangent to the surface and no wear is taking place at this point due to horizontal forces. However, from the center progressing to the very edge, this horizontal force is tending (on the trailing side) to lift the mirror off the tool, and on the leading side the pressure is diminishing negatively toward the edge and is creating a vacuum rather than a pressure on the edge of the mirror. Nothing in this situation to cause turned edge!

Note in both figures how the sub-diameter tool inherently reduces pressure on the mirror over what it would be for a full-sized or over-sized tool. It can also be visualized that if handles are used on the mirror or tool, as referred to in *A.T.M.* articles mentioned above, the horizontal forces are increased by the leverage effect, and the above tendencies are exaggerated. It might appear that a handle on the mirror might be an advantage; but a handle on the tool might be a serious handicap insofar as the possibility of turned edge is concerned.

DRAWINGS FOR AN EDGE-MEASURING JIG

by J. P. Davis



MAKING FIGURING LAPS
by Ferdinand I. Baar D.P.M.

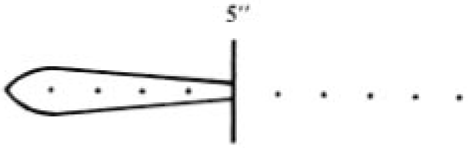
The making of pitch laps for spherical polishing and parabolizing is well documented. However, when dealing with compound systems such as the Maksutov and Schmidt, very often oddly shaped laps are called for. It is quite difficult to cut out, for instance, 6 willow leaf patterns, or wedge patterns, or petal patterns, and keep them the same size and shape so as to control the "figure" being created on the glass surface.

In my experimenting, I tried to devise a system that would be clean, control the thickness of the pitch, and be able to duplicate patterns of the pitch. The answer proved to be quite simple. Let us take a hypothetical case: a 10" diameter surface is tested by the Foucault test under autocollimation and shows a turned down edge, 1" in from the edge, and a moderate amount of undercorrection. In profile, using the Everest pinstick method, it shows:

Fig. 1

It is obvious that the polishing action has to be greatest at the 1" zone, taper to 0 at the edge with a lessened wear pattern graduating to the center. If the surface is then:

Fig. 2.



we duplicate it on the bottom and have the approximate shape of one of the six shapes of pitch needed. Of course, the actual shape will depend on the arbitrary vertical scale of the graph, and this has to be left to the experience of the operator.

At this point, using a compass, a series of concentric circles are drawn of 1" radius, 2", 3", 4" and 5" and, using the 5" setting, the six points on the circle are laid out in the classical manner. On this a petal leaf, or whatever shape is needed, is then laid out to scale:

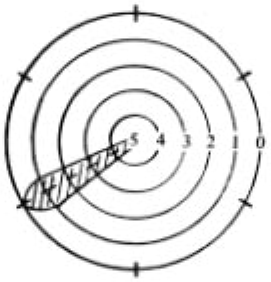


Fig. 3.

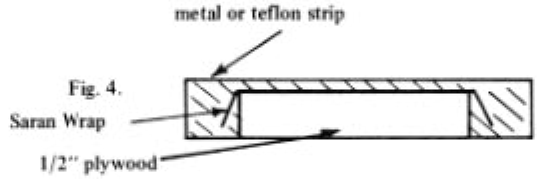
This is then traced twice on a piece of ½" plywood and cut free, leaving two wooden templates. They are edge sanded together so that they are reasonable duplicates. We now take two strips of flexible metal (1/32" aluminum or some such) 8"–10" long. The difference between the width of the strips and the ½" thickness of the plywood determines the thickness of the pitch, so 5/8" width will give 1/8" thick pitch. 11/16" will give 3/16" thickness, etc. In the ease of a reverse curve, such as a petal lap, the petal template can be placed on a plywood base and the metal held to the curve with a number of brads; alternatively, the metal can be tacked directly to the template.

The top of the wooden pattern is covered with a piece of Saran Wrap which is folded well over the sides. The two metal strips, well soaped, are then clamped in place, using clothes pins, and the form is ready for pouring. After the pitch has been poured, the whole is put into a refrigerator and left there until the second form has been poured and put into the frig.

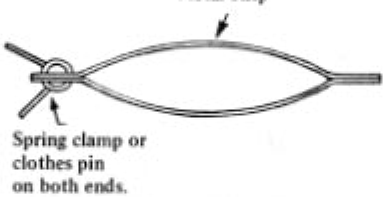
By this time the first form has stiffened enough so that it can be taken out; the clamps or clothes pins are removed, the metal strips fall off and the pitch is slid off the wooden form, being handled by the Saran Wrap. When all six shapes have been made and stiffened, the lap surface should be warmed and the six pitch shapes floated in a pan of warm or moderately hot water. They are picked up, using the Saran Wrap edges, and placed in position on the lap surface *with the Saran Wrap side uppermost.* Cover the Saran Wrap with another piece of Saran Wrap for separation insurance, place the glass surface atop of all this and apply sufficient weight for hot pressing (a couple of hot presses may be necessary for good contact). The Saran Wrap is then lifted off, polishing solution applied and a couple of cold presses should do the trick. It is clear that all of these operations can be done in stages at different times, or as one procedure. It is clean and shapes can be duplicated or changed as the need warrants. If teflon strips are available, then no separating medium such as soap is needed.

Side view

Fig. 4.



Top view



In the event of imperfect adherence of a pitch shape to the lap surface, a couple of touches of a small soldering iron will tack the pitch into place. A further refinement is to use a piece of plastic window screening, open mesh, available from Sears Roebuck, and hot press this into the pitch surface. On removal of the mesh, a pebbled surface is left on the surface of the pitch, allowing faster contact and polishing action.

FLEXIBLE POLISHERS
by Doug Smith

The James H. Rhodes Co. (48-02 29th St., Long Island City, N.Y. 11101) has for some time offered a plastic polishing material called "polyurethane bonded cerium oxide" or just "polyurethane" that has been applied in the optical industry as a fast polishing material used at high speed. Recently they made polyurethane available in half millimeter thick sheets, and it has been my experience that, made into flexible polishers, it is an excellent way to remove glass in figuring either steep surfaces or shallow aspheres, such as Schmidt corrector plates. Faced with the problem of figuring a convex ellipse with an f/1 surface, I found that flexible pitch or soft, solid pitch polishers worked very slowly on zones that polished out far from null. (The element was a focusing lens that could be tested by autocollimation.) Polyurethane with a cushiony backing was tried and it was found that with moderate effort the areas around a low zone could be similarly treated. To speed the process even more an annular polisher was tried, and it worked well with a slow spindle, to reduce a particular zone or set of zones. When irregularities had been reduced enough no longer to require drastic action, the same polisher was turned into a much gentler one, which was still flexible, by dabbing a piece of pitch, partially melted in a flame, onto the polyurethane and pressing repeatedly on the wet surface of the work. The resulting pitch surface had many hollow spots and extra stiffness from the plastic underneath, with light channels scratched in.

Other applications could be for fast polishing primary mirrors and for shaping Schmidt plates. The normal faceted pitch lap for a mirror could be given a coating of polyurethane by cutting out squares and sticking them onto the pitch by flaming lightly and then pressing. A petal lap might also be made of polyurethane with a flexible backing and later given a coating of pitch, with the added convenience that the petals could be cut out with scissors.

The backing for any such flexible polisher should consist of a solid substrate—wood, glass or tile—well beveled to prevent digging into the work by accident. The substrate should have nearly the same shape as the surface being polished. Onto this layer of foam plastic is stuck with pitch. I have found certain packing material that works very well, it has a texture coarser than foam rubber but finer than plastic sponge. A good thickness is a quarter to half an inch. Do not allow the melted pitch to soak into the foam. Hold it in place with a light weight on a piece of cardboard covering the whole surface so that the foam is not compressed. Let this cool completely before applying the polyurethane. The latter is done by heating a piece of pitch in a flame and dabbing it onto the foam. When there is an even layer, flame it very quickly, lay on the polyurethane and press immediately.

The disadvantage of using polyurethane is that is has a tendency to sleek, especially with Barnesite (use cerium oxide for best results) and it leaves more texture on the work. Always be prepared to switch to pitch for final figuring.

Chapter 2
TESTERS AND TESTING

A PRECISION FOUCAULT TESTER
by Allan Mackintosh

There is a widespread belief among TNs that it is not possible to make a precision Foucault tester without micrometer screws, precision ground ways, etc. In precision measurement there is what is known as the 10% rule—that our measuring instruments should be accurate to within 1/10th of the smallest dimension that we wish to measure. It is a very controversial subject, but the general consensus seems to be that some adepts are able to read the Foucault test to .01" and, therefore, under the 10% rule, out test setup should be accurate to within .001". Even if you do not consider yourself to be an adept, it is a comforting feeling to know that your test setup is much more accurate than you can read the test and that any mistakes that crop up are due to error of judgment and not to inaccuracy of the apparatus.

I have seen many Foucault testers, ranging from a common block of wood on a board to a very beautiful job made by a skilled machinist who must literally have spent more than 100 hours of work on it—the latter tester suffered from the drawback that the settings depended on micrometer screws in both directions and it was slow in altering from center to edge to the 70% zone, and equally slow in reading all the other zones. I have also seen two testers produced commercially; the less said about these, the better because the "ways" were made out of bent tin, the screw adjustments were chiefly remarkable for the play in them, and error at the knife-edge was approximately 1/16" in one and 1/32" in the other! A block of wood set up with a Barr scale is far more accurate than either of these commercial frauds which cost in the neighbourhood of $25—a lot of dollars thrown down the drain.

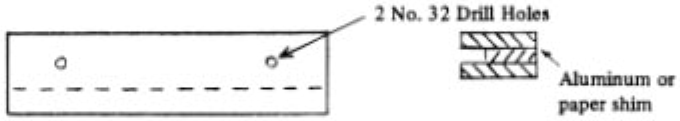
In the January 1956 issue of *Sky & Telescope* there appeared a short account of a new approach to the problem by Mr. Kelvin Masson of St. Louis, Mo. Mr. Masson's tester depends on a differential between the distances of three points and consequent amplification of the movement of the knife-edge for reading purposes. Mr. Masson was very modest about his setup, made no claim for great accuracy and said that the greatest amplification reasonably possible was from 4 to 6 to 1.

It occurred to me that a slight modification of his design would result in an amplification of 10 and a tester of high accuracy, capable of reading to .001". I set about making it and had it finished in about two weeks. At that time I was living in an apartment and did not have the tools that I have now; the only "machine" tool I had was a ¼" electric hand drill with a clamp drill-stand—even this was not necessary for the job, though it was convenient—and the whole setup could have been made with hand tools only, though I must confess that I am not a hand tool enthusiast.

I bought two pieces of ground flat steel, 1/8" x 1½" and 1/8" x ½", both of them 18" long and costing under $5 for the two. I also gathered in two 1/8" x 1" commercial dowel pins and two 1/8" commercial jig bushings; in the last resort the dowel pins and bushings can be bought for a modest price from any machinists supply house, or any good hardware store will order them for you. Drill-jig bushings in the smaller sizes are generally .001" oversize from nominal and dowel pins are about .0002" oversize, so that a good swivel fit is assured; if the fit appears to be rather tight, some treatment with 305E in oil will put matters right but be careful that you get no perceptible side-play in the fit.

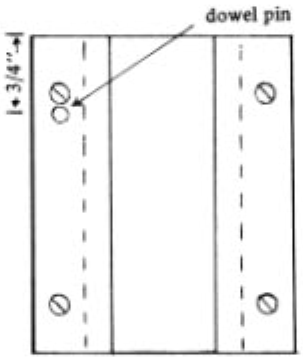
For the main slide, saw three 3" lengths from the piece of ground steel 1½" wide and saw two of them down the middle so that you have four pieces 3" x 3/4" x 1/8" and one piece 3" x 1½" x 1/8". Clean up the rough edges with a file and carefully remove any burrs remaining. Incidentally, in order to avoid marring ground surfaces, my favorite method is to line my vise jaws with about 10 thicknesses of newspaper, it is soft and grips excellently. Next saw two 3" lengths from the ½" x 1/8" ground steel, clean up the saw cuts and remove burrs as before.

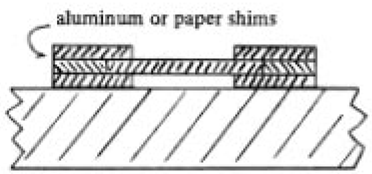
Sandwich one piece of ½" steel between two pieces of 3/4", thus:



Clamp together and drill through with a No. 32 drill, countersink for No. 4 wood screws; take them apart and re-drill the holes in the ½" x 1/8" pieces only with a No. 28 drill.

I used a 10" x 18" piece of 3/4" plywood as a baseboard and assembled the slide on the board, as below:



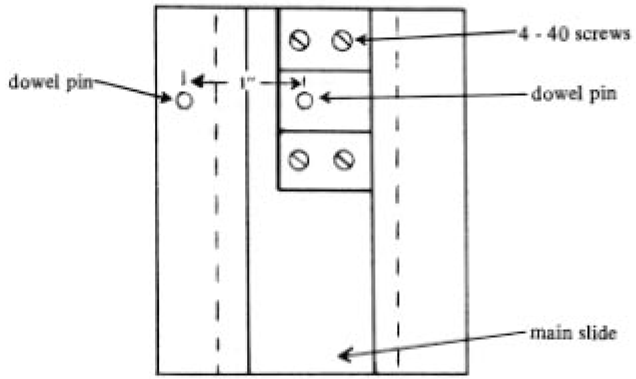


In order to get clearance for the slide, I raided my wife's kitchen and made shims out of aluminum wrap—this is .001" thick and is ideal, but paper would do as well. As the holes in the ½" pieces were larger, I was able to press in the sides of the slide with my fingers before screwing down, and so got a smooth close fit for the slide.

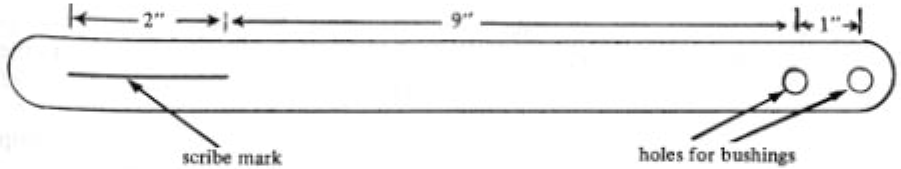
I next prick-punched the position of the dowel pin 3/4" from the end of the left-hand runner, drilled with a No. 31 drill and carefully hammered in the dowel pin; this has to be done gently in order to avoid upsetting the assembly.

I then sawed three 3/4" pieces from the ½" steel, cleaned them up and drilled two of them with a No. 31 drill for 4-40 round-head machine screws (any other small machine screws that you happen to have handy will do), placed them on the slide as below, carefully marked the holes and drilled and tapped the main slide for the screws.

I was fortunate in having some .0004" shim paper handy but ordinary tissue paper would do as well. I assembled the cross-slide by clamping the three pieces side-by-side with one thickness of the shim paper, screwed up, marked the slide for the other dowel pin as shown, and got out the center piece with a screwdriver and brute force. I cleaned away the remains of the shim paper, greased the slide and found that I had a good slide fit with no side-play at all. I then drilled the cross-slide for the dowel pin and carefully pressed in the dowel pin with the vise in lieu of an arbor press.



Next thing to deal with was the lucite arm. Leaving the adhesive covers on both sides, I marked off the positions for the bushings, rounded off the ends and drilled for the bushings, as under:

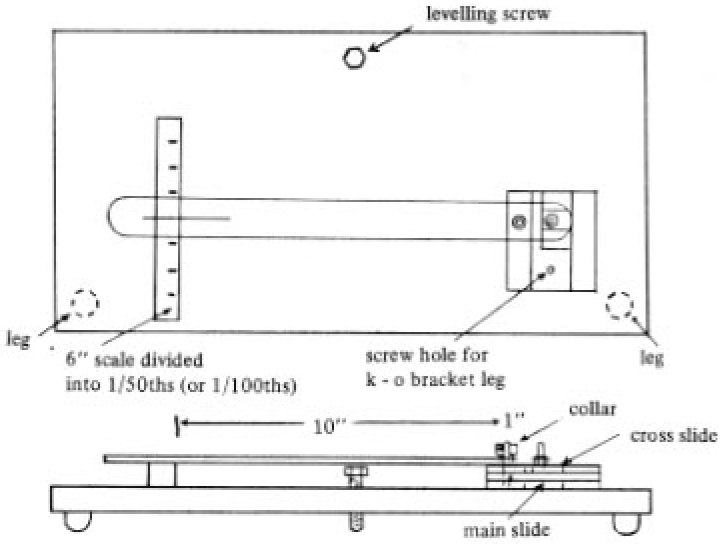


The bushings were pressed in. The drilling has to be done very carefully because if you have too much interference, the lucite will "star," if too little, the bushings will come out—if I had to do it over again, I would drill full size for the bushings and seal them in with epoxy. Having got the bushings in, I removed the covers, scribed a line on the lucite as shown and filled in the scribe mark with black.

This arm could equally well be made out of aluminum, but you would have to drill and file out an elongated hole and stretch a wire across instead of the scribe mark. This means more work but would get away from the fussy job of pressing into the lucite because the aluminum will stand much more stress.

All that remained to do was to make a strip of wood to bring up a 6" scale to the level of the lucite arm, and assemble it. The 6" scale is divided into 50ths and 100ths.

The finished job looks like this:



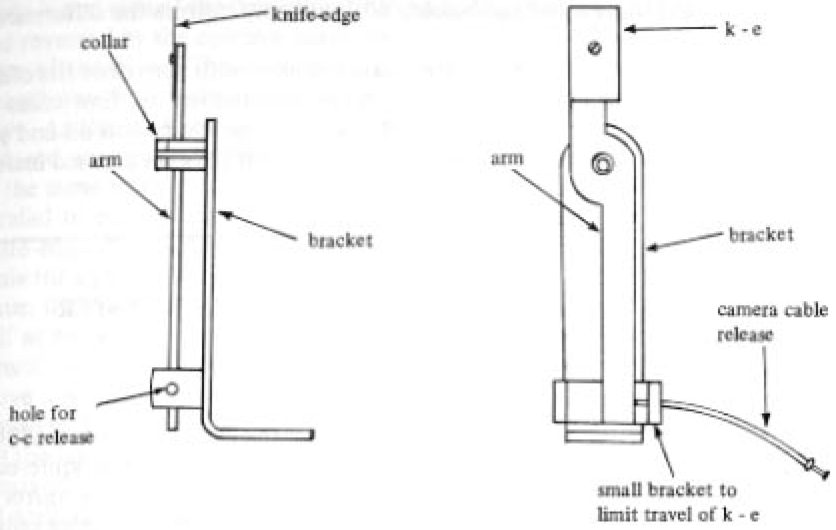
Owing to the difficulty in counting 1/100th divisions on the scale, I have mounted my scale with the 50th divisions uppermost. The scale is one that I picked up for 10¢ and is graduated in 1/100" on one side and 1/50" on the other. Every 1/50th on the scale represents .002" at the knife-edge, and interpolation to .001" is easy.

I have gone through the construction of this setup in considerable detail because the order in which you tackle the various operations will make a difference to the eventual accuracy of the tester.

Having got my .001" readings, the next thing to think about was my knife-edge arrangement because a precision setup of this kind does not lend itself to the old standby of leaning on one side of the table to bring the k-e across the cone of light.

I "acquired" another dowel pin and bushing, some 1" x 1/8" aluminum strip and bought myself a 24" camera cable release with a screw to lock the plunger.

I then made the setup shown below—I hope the drawing speaks for itself.



It can be made any height which is convenient. My k-e is about 6" above the baseboard because I like plenty of room for my nose and chin. A later improvement was to make the knife-edge setup into a coaxial job; this was done by putting the light source and an adjustable slit into a piece of household sink drain tubing (the chrome plated kind) and mounting a microscope cover glass on the top at 45° as a beam splitter—this was done after I had acquired a lathe.

The advantage of this setup is that it is not necessary to touch anything except the camera cable release to bring the knife-edge across; the locking screw on the release enables you to lock the k-e when you have got the doughnut and stare at it for as long as you like—a small spring opposing the cable release plunger allows return of the knife-edge. The differential arrangement on the arm allows a very fine setting on the knife-edge.

The first job that I tackled after making this tester was refiguring a 10" f/7.6 mirror. I found that after looking at a *steady* doughnut for five minutes or more, my eye became much more sensitive to minute zonal variations. I figured the mirror until it looked perfect, and then put my caustic tester onto it; I found that the maximum deviation from the theoretical paraboloid was 1/18th wavelength. Although I finished off the mirror to 1/22nd wavelength using the caustic tester, the preliminary figuring spoke excellently for the precision and sensitivity of the Foucault tester.

I thought at the time that this was largely luck, but later tests, in which I have adjusted my ideas of what a doughnut should look like to what the readings on the caustic tester tell me it is like, have shown me that I can figure to 1/15th wavelength or better every time without putting the caustic tester onto it. This is a convenience because, although the caustic test is very much more accurate, the Foucault test is quicker and handier during preliminary figuring.

If you want to be very fancy, you can put a small table of tangent effects on your baseboard. I have done so on mine but have never had occasion to use it because the effect is very small—amounting to only .025" between the extreme ends of the slide travel, and remember that this would be a r^2/R of .600", correction of a large and short focus paraboloid. With ordinary mirrors the difference is negligible.

One further comment is that when you are dealing with very close fits of the order of .0003" and smaller, it is well to remember that an oil film takes up appreciable room. Grease, believe it or not, takes up less room than oil and you will get better action in close fits of bearings and slides if they are greased instead of oiled.

A SINGLE-EDGE SLIT FOUCAULT TESTER
by Ralph K. Dakin

The usual Foucault test apparatus consists of a tiny illuminated pinhole separately mounted from the knife-edge (razor blade). Zonal measurements are made on the parabolic concave mirror by measuring the longitudinal movement of the knife-edge. When the edge only is moved, the knife-edge motion formula for the paraboloid tested at center of curvature is $d = r^2/R$, where r is the radius of the zone under test (as measured from the center of the mirror) and R is the central radius of curvature of the mirror.

It is very difficult to make a good "tiny" pinhole and even more difficult to get any light through it. The pinhole shows every bit of dirt on the operator's glasses or in his eye, making it very difficult to see fine zonal irregularities on the surface of the mirror. When a pinhole is used, it is usually necessary to make the zonal tests in a dark or semi-dark room.

Substantial improvement in light level can be obtained by replacing the pinhole with a slit, since even a short slit will let through a great deal more light than a pinhole. When a slit is used, it is essential that the slit and knife-edge be absolutely parallel to each other. Lack of parallelism will cause the shadows to cross the mirror at odd angles, giving the appearance of an astigmatic mirror.

The Foucault test device described here eliminates all of the problems of the pinhole and slit methods without any loss of sensitivity. In fact, zonal irregularities that are difficult to see or invisible with a pinhole test, show very plainly.

Fig. 1 shows the essential parts of the Foucault head:

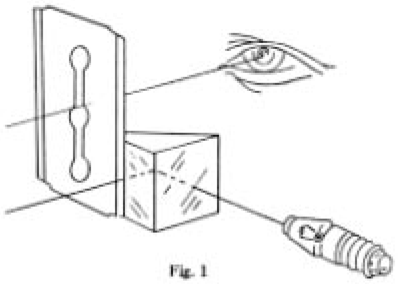


Fig. 1

The illumination from the light bulb is directed toward the mirror, using a small right-angled prism past the lower edge of the razor-blade. This edge of the blade is one side of the final slit of the tester. This sharp slit edge is reflected from and reversed by the concave mirror and returned (above the prism) past the *same* edge of the blade. The extended edge of the blade and its reflection (reversed image) now form a slit, whose width varies as the entire assembly is moved sideways. As the blade cuts into the return image from the mirror, the slit width is reduced, increasing the sensitivity of the test apparatus. Since the bottom and top of the same straight blade form the two sides of the slit, both sides will always be parallel to each other. Since the source, (bottom section of the blade) and the knife-edge (top section of the blade) move together, the zonal measurement formula for a paraboloid test at its center of curvature with this device is: $d = r^2/2R$. Thus, the measured difference in radius from the center to the edge zones is only half as much as when only the knife-edge was moved. Tests have shown that the sensitivity of making any zonal setting is doubled when source and knife-edge move together; therefore, there is no loss in final measurement precision. However, this does mean that the tester should be mounted on a slide that will permit the reading of 0.002" to 0.004" longitudinal motion of the assembly. An inexpensive 0.001" micrometer can be adapted as a measuring device or a 0.1mm interval scale can be used with vernier readings to 0.05mm (0.002").

Construction Details. The face of the right-angle prism that is just behind the razor blade should be ground with 400 to 800 carbo. A suitable small lamp is the Mazda No. 222 (with built-in condensing lens). The new stainless steel razor blades are very satisfactory since the fine edge will not corrode. Before the availability of these stainless blades, it was necessary to replace blades every few months even in my very dry basement.

The first instrument was built in the form shown in Fig. 1, but after getting an extremely deep hand cut on the badly exposed razor blade, a revised and improved model was built as shown in Fig. 2.

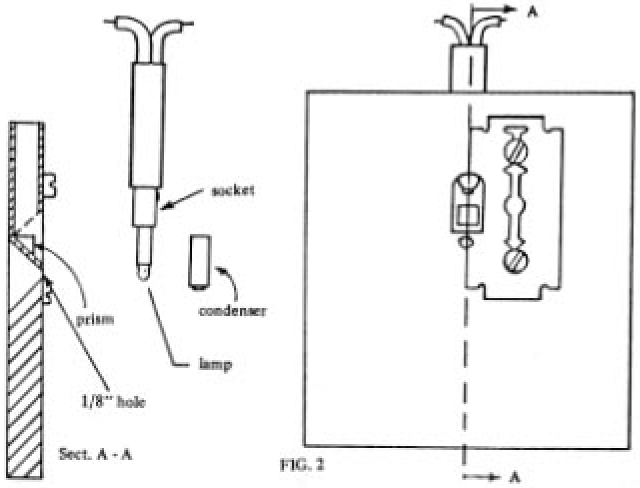


FIG. 2

The lamp and condenser assembly is dropped into a drilled hole in the upper edge of a 5/16" thick aluminum plate. The small (3/16") prism is cemented to a milled recess below and in line with the lamp hole. Below the prism a 1/8" drilled hole returns the beam from the mirror to the operator's eye. The front surface of the 3" square aluminum plate is painted with white paint and serves as a screen to help line up the return image from the mirror. The complete test assembly is now mounted on a "surplus" microscope moving stage unit with a metric scale, allowing readings to 0.05mm (0.002"). This particular stage is not rugged enough and an improved unit using a micrometer measuring head has been built. The distance between the center of the prism and the 1/8" hole is only ¼" vertically; thus there is no sideways displacement and the test is made with an effective slit length of about 3/8". This device was used to test a 12½" spherical mirror with a 30" radius of curvature without running into off-axis astigmatic shadows. This type of modified slit tester is mentioned in *A.T.M. I* in the "Miscellany" section under the discussion of the slit test (p. 380 in the 1935 edition) and also in John Strong's book, *Procedures in Experimental Physics* on pp. 75-77.

Small prisms are available from A. Jaegers and Edmund Scientific Corp., also a ¼" prism is available from Bausch & Lomb.

USE OF AN AUXILIARY TELESCOPE IN FOUCAULT TESTING
by Ralph K. Dakin

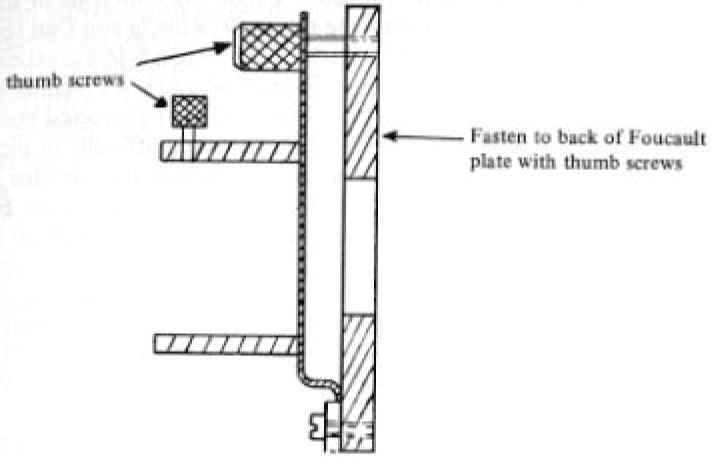
It is almost impossible to use Foucault testers on high speed or short radius of curvature mirrors because it is difficult to bring the operator's eye close enough to the knife-blade to accept the entire light cone. We unfortunate old-timers who are forced to use eyeglasses find it even more difficult to get the eye close enough to see the entire mirror surface.

By using a small telescope behind the knife-edge focused on the mirror surface, this problem disappears and the Foucault testing of mirrors becomes a real pleasure. It is important that an erecting telescope be used to avoid confusion in the shadow movement on the mirror. Without an erect image of the mirror, hills appear to be holes and vice versa, making it difficult to interpret zonal troubles properly.

My auxiliary telescope uses a small porro erecting prism system from a stereo microscope but there are several surplus systems that can be used. Binocular porro systems or the tiny unit from the 1 1/3x telescope listed by Jaegers could easily be modified for the job. One of the surplus low power telescopes with an erecting 90° roof prism could also be easily adapted.

My telescope has a long focus eyepiece (49mm) from a rifle sight, providing an extremely long, comfortable eye relief. Two interchangeable objective lenses are used: one with a focal length of 60mm for high speed mirrors and the other with a focal length of 163mm for slow-speed long focus mirrors. The telescope is mounted on an adjustable flexure plate fastened to an auxiliary plate, allowing fine

vertical tip adjustment to center the image of the mirror into the telescope field. Two thumbscrews provide easy removal of the telescope and mount assembly from the Foucault test head.



Auxiliary Telescope Adaptor

The use of an auxiliary telescope is only possible with a slit type Foucault test rig, since, with a tiny pinhole, there is just not enough light. The drawing shows the auxiliary plate with the telescope adaptor tube fastened to the adjustable flexure plate. The telescope fits into the adaptor tube and is locked in place with the thumbscrew shown at the top.

Using an auxiliary telescope behind the knife-edge permits the viewing and testing of the entire surface of short radius and high speed mirrors and also makes it possible to see fine detail on the surface of long radius and slow speed mirrors. Like the modified slit tester described earlier, once a mirror has been tested with this convenient accessory, it will be difficult to get along without it.

CAUSTIC TESTERS
by Allan Mackintosh

On getting my advance copy of *A.T.M. III* back in 1953, the chapter which most impressed me was Irvin Schroader's comprehensive and lucid account of the caustic test. I decided at once to tool up for this test as it immediately appeared that it was very much more precise than any other except, possibly, the Hartmann test and did not depend on personal judgment to any great extent. I have now built three caustic testers and possibly the methods I use for building them may be of interest. I should say at this point that if readers have not got the facilities for precision building and measurement of the testers themselves, it is far better to leave the caustic test alone because a faulty tester will give wrong measurements and will only serve to fog the issue.

Before beginning, it may be of interest if I state my criticisms of the other mirror tests normally used by amateurs—the Foucault, Ronchi and Dall tests. The Foucault test is, of course, much the most used, but it depends to a great extent on personal judgment and I have known three experienced amateurs reading a mirror one after the other to say that it was under-corrected, over-corrected and on the nose. Quite apart from judgment, there is the ever present difficulty of picking up the edge zone accurately (and if an error is made in picking up the edge zone, it throws all the rest of the readings out); I use the Everest method when Foucault testing, but although I think that the pinstick is much the best method for locating the crest of the doughnut, it is not accurate in picking up the edge zone—therefore I use a mask for this. If the edge zones exposed by the mask are wide, one can see the shadow creeping up and it is difficult to determine when the zones darken simultaneously; if the zones are narrow, the reading is masked by diffraction effects—I have never been able to arrive at a satisfactory compromise. With the Ronchi test, unless the wires are spaced to suit the mirror being tested, the test can show a spurious turned edge and, from the very nature of the test, it is no more accurate than the Foucault test. The Dall test depends on being able to judge correctly when a mirror blacks out, but I have always found that this is more difficult to do than to locate the crest of the doughnut; besides, the spacing of the lens from the pinhole in the Dall tester is critical and if there is any error in construction of the tester, an unknown error will be introduced which cannot be evalutated except by comparison with one of the other tests. Another difficulty that I have experienced with the Dall test is that the spacing between the ground glass, the light bulb and the pinhole is also critical—if wrongly spaced, a granular appearance of the image results which greatly increases the difficulty of deciding when the mirror blacks out.

When I had completed reading *A.T.M. III*, I went back to Schroader's chapter and read it through again two or three times in order to get it well into my head. I noted his remarks about weight lending smoothness to the motion of the stages and decided that my two top stages would be made out of 3/4" thick steel—in the other two testers I used ½" steel and found that it was quite heavy enough. After getting the chapter into my head, I sat down and thought.

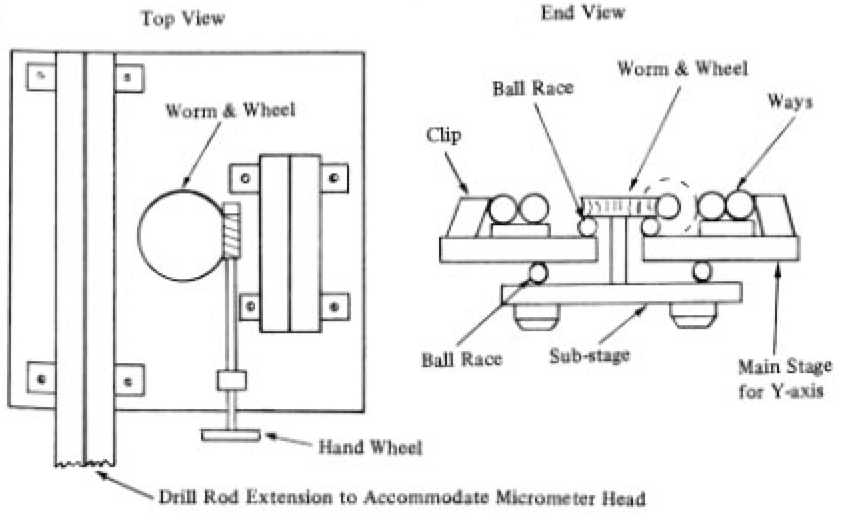
One of the testers described by Schroader (the one illustrated in Fig. 7 and 8, *A.T.M. III*, pp. 447 and 448) appeared to me to be the best; rolling on balls should give admirable freedom of movement and clamping the micrometers in the ways themselves would ensure proper alignment. There remained the question of material and the size of the rods for the ways. Considering cost and requirements, there was really only one choice—drill rod; a little arithmetic led me to use 5/8" drill rod and 3/8" balls; this would require .515" ground stock for the flat ways and a look at a list of ground flat stock showed me that there would be no difficulty in obtaining this dimension.

The next choice I had to make was which method of viewing the mirror would I use? (See p. 452, *A.T.M. III.*) I decided that if I were to make use of the full accuracy of the test, there was only one choice between two methods—the eyepiece and diffraction methods. I chose the eyepiece as the least cumbrous and a short computation showed me that a 1" Ramsden with a fine wire stretched across its field would give satisfactory results. I also decided that as there was going to be a lot of work and some little expense in making the tester, I would give it sufficient travel to take in the largest mirror that I was ever likely to make; there was no difficulty about the X-axis as a standard micrometer head would take in a perfectly Gargantuan mirror—with regard to the Y-axis, I decided on a 1" micrometer head and measuring standards 1" and 2" long, this would give a total travel of 3" and sufficient to accommodate a 30" f/4 mirror.

Two further items occurred to me. The first was that if the stages were to be properly centered with regard to each other, the rods to which the micrometer heads were to be clamped would have to be extended in order to make room for the heads themselves. The second was the difficulty in aligning the tester with the axis of the mirror under test; the X-axis has to be measured to a point where a difference of .0001" in the micrometer reading makes an appreciable difference in the image of the part of the mirror shown in the eyepiece. Although, mathematically speaking, the test is quite insensitive to correct alignment because the measurement is that of the difference between two readings rather than between the axis and one reading, in practice I thought that the tester would be much easier to handle if it were correctly aligned and that the readings would be much more easy to check one against the other if the micrometer settings bore some relation to each other.

I therefore decided to add a further sub-stage to Schroader's setup—this would be connected to the first stage which carries the Y-axis through a couple of thrust bearings, a shaft and a worm wheel, thus allowing the whole tester to be swung radially about its center point. In practice this arrangement has worked out excellently and I have had no reason to modify it at all; the general arrangement is shown on the following page.

Having decided on my requirements, the next thing was to make drawings and find out how the various dimensions worked out. The sub-base was planned for 6" diameter of 3/8" thick aluminum plate, with three feet. The first stage (to



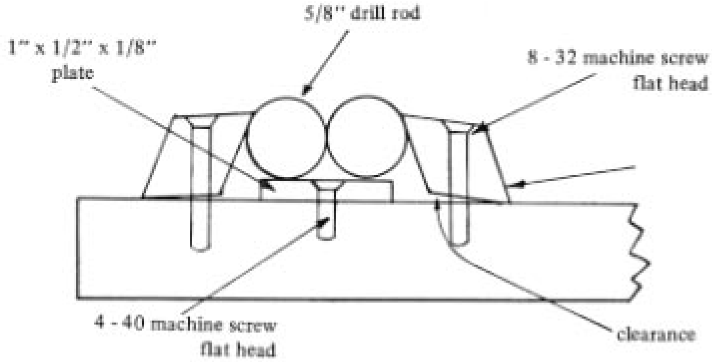
carry the Y-axis) was planned 9" square and since it had nothing to do except support the upper two stages and maintain rigidity for the ways, it appeared that 3/8" thick steel would be sufficient. As the two top stages would have to provide weight as well as rigidity, they were planned for 3/4" steel—the X-axis being 7" square and the stage to carry the eyepiece being 6" square. The whole setup weighs some 40lbs. and is admirably smooth in its movement, but as I said earlier, I cut the thickness of the two upper stages to ½" thick steel for the two other testers that I have made and found that there was no sacrifice in smoothness of operation.

In ordering the material, the steel was ordered already cut roughly to size as my workshop is not set up for dealing with large chunks of steel like these. Five pieces of drill rod were bought and were tested for straightness by placing each end in a V-block and rotating them against a dial indicator placed in the middle; two of them gave an indicator reading of .004", one of .003" and two of .002". The .004" ones were discarded and reserved for other applications, the .002" pieces were carefully cut to length in the lathe for the longer ways and the .003" pieces cut up for the shorter ways; in all these operations the chuck jaws were padded with newspaper in order to avoid making any marks on the steel—as all pieces were 36" long when bought and first tested for straightness, after they had been cut to length, they showed no appreciable lack of straightness even though they were tested with an indicator reading to .0001".

In order to get the .515" dimension for the flat ways, two pieces of ground flat stock were bought, 9/32" and 15/64" thick by ½" wide. Both of these were 18" long and showed a total deviation from straightness of less than .001"; two 4" lengths were cut from each of these, care being taken not to mark them by lining the vise jaws with several thicknesses of newspaper. These were carefully burred, paired and drilled for the holding screws.

The method of holding the rods in place was considered and clips were chosen. In order to facilitate aligning the rods, they were mounted on short pieces of 1/8" x ½" ground flat stock held to the stages by flat head screws, one screw to each piece. The clips were made from 3/8" x 5/8" cold rolled steel with the hole for the holding screw drilled at an angle so that the clip could be drawn downwards and inwards as the screw was tightened—the following shows this arrangement.

The plates were laid out with a height gauge and scribed and were then drilled and tapped. Everything was put together to see whether any mistakes had been made; one pair of tapped holes had to be relocated.



The next thing to consider was the method of holding the eyepiece. My first Foucault tester was made in such a way that I could never get my eye to the eyepiece without running my nose or chin into something, and I decided that this would not happen with this rig. I had a suitable aluminum bracket cast which would hold the eyepiece 5" above the top of the carriage—as the ways were 5" apart, I realized that the ways would have to be aligned within .0001" if error at the eyepiece due to tilt was to be held within .0001". I "borrowed" some .0004" shim paper and took the whole assembly into the plant where I spent some six hours of unpaid overtime in getting the ways properly aligned. This was a very tedious job but it was found that, with patience, the shim paper and variation of pressure on the clips gave satisfactory results. The actual method used was to mount the plate on three toolmakers' jacks and then to adjust the jacks until one of the longer rods showed no difference end-to-end against an indicator mounted on a height gauge (reading to .0001"). The second long rod was then shimmed up until the difference end-to-end was .0004" or less and the pressure on the clips was varied until the total difference at the four ends of the rods was .0001" or less; the second shorter rods (or piece of flat stock) were then aligned against the first pair by the same methods.

Two B & S micrometer heads had been bought, one reading to .001" for the Y-axis and the other reading to .0001" for the X-axis. In the plant I had access to a set of precision inspection grade gauge blocks and both heads were checked for error against these. The X-axis mike showed an error of .0003", this was beyond tolerance because micrometer heads should show an error of not more than .0002"; I took this back and exchanged it for another, measurement of the new one showed an error of .0001" which was satisfactory.

Estimated accumulated tolerances at the eyepiece amounted to .0002" and I allowed another .0001" for errors not accounted for; this would give an accuracy for the tester of 1/30th wavelength for normal mirrors and I decided that this was good enough (and probably better than my patience in figuring would bear). A final check of the assembly against a Leitz toolmaker's microscope showed an error of about .00015"—five readings of the X-axis being made on each of three readings on the Y-axis mike. I decided that this was sufficient as I knew nothing about possible error in the toolmaker's mike and I did not have the time to check it.

The tester has now been in operation for about 20 years and has proved very satisfactory; not the least of the satisfaction has been the fact that I have been able to educate my reading of paraboloids by the Foucault test against the absolute caustic test and now have a fairly good idea of what the various paraboloids look like under the knife-edge.

Quite shortly after making the tester, I decided that the slit I was using was not good enough, so I made up a new light source fitted with one of the slits described by Dr. John Strong on p. 144 of *A.T.M. III.* This slit is capable of very fine adjustment and with it I use a reticle made out of a brass ring which fits over the end of the eyepiece; across this is stretched a piece of .005" dia. piano wire and the slit is adjusted so as to show a hairline of light on each side of the wire when reflected from the mirror under test. When the hairlines of light are equal on each side of the wire, the micrometer reading is taken; I have found that a difference of .0001" in the X-axis position unbalances the lines to a very appreciable extent—to such an extent, in fact, that it is clearly visible to a person who has not previously had any dealings with a caustic tester.

The second caustic tester I made was smaller, with only a 1" travel on the Y-axis, but no general change was made in the construction; it was made for a friend who said that he was never likely to tackle anything larger than a 12½" and so did not need the capacity of the larger tester. The third one was made for the University of the West Indies for the testing of the optics of their 21" Cassegrainian and has proved very satisfactory in use; it was made the same size as the first one with the exception that the two upper stages were made of ½" thick steel instead of 3/4"; it proved to work just as smoothly as the first one.

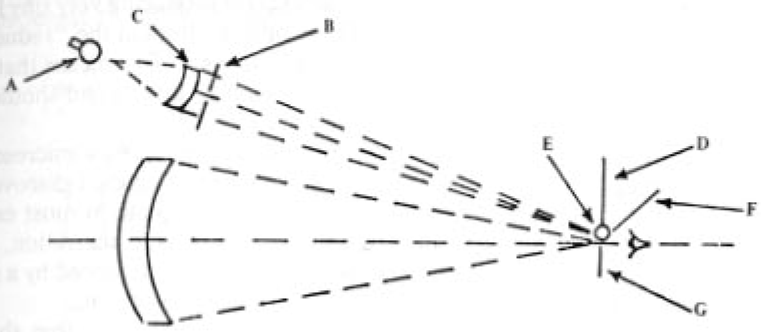
One last word about caustic testers. Unless you have a means to align the ways to a very high degree of accuracy, do not begin building one because misalignment of the ways will result in errors of measurement in the X-axis which you will not be able to evaluate. A caustic tester must be properly built to begin with and the ways should be checked for alignment periodically. I do mine once every two years unless I have reason to believe that one of them has gotten out of alignment in which case they are checked and corrected if necessary before the next optical surface is measured. If you have not got facilities for checking the ways properly, it is far better to make yourself an accurate Foucault tester and content yourself with that.

There is little doubt that the caustic test is by far the most accurate that is now available to amateurs (and to professionals for that matter). My estimate is that it is about ten times as sensitive as the Foucault test and is good, in competent hands, to better than 1/50th wavelength—maybe even to 1/100th. In the final critical test of a mirror, it is well to make two or three separate sets of readings, and it goes without saying that the mirror should be allowed to come to thermal equilibrium before the testing is begun; it is so sensitive that thermal differences even in a Pyrex surface under test will throw the readings out to such an extent that it is difficult to determine the shape of the mirror.

HIGH INTENSITY LIGHT SOURCE

by Arthur S. Leonard

In order to test Maksutov optics, we use the setup shown below:



A. Almost any clear glass tungsten filament bulb which has a fairly compact filament (we use a 6V bulb, G.E. No. 1493).

B. Diaphragm with No. 80 drill hole (or a slit if more light is desired).

C. Condensing lens. (Any old lens will do, but use a fairly long focal length so that the image of the filament projected onto the steel ball will be small and thus easy to screen out of the observer's eye.)

D. Supporting rod.

E. 1/8" diameter steel ball.

F. Small piece of electrical scotch tape to shield the light source from the observer's eye.

G. Knife-edge.

The 1/8" steel ball was soldered to the end of a small brass rod (about 1/16" diameter) and supported from above. When used just as it was received, it gave a mottled illumination over the surface being tested, due to tiny pits in the steel ball surface. After a little polishing by rubbing the steel ball on a rag with a little rouge, it gave a very uniform illumination over the entire surface of the glass.

In order to collimate the light source, remove the diaphragm from the front of the condensing lens and move the light bulb around until a sharp image of the filament falls on the steel ball. (Use a reduced voltage for this operation so that the image of the filament will not be too bright for the eyes.)

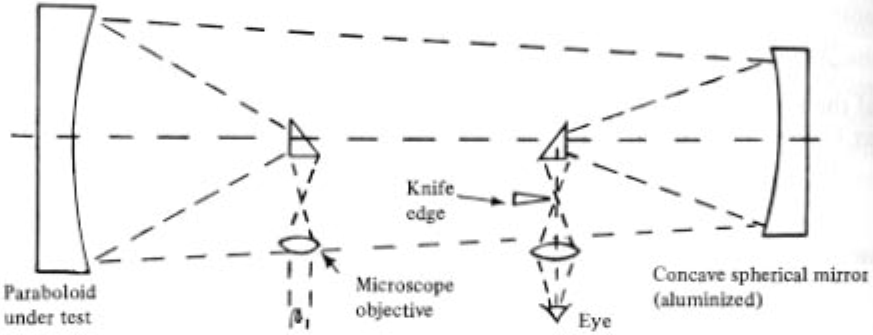
We started out using a diaphragm with a 1/8" hole in front of the condensing lens and gradually worked down to the No. 80 drill size as we became accustomed to using the apparatus. Theoretically this setup should produce an artificial star 30×10^{-6} inches in dia. With the shop well darkened, there was sufficient light to make the test. If more light is desired, a diaphragm with a long narrow slit instead of the No. 80 drill hole can be used.

It will be noted that in this setup we do not have any ground glass. We are always looking at the bare tungsten filament image (or a small area of a condensing lens which has the bare filament located at its focal point behind it). No matter how much light you condense on a piece of ground glass, its surface brightness will never be anywhere near as high as that of a bare tungsten filament (even when you make allowance for the space between the turns of the filament). When you need the highest possible brightness, you should turn the lamp so that you are looking into the end of the filament coil. The inside is appreciably brighter than the outside.

One thing about these optical reduction methods for producing very tiny light sources which should be pointed out is that all the optical errors in the "reducer" as well as those in the surface being tested show up in the test. This means that the optical elements in the "reducer" should be of known high quality and should be collimated perfectly.

Years ago I started out by using a bare tungsten filament and a microscope objective to test long focus spherical mirrors and achromatic lenses. I discovered later that an ordinary plano-convex lens will be entirely adequate in most cases. However, to be sure of not getting into trouble with chromatic aberration, you should be able to calculate the amount of chromatic aberration produced by a simple lens and know the tolerance of your test for chromatic aberration.

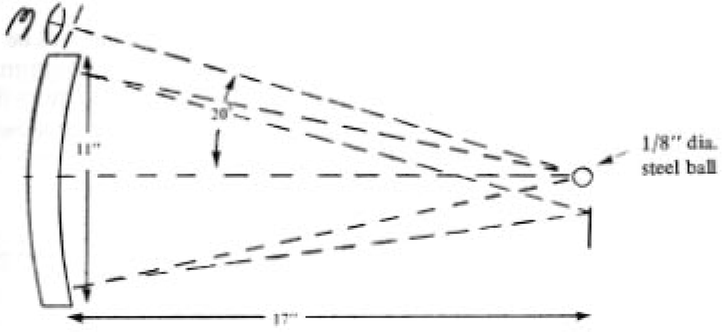
We first started to use the steel ball idea in a setup similar to that shown below:



We wanted a minimum sized obstruction in the lightpath and no heat generation there which might produce convection currents in the air around it. My first attempt to meet these specifications employed the setup shown. It worked pretty well, but it was messy to collimate as accurately as I would have liked.

The steel ball takes the place both of the microscope objective and the diagonal mirror, produces a much smaller obstruction and is easy to collimate to the desired accuracy (or, I should say, easier to collimate to the desired accuracy). Like the simple lens, the steel ball may introduce aberrations into your test. In the first place, the ball is a spherical mirror and thus produces a certain amount of spherical aberration. In the second place, the light, upon being reflected from the ball, does not retrace its path exactly but is reflected off at an appreciable angle. Thus there will be tilt aberrations (coma and astigmatism) as well as spherical aberration in the system. Unless you know what you are dealing with, these can cause trouble. However, in the setup shown below, I feel that these aberrations can be kept within acceptable tolerances, and the steel ball idea made to work very well.

In using the steel ball in the test of a Mak corrector, however, I felt that we were stretching the idea—just a little. The reason for this difference is the very fast f/ratio of the surfaces being tested. This makes *all* the aberrations very much larger (using the given size steel ball, they vary inversely as the 4th power of the radius of curvature of the surface being tested). Since the Maksutov we were building was to be used only as a photographic instrument, I felt that the steel ball would get by. The excellent results that we got in the final test of the assembled optics seems to verify this opinion.



View in vertical plane

In order to give some idea of the magnitude of the optical errors involved, let me take the following example (a typical test setup for one of the 11" Maksutov designs) and run through the calculations:

With this setup the maximum path difference due to spherical aberration (assuming the knife-edge to be located at the point of best focus) is calculated to be 2.7×10^{-6} inches.

This should be satisfactory for a photographic instrument, but some people may consider it to be intolerable for a visual instrument.

Coma (again at the point of best focus) is calculated to be 18.5×10^{-6} inches.

If the steel ball were to be collimated with respect to the concave surface being tested so that the virtual image of the light source would be located accurately at the center of curvature of the latter (this would require a beam-splitter to get the returning light out to the knife-edge and the observer's eye), the astigmatism would amount to 25.1×10^{-6} inches. However, if the corrector is tilted a little so that the returning beam comes to a focus 0.18" directly below the virtual image in the steel ball, the astigmatism from the tilt of the concave spherical surface under test will just cancel that produced by the convex surface of the 1/8" dia. steel ball and there will be no astigmatism in the test.

This is the setup we shot for. Even this would not have been satisfactory (too much coma) if it were not for the fact that both the coma and any residual astigmatism (from not having the corrector tilted so as to make the returning light come to a focus exactly 0.18" below the image in the ball) can be made not to show up *in the knife-edge test* merely by locating the primary light source directly over the axis of the corrector so that the final focal point is directly below the axis (in the same vertical plane and making the knife-edge vertical, also in this plane).

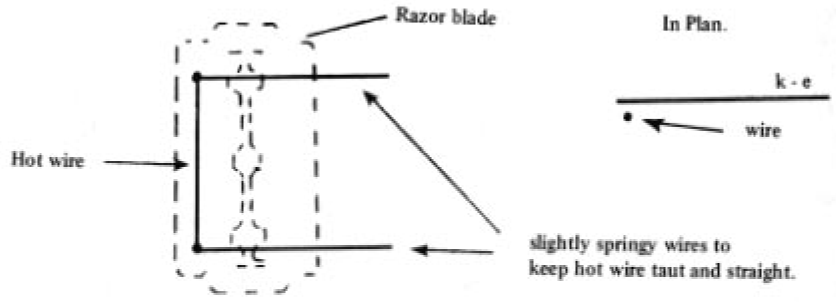
Another difficulty which comes up in testing at the center of curvature with the steel ball is that some of the light from the very intense light source just over the upper edge of the corrector falls directly into the observer's eye. No matter how well you locate the little piece of black scotch tape on the back side of the steel ball, you can still see the light source (mostly diffracted light from the edge of the little aperture) from the knife-edge. This is annoying, but you can get used to it and make the test in spite of it. If you were to locate the primary light source higher above the corrector, for example directly above the steel ball, the coma and astigmatism would be increased so much that they might give trouble in making the test.

By going to a smaller steel ball, say 1mm, all the aberrations will be reduced in direct proportion to the diameter, but you will need to use a larger primary light source (larger stop in front of the condensing lens). This may send more light into the observer's eye and make it more difficult for him to see the shadows on the surface being tested. To sum it up—the steel ball can be made to work, but you must be careful.

THE HOT-WIRE LIGHT SOURCE
by E. G. Onions

Much perturbed by the apparent necessity for complicated and often very expensive apparatus for testing Maksutov elements, I cast around for something simple and easy and came up with what I call the hot-wire test which appears to be something new. It consists in essence of an incandescent wire glowing in air, mounted in front of and very close to the knife-edge.

Herewith a sketch of the essential arrangements, shown without supports (which can be made as desired):



Ideal for the incandescent wire would be, I think, No. 40 gauge platinum wire, but not having any of this I used ordinary 36 gauge resistance wire which has a surprisingly long life if care is taken not to have too much tension on it and it is not run too hot. Intense light does not seem to be necessary—a fairly bright red showed me all I needed to know about the surface being examined. For power I used a small low voltage filament transformer from an old radio set, with a rheostat to control temperature.

I make the resistance element thus:

Just a loop twisted at each end which slips onto the ends of the support wires. When one burns out, just slip on another—a matter of seconds. The burn-out, incidentally, is quite safe—it does not go off with a bang like a high-voltage fuse—just parts company and fades out.

The modus operandi, of course, is obvious. On setting up, a vertical line of light is seen like an illuminated slit. On drawing back the assembly towards center of curvature, this expands into a bank or ribbon giving the characteristic Ronchi appearances. On reaching the center of curvature we get the full-moon effect, and the Foucault test.

Advantages:
- Easy to make and set up.
- Cost negligible.
- Wide-angle light source (couldn't be wider!)
- No abberations introduced by optical elements in the setup (there are none).
- On axis testing—k-e and light source can be very close.
- Light source shielded from observer's eye by k-e.
- Versatility (obvious).

Disadvantages: For long focus mirrors and curves shallower than f/4 there may not be enough illumination. One disability, which I suppose is inherent in all k-e testing of wide-angle curves is the difficulty of getting the eye close enough to the k-e—it has to be *very* close.

EXTENDING THE CAUSTIC TEST TO MIRRORS OTHER THAN PARABOLOIDS
by R. D. Sigler

In his article in *A.T.M. III*, I. H. Schroader gives the equations for the caustic surface of a paraboloid with a stationary source located at the vertex surface of curvature. The equations for the other conic sections, however, are not given. As *ATMs* frequently want to make mirrors which are not paraboloids, it would appear worthwhile to calculate the caustic surface associated with a general conic section.

Let us consider a mirror section in the yz plane (see Fig. 1) whose sag along the principal axis is given by the equation:

$$z = \frac{y^2/R}{1 + \left[1 - (1+b)(y/R)^2\right]^{1/2}}$$

Here y and z are the coordinates of a point (or a very small zone on the mirror surface) and R and b are the vertex radius of curvature and the conic constant, respectively. An illustration of the conic constant can be found in Chap. 9, "General Cassegrain Formulas."

Using calculus, the center of curvature (Y_k, Z_k) of any point on the mirror surface is found to be:

$$Y_k = y + \frac{1 + y'^2}{y''} \qquad Z_k = z - \frac{y'\,[1 + y'^2]}{y''} \qquad (2)$$

performing the indicated differentiation of eq. (1):

$$y' = \frac{R - (1+b)z}{y} \quad (3) \qquad y'' = -R^2/y^3 \quad (4)$$

Substituting eq. (3) and (4) into eq. (2):

$$Y_k = -\,by^3/R^2 \qquad Z_k = z + \frac{(R^2 - by^2)\,[R - (1+b)z]}{R^2} \qquad (5)$$

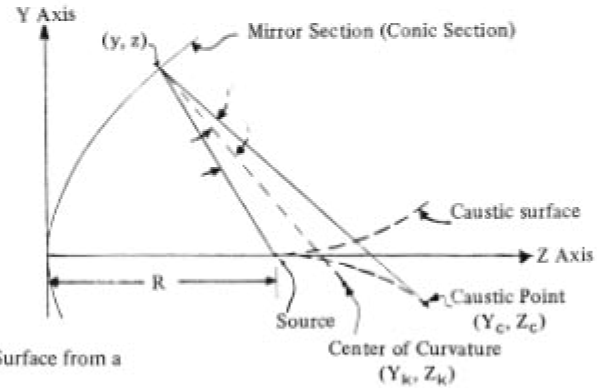


FIG. 1. Caustic Surface from a Conic Section.

Referring to Fig. 1, it is clear that the source (at the vertex center of curvature) is not located at the center of curvature of a general point on the mirror surface (y, z). They are coincident only for a sphere. If the angle of incidence (i) were zero, then a source displaced a small distance from the center of curvature toward the mirror (Y_k, Z_k) would have its image displaced an equal distance on the other side of the center of curvature. Since the vertex radius is very much larger than the caustic surface associated with a mirror, we would have no great loss of accuracy if we assume that the angle of incidence is zero. Using this assumption, the caustic surface is given by:

$$Y_c = 2Y_k = \frac{2\,by^3}{R^2}$$

$$Z_c = 2Z_k - R = 2z - R + \frac{2(R^2 - by^2)\,[R - (1+b)z]}{R^2} \qquad (6)$$

Trying out eq. (6) on a few cases:

Case 1: Sphere (b = 0) $\quad Y_c = 0 \quad Z_c = R$ Just as expected.

Case 2: Paraboloid (b = −1) Note $z = y^2/2R$

$$Y_c = -2y^3/R^2 \qquad Z_c = R + 3y^2/R$$

When we consider that y has both positive and negative values, we see that these results agree with those of I. H. Schroader in *A.T.M. III*.

Case 3: Ritchey-Chretien primary (b = -1.04167)

$Y_c = -2.08334\,y^3/R^2$

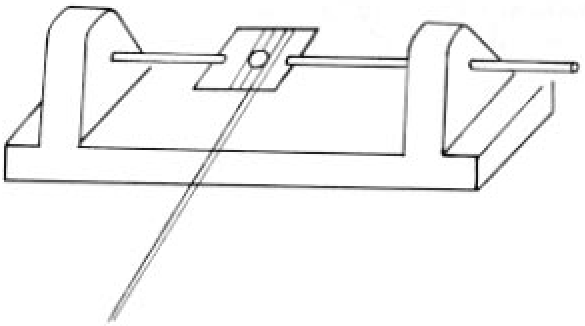
$Z_c = R + 3.1250\,y^2/R + 0.032558\,y^4/R^3 - 0.0005\,y^6/R^5$

MAKING RONCHI GRATINGS
by Ernest T. Thompson

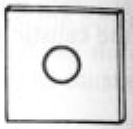
Make a small wood stand with spindles that are slotted to receive two plates, drilled ¼" through the middle. Wood screw through the spindles to hold the plates secure. Run off enough wire to allow for two strands, fasten both to one end of the plates and proceed to wind the two on, being careful to hold tension and push the two wires together as wound. It is only necessary to cover the drilled hole. Fasten the end of one wire and unwind the other wire, being careful not to disturb the setting.

When the plate is covered satisfactorily with the other wire, fasten it to the plates with Duco cement (do this on the faces of each side, top and bottom), *keep it off the edges*. When the cement is set, file the wire through at the top and bottom edges and you have *two* excellent Ronchi gratings.

I use the finest enamelled wire from an old radio transformer to wind the grids and with a little practice it is easy. The enamelled wire does not shine and does not require smoking. The number of grids to the inch can be controlled by the thickness of the wire. I have had them so fine that I could make a Foucault test "under" one wire, seeing the mirror just as through a pinhole.



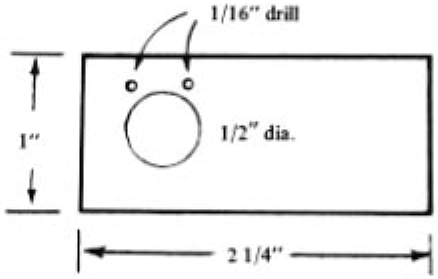
Two wires held with tension



Two plates held together with Scptch Tape.

MORE ON RONCHI GRATINGS
by Henry Steig

My frames are shaped as in the sketch to provide means to hold them in front of the slit and knife-edge; if you want to use a screen in a permanent arrangement, the extra metal is not needed. The hole should be somewhat larger than the space between the knife-edge and the slit, and probably ½" will do in most cases. I had some 18 gauge brass (.040") and used that, with the dimensions shown. Rounding off sharp edges facilitates winding.



The holes can be drilled after the plates have been taped together. The small holes, whose purpose will soon become apparent, should lie slightly outside the diameter of the large one.

The problem in winding the wire by hand is to avoid twisting, overlapping and kinking, and it is not practical to try to wind the wire directly from a spool onto the frames. You will need enough wire to cover the ½" hole plus about two feet. If you use .005" wire and the same screen dimensions as mine, you will need 20 feet, that is a double strand 10 feet long. Start a brad vertically at a corner of your work-bench, and another 10 feet away. Attach your wire to one of them, then run the wire around the second brad and back to the first without much tension. Lift the looped end off the second brad, pass it through one of the little holes in the double frame and pull it through far enough to permit the frames to be put through it, then snug the noose up tight. You should now have the frames attached to your double wire, the strands of which lie nicely side by side, without any twist or kinks—make certain of this before you start winding. It is also a good idea to try tearing a doubled piece of wire so that you will know how much tension it will take. Plain copper wire is too weak; cupron is excellent. Nichrome should also be good; piano wire is very strong but is difficult to handle and rusts.

Wind the wire on the double frame by turning it in your hands, maintaining the tension and pushing the turns up close together with your thumbnail as you advance. Unless you have exceptionally good eyesight, you will need a magnifying device of some kind. I use a 4x jeweler's loup.

A RIG FOR MEASURING THE CONCAVE SURFACE OF A MAKSUTOV CORRECTOR
by E. C. Melville

Materials Required.

1. A metal tube 1/16" thick and sufficiently long for the concave radius of curvature. This tube or cylinder may be anything between 4" and 2½" diameter— preferably the former (I shall use 4" in the following description). The internal diameter should be known accurately to ±001" and the ends must be squared off and parallel to .001" (for machining details see short operation sheet at the end).

The bottom end of the cylinder, where it rests on the glass, must be chamfered from the outside. The opposite end is threaded 40 t.p.i. for 5/8" externally. Before removing from the lathe, three equally spaced longitudinal lines are scored down the internal length of the cylinder with a sharp tool.

2. A cap to fit the threaded end of the cylinder is made from a disc of metal 7/8" thick. This is bored out to a depth of 5/8" and the inside of the bore so formed is threaded to screw smoothly on to the top of the cylinder, a hole is drilled and threaded for a lock screw. A hole 5/8" diameter is drilled through the center and the cap reversed in the chuck. The outside of the cap is then faced off to a thickness of 1/8" and a recess machined at its center 1/16" deep and of a suitable

diameter to form a seating for—

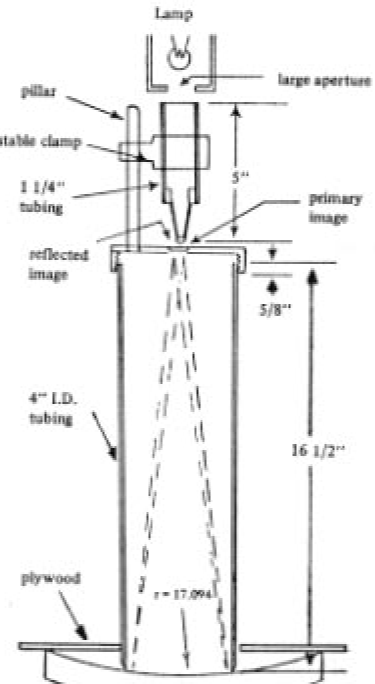
3. A reticle with cross hairs defining its center. This reticle is fine ground over one half of its area to within 1/64" of its center line. This is best done by clamping it between two pieces of soft wood, one of which leaves one of the cross hairs just covered. The exposed side is then fine ground, using a small piece of glass—the ground side should be the side on which the cross lines are engraved.

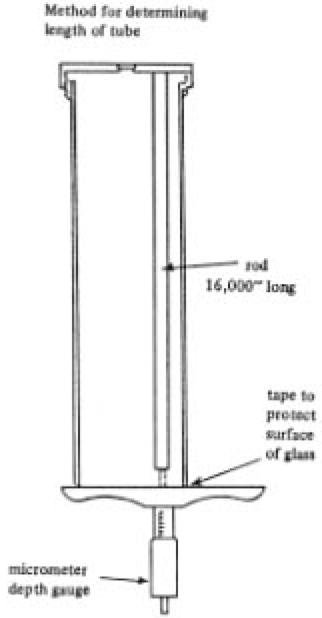
4. A microscope objective is needed; this may be low power—a numerical aperture of 0.25 should be suitable. This is fitted into the end of a piece of eyepiece tubing, 1¼" internal diameter or less, and about 5" long. The inside of the tube is fitted with a bushing to make a tight fit for the microscope objective. These objectives are made for a tube length of 160mm and will, of course, perform best with a tube of that length, but in practice no fault will be found in definition if the tube is made shorter, and it has the advantage of increasing the rather short gap between the end of the objective and the focal point.

5. Some means, as is shown in the drawing, of attaching the tube and objective to the cylinder cap.

6. A light source.

7. A chemist's retort stand or equivalent with a heavy base and adjustable clamp.





Principle of the Test.

The microscope objective forms a small image of the large "port-hole". This image can be very accurately focused on the ground portion of the reticle which lies just below the objective. After focusing, the ground portion of the reticle is revolved in its cell to allow clear glass for passage of the light and its reflected image from the silvered concave of the corrector, which is returned to a focus on the ground surface of the reticle, now turned to intercept it. When both images are in perfect focus at the same setting, the surface of the reticle is at the center of curvature.

The corrector is assumed to have been tested for sphericity and to be of the correct radius within the limits of measurement by spherometer, and to have some polish and a flash coat of silver. Two simple methods for silvering are described later.

Now, take the reflected ray from the periphery of the cylinder (which, of course, is equal to any other ray) and it will be seen that this makes a right triangle with the side of the cylinder and the internal surface of the machined cap. Of this triangle we know that the base is one half of the cylinder diameter; the hypotenuse, which is the afore-mentioned ray, is the radius of curvature. For this discussion, we will assume that the figures are 2.000" and 17.094"; so if we measure the other side of the triangle, i.e., along the inside of the cylinder to the level of the reticle surface, we should get (if everything is correct) $17.094^2 - 2^2$, or 288.204836, of which the square root is 16.977", and this should be the measurement. There is necessarily a slight offset between the image formed by the objective and its counterpart reflected from the corrector. This need not amount to more than 1/32" and the ray-tracing fraternity can, no doubt, provide a correction for any given radius and offset, if one is needed.

It is now necessary to describe some means for accurate measurement along the cylinder wall. To begin with, before placing the cylinder on the glass, it is necessary to protect the latter against scratches. Three bits of scotch tape, about 1" long x 1/8" wide are stretched over the edge of the cylinder at points 120° apart, i.e., over the internal marks scored on the cylinder wall. It is on these that the cylinder rests and from these that all measurements will be made. A radius bar with squared ends and 16.000" long is made and inserted into the cylinder, following one of the scored lines and abutting on the internal surface of the cylinder cap. This will come to between 1/2" and 3/4" of the chamfered end of the cylinder and this distance is measured with a micrometer depth gauge which rests on a chord of the cylinder opening and on two pieces of scotch tape temporarily applied for the purpose. This gives the measurement to the base of the cylinder, to which must be added the thickness of the flange on which the reticle rests and the thickness of the reticle itself, both of which are measured with care and recorded for future use. Three such measurements around the cylinder when averaged should give a figure accurate to a very few thousandths. If a correction for the offset is needed, this can then be added.

Setting Up.

Calculate what the side measurement should be (in this case—16.977") and screw the cylinder cap on enough to make this measurement add up correctly. Place over the corrector a protective square of plywood or masonite with a hole bored in the middle amply large enough to pass the cylinder, so that you are sure that it is actually in contact with the glass and not canted in any degree. The corrector had best be placed on a table and under the convex side can be placed three wedges or adjusting screws for levelling. Now bring up the chemist's stand with the light source clamped in position and center the light source over the end of the microscope tube and nearly in contact with it. Turn on the light and, with the help of a powerful magnifier (an eyepiece attached to the end of a short holder will do), examine the image formed on the ground glass. Move the objective in its clamp until the aperture is in focus. When this is the case, a diffraction ring will appear around the image, much more perfect than any that one gets with a telescope. Now switch the reticle around in its cell (a small knob attached to the reticle by cement or otherwise will facilitate this) so as to permit clear glass for the outgoing light and ground glass to intercept the returning image. If everything is correct, both of them will be in good focus; if not, screw the cap one way or the other and repeat the focusing of both images until they are equally well focused. Lock the cap with the set screw and measure the internal length again having, of course, removed the lamp and all overhanging equipment from above the glass. As a guide, and until the very final measurement, it is sufficient to note how many turns, and what fraction of a turn, of the cap brings about a good focus; this can then be estimated in units of 1/40" per turn.

A correction to your spherometer reading may be derived from this initial measurement which should enable you to hit the bullseye on the following grind. A point to note is there should be the very minimum of offset between the outgoing and reflected images and that these should be equidistant from the center of the reticle and along one diameter. This will involve some "fiddling" with the adjustments, but the trick will easily be learned.

Having achieved an accurate measurement of the concave, that of the convex may be deduced by careful micrometer measurements of the center and edge thickness. If it is certainly spherical as tested with the mercury bath (see succeeding article) and the concave is also spherical *and* of the correct radius, the thicknesses will tell the story.

Silvering.

1. On page 173 of *A.T.M. I* edition of 1933 (I don't think this appears in recent editions) is the following emergency technique:

Put ¼ oz. silver nitrate in 3/4 glass distilled water. Add ammonia until precipitate disappears entirely. Dilute one teaspoonful of formaldehyde with ¼ glass of distilled water. Mix and pour on the glass.

I must confess that I have never had a good coat with formaldehyde, but here a good coat is not necessary. A very little silver goes a very long way in increasing reflectivity.

2. In Sidgwick, *Amateur Astronomer's Handbook,* page 128, the Rochelle salt process is described. This allows making two solutions which can be kept for some time. It is slow acting, but here again it is not necessary to have a thick coat if one is impatient.

1. Silver nitrate—5 grams.
   Distilled water—300cc.
2. Rochelle salt (Pot.-sodium Tartrate)—
   0.8 grams
   Distilled water—10cc.
3. Silver nitrate—1 gram
   Distilled water—500cc.

Add ammonia to No. 1 until the precipitate nearly re-dissolves. Filter if necessary. Boil No. 3 (in a porcelain or pyrex dish) and add No. 2 to the boiling solution. Continue boiling until a grey precipitate is thrown down. Filter and dilute to 500cc.

Mix equal quantities of 1 and 2-3 and pour on mirror.

For both processes the glass, of course, should be chemically clean. For this job, cleaning with detergent followed with nitric acid should be sufficient. The nitric acid is rubbed on the glass by means of a glass rod covered with a "policeman" (a 3" length of rubber tubing slipped half way on the end of the rod and securely tied doubled over), covered with a thick wad of cotton tied on. Tap water, even if chlorinated, can be used throughout cleaning but must be followed with a rinse of distilled water. If the corrector is perforated, fill the ditch with paraffin wax (rouge and pitch will cause failure in silvering, as will allowing the glass to dry after cleaning). Keep covered all the time with distilled water.

Operation Sheet for Machining the Cylinder.

Turn two tight wooden plugs for the ends of the cylinder. Rough cut the length to 1/8" overlength with a hacksaw and ram in the plugs. Chuck one end of the tube lightly and indicate concentric. Support the free end of the tube with the center rest (if you have no center rest for your lathe or if your center rest has not got sufficient capacity, an adequate center rest can be made out of plywood with three screws to take the place of the center rest dogs); indicate the free end concentric and take a light cut to square off the end of the tube. Reverse the tube and chuck lightly on the finished end. Indicate both ends concentric as before. Finish off the other end to size and chamfer the end, leaving a land of approximately .005", do not attempt to make this end completely sharp because you will spoil the length of the measurement. Add the .005" land to the measurements.

TEST RIG FOR MAKSUTOV CORRECTOR CONVEX

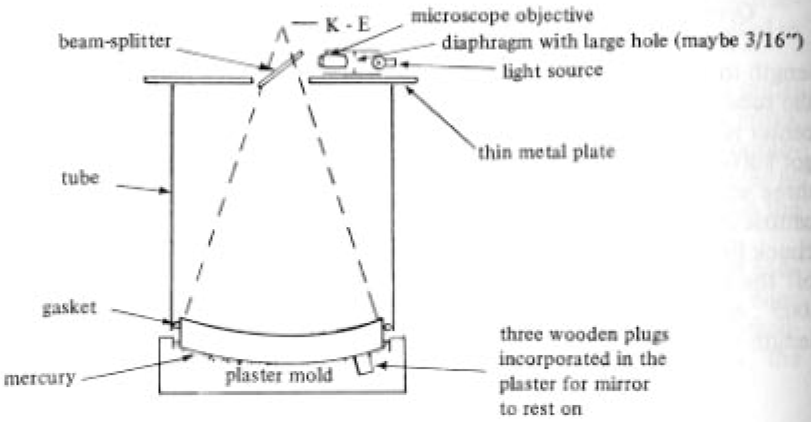
by E. C. Melville

Testing the convex surface of a Maksutov corrector can be a real problem. It can, of course, be done against a concave master, but this involves the extra work and expense of making the master and would hardly be worthwhile unless a number of identical Maksutovs were to be made. Another alternative is to figure the convex surface by autocollimation after the primary and the concave surface of the corrector have been finished, but I have always preferred to finish all my surfaces to the best of my ablility and then to test by autocollimation only for the final touches. The following setup enables me to test the convex without reference to the other surfaces; it is a combination of the King test (*A.T.M. II*) and the vertical mercury test.

A tube (metal, fiberglass or other material) is cut to appropriate length, depending on your testing apparatus, and the bottom fitted with a suitable gasket to fit or be clamped around the edge of the corrector plate so that it won't leak. This is filled with a fluid of the same refractive index as the glass and the whole is then placed on mercury, to give a reflective surface to the convex, and the tester is placed across the top of the tube.

This arrangement seems to have some advantages. True, it does not help measurement of the convex radius, but it gives a very clear picture of its figure. If anything drops in the tank, it will have to fall through the fluid before it "crashes" onto the glass. The end of the tube makes a ready-made support for the tester, and the concave need not be finished in any way as the glass will be "eliminated" by the fluid.

The plan of the apparatus is as follows:



As the internal parts will be in almost complete darkness, testing can be done by day. The whole thing can be placed on a stand of sufficient height to enable the worker to sit on a chair. By cutting down the air path as much as possible, the error should be very small. Length of the tube will have to be calculated as it will differ appreciably from the air path.

It will probably not be possible to find a liquid with the exact index desirable, and with other characteristics to make it usable. I suggest tetrachloroethylene (or, more simply, perchloroethylene), which has an index of 1.50547, a boiling point of some 120°C., (note this) and is NOT flammable; the vapors are slightly toxic in concentration, although nothing like those of carbon tet. The vapors (and the liquid) are very heavy—vapors tend to settle to the floor. It does not evaporate excessively from an open vessel at room temperature. It is usually water white.

Concerning the sketch, of course there has to be a top to the liquid and there will be some refraction occurring there. The mathematics of the situation can be worked out using the thickness (or depth) of the liquid, its index, the air path, etc., and possibly allowing for the thickness of the glass and its index.

With regard to the tube to hold the liquid and the gasket situation, there are available on the market polyethylene plastic bowls or dishes, round, some of them even as large as dishpans. Get a suitable bowl, cut the bottom out and press the lens blank into the remaining rim until it makes a tight fit, thus sealing all around the lens; pour in the tetra., set the rig on the floor and set the test rig up above. (The point about the King test is that the air path is short, and consequently refraction is small, but a trig. trace would be in order to find out how much refraction is to be expected.)

With regard to the statement that the concave need not be finished as the glass will be "eliminated" by the fluid—such will be the case only when the indices match exactly; however, since in the natural course of events there must be a difference, the concave should be finished as well as possible, even right up to the final polish.

There is a statement in *A.T.M. II* by Ferson that trichloroethylene seems to etch glass. I have found that tetrachloroethylene is not so "acidic" and does not etch glass, BUT I think that because it removes pitch, wax, etc. from minute sleeks and scratches, they become visible after cleaning where they were invisible before.

WEDGE TESTING OF MAKSUTOV CONVEXES

by A. S. Leonard

In testing the convex surface of a Maksutov corrector, it is possible to test it as a concave through the polished concave surface. To do so, however, it is necessary to separate the images of the concave-convex surface and the concave surface. To do this, "wedge" is deliberately introduced between the convex and concave surfaces.

I have gone into the amount of wedge required for testing the convex surface in this manner, and here are my results:

Let D = diameter of the corrector

t = thickness of the corrector

Δt = the differential thickness of the corrector (max.)—the amount of wedge

n = index of refraction of the glass

L_1 = distance from the concave surface to the image plane (if the pinhole and image distances are the same, it will be equal to R_1)

S = lateral separation, in inches, of the two images of the pinhole (from the two spherical surfaces)

L = $$L = L_1 + \frac{t}{n} \qquad (1)$$

$$S = \frac{2nL\Delta t}{D} \qquad (2)$$

Now for the Airy diffraction pattern:

let d = diameter of the diffraction pattern from the convex surface (in order to be specific, we will take the diameter of the first dark ring).

λ = wavelength of the light being used in the test $d = 2.44\lambda\frac{L}{D}$ (3)

Combining equations (2) and (3), we get the ratio of the lateral separation to the diameter of the diffraction pattern:

$$\frac{S}{D} = \frac{n\Delta t}{1.22} \qquad (4)$$

You can see from equation (4) that the ratio of the separation of the two images to the diameter of the diffraction pattern from the convex surface is directly proportional to the amount of wedge, in inches, and is independent both of the radius of curvature and of the diameter of the surface being tested. For 0.006" of wedge and BSC-2 glass, this ratio turns out to be:

$$\frac{S}{D} = \frac{1.52 \times 0.006}{1.22 \times 21.8 \times 10^{-6}} = 342$$

Although this is much greater than would be required just to get a good separation of the light from the two surfaces, I would recommend making it this large in order to give yourself as much leeway as possible in hitting the desired radius of curvature on the concave surface. The greater the amount of wedge, the greater will be the working tolerance on the difference in radii of curvature of the two surfaces.

On the matter of getting the wedge out of the corrector after the convex surface has been figured, this is something that will have to be done no matter how you test the surfaces because the blanks will have a lot more than 0.006" wedge in them when you get them. When using this method, you merely split the job of removing the wedge into two parts, you finish the second part when you have polished and figured the convex surface. The total amount of work is not increased appreciably (unless you have received a blank which by rare chance happened to have been cast nearly uniform in thickness all the way round).

Removing the wedge is rather a simple operation. While grinding, you merely apply pressure near the edge of the corrector where it is thickest, and check its edge thickness with a micrometer caliper every few wets until it is uniform all the way round and within the tolerance you have set. After the thickness is uniform, a few wets with light pressure in the center of the glass should bring the surface to a good spherical curve.

If you are NOT going to use this test method, my recommendation is that you get rid of whatever wedge is present in the blank as early in the grinding operations as possible, and then go after the radius of curvature. Then maintain these conditions by frequent checking with the micrometer and spherometer as you grind the blank down to the specified thickness.

If, on the other hand, you are going to use my test method, you would start out about the same, except that instead of trying to eliminate the wedge completely right at the start, you stop working on the wedge as soon as you have it down to .006" to .008". As soon as you have reached that point, go to work on the radius, shooting to make R_1 equal to $R_2 - t$ (t is whatever the thickness happens to be at

that stage). When you have reached this condition, polish both surfaces and make your tests. This procedure will leave you with the maximum amount of extra thickness with which to finish the job after you have polished and figured the convex surface.

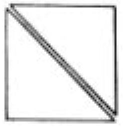
After the convex surface is finished, start grinding again and remove the remaining wedge first, then proceed as per recommendations. This procedure will not increase the total time spent in grinding very much over that required by any other test method and will pay dividends in convenience in testing because the test apparatus can be set up in the horizontal position usually used.

A BEAM-SPLITTER FOR VIEWING THE WHOLE SURFACE OF A MAKSUTOV CORRECTOR

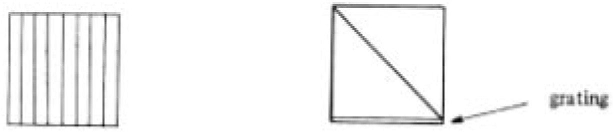
by Paul Charles

Owing to the very short radii of curvature used in Maksutov correctors, it is very difficult to get a view of the whole surface. After trying all kinds of test equipment to see the corrector lens as it should be seen, I have come up with the following:

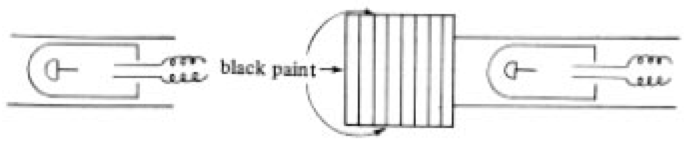
I took two 1" prisms and cemented them into a 1" cube.



Next, at all corners with Duco cement, I cemented a piece of grating with 100 lines to the inch.

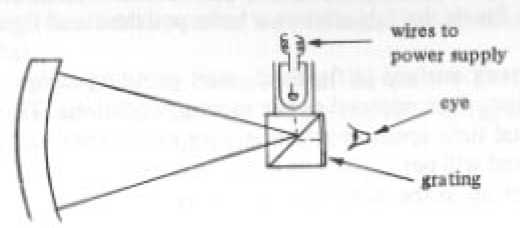


For the light-source I used a Zirconium A2 bulb and placed it in an aluminum tube to act as a holder and keep out side light.



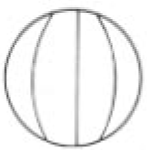
Then I placed the tube right side up against the cube and painted the top, bottom and left side black.

Looking down on the setup from the top, it looks like this:



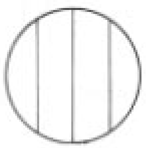
Your eye must be very close to the grating. If your lashes are very long, you might try your wife's eyelash curler so you won't be bothered with unwanted lines.

Believe me, it is a beautiful sight to see the whole of the lens and then some. Before this arrangement, I thought that I had good spherical curves with knife-edge check, but this is what I had:

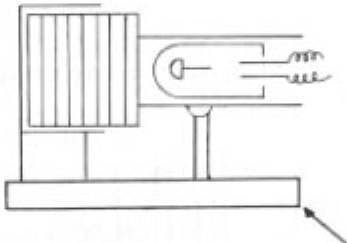


bad paraboloidal curves on both R_1 and R_2

After refiguring with the beam-splitter setup, I had:



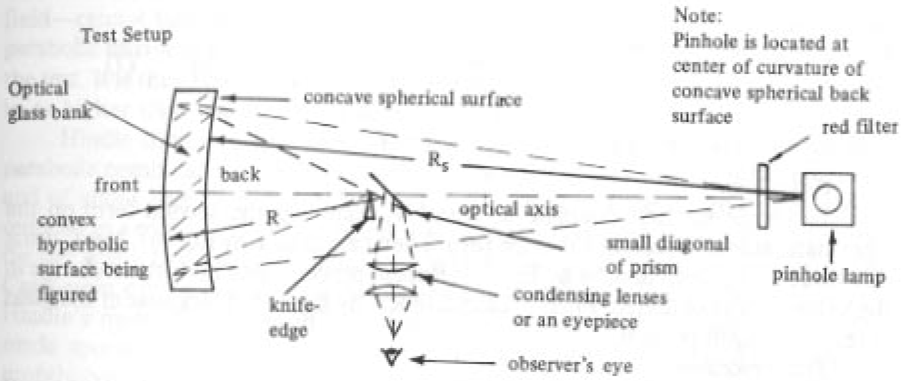
nice straight lines, both R_1 and R_2—you can see R_2 equally as well as R_1.



After completing the corrector I did some experimenting. I found that almost any kind of light source would work, but that Onion's hot wire source gives a more sensitive reading although it requires a little more darkness (but not total by any means).

As far as cementing the prisms together, Canada Balsam is O.K. I used what is called "Liquid Cloth"; you can buy it almost anywhere, it is very much like Duco only 100 times stronger; I use it for cementing my diagonals. Of course, beam-splitter prisms can be bought already made up. For a 6" Mak a half-inch prism is all that is necessary—for an 11" Mak a 1" prism is necessary and this, of course, will do for a 6". I might add, the filament in Onion's light source should be as close to the prism as possible.

A NULL TEST FOR CASSEGRAIN SECONDARIES
by Arthur S. Leonard



Nomenclature.

- m = magnification ratio of secondary.
- n = index of refraction of the glass for the color of light used in the test.
- p = smaller of the two focal lengths of the secondary.
- q = larger of the two focal lengths of the secondary.
- R = radius of curvature of convex hyperboloidal front surface of the secondary.
- Rs = radius of curvature of concave spherical back surface of the secondary.
- d = distance from the surface of the secondary to secondary focus of the telescope.

Working Formulas.

$$m = \frac{q}{p} \qquad (1) \qquad\qquad R = \frac{2pq}{q - p} \qquad (2)$$

$$u = 4\left(m^2 - 1 - \frac{m}{(m-1)^2}\right) \qquad (3)$$

$$v = (6n^2 - n - 4) \qquad (4)$$

$$w = (12n^2 - 4n - 7) - \frac{2(2n^2 - n - 1)}{Y} \qquad (5)$$

$$Y = \frac{v + v^2 - uw}{u} \qquad (6) \qquad\qquad R_s = RY \qquad (7)$$

Calculations.

To obtain R_s, first calculate u, v and w, assuming the second term on the right-hand side of equation (5) to be zero. Then calculate Y by Eq. (6). Next, using this value of Y, recalculate w by Eq. (5). Repeat process until no further change in the value of Y is obtained. Finally, calculate R_s by Eq. (7). Thickness of the glass is relatively unimportant.

Test Procedure.

Before performing the test, collimate the setup by adjusting the pinhole or the mirror to bring the pinhole into coincidence with the center of curvature of the concave spherical back surface. Because the test is made from the back side of the surface being figured, areas which are high, and therefore need to be polished down, appear to be low. Note: The small diagonal mirror introduces a reversal, and the condensing lenses an inversion of the observer's view of the mirror.

Finished Mirror.

The optical axis of the secondary is accurately defined by the center of curvature of the concave spherical back surface, and its image point formed by reflection from the back side of the silver coat on the convex hyperboloidal front surface.

TESTING CONVEX SURFACES

by Enrique Gaviola.

This paper was first printed in November 1939 in the *Journal of the Optical Society of America,* Vol. 29. It is reproduced by kind permission of the Editor of the Journal. - Ed.

An arrangement for testing Cassegrain mirrors is described which does not require the use of large mirrors as auxiliaries. It consists in placing a convergent lens in front of the mirror so as to form a real image of the illuminating pinhole and measuring the resulting aberration. The aberration of the lens is numerically eliminated after an independent measurement with the help of a small plane mirror placed at an appropriate distance. The longitudinal aberration of the Cassegrain alone can also be directly obtained by displacing the small mirror. The method permits high precision. It can also be applied to any convex surface.

The problem of testing accurately a Cassegrain reflecting telescope mirror up to now has been a difficult one. The autocollimation method of Ritchie requires the use of the main parabolic mirror of the telescope, of a master flat of at least the same size and of a spherical mirror of at least as large a diameter to test the flat. The central part and peripheral zone of the Cassegrain—needed for having a finite field—cannot be seen or tested. One has to use light that has suffered five—if the parabolic mirror is not perforated—seven, reflections, so reducing the accuracy of the test. It is thus practically impossible to test the Cassegrain with precision (equal to or higher than the parabolic) as would be desirable.

Hindle eliminates several of these drawbacks by using, instead of the flat plus parabolic combination, a spherical mirror of a size about the same as the parabolic and of about half its radius of curvature. The unseen zone in the center is now reduced to a minimum and the rest is visible to the very edge. As the spherical mirror can easily be tested and therefore made with great accuracy, the survey of the Cassegrain can be made nearly as accurate. The difficulty involved in the use of Hindle's method is the need of a large spherical mirror that generally has to be made specially for the purpose. For large telescopes this procedure becomes prohibitive.

Most observatories possessing telescopes with Cassegrains do not have large plane or spherical mirrors and have no optical shops that could build them. The resource of testing the Cassegrain from the back through the glass is unsatisfactory as there is no way of controlling independently the errors introduced by irregularities in the glass. The test of the Cassegrain in the telescope with starlight can never be as accurate as there is no possible temperature control. Besides, the center and peripheral zone cannot be seen from the axis. The use of a spherical or hyperbolic concave mirror to produce interference fringes upon superposition, offers large practical difficulties. Its accuracy cannot be carried very far.

In 1936, while at La Plata Observatory, I was confronted with the problem of testing and correcting the Cassegrain mirror of its 82cm reflector. It was apparent that it had errors exceeding half a wavelength. As we had no plane mirror of that size and no possibility of making either a flat or a Hindle spherical mirror of 82cm diameter it became necessary to find a new simple method for testing the Cassegrain using only the available equipment. After some experiments, a satisfactory method was devised.

Principle of the Method.

The new method is based on the following considerations:

In order to test an optical surface, we need an arrangement that will form an image of some kind. If the image is very good, the study of it is generally sufficient to tell about the quality of the optical surface or system. This is the qualitative null or autocollimation method. If the image is not so good, we subdivide it into a number of good images by decomposing the main optical surface into sufficiently small parts or zones. One can always calculate the aberrations of the system or the curve of shape of the surface by *measuring the relative positions* of the partial images, observing one after another. This method is quantitative and—if properly applied—more exact than the other one.

If the image is not formed by the optical system to be tested alone but with the help of an auxiliary optical system, it is necessary to have an independent test for the auxiliary optical system.

To make a convex reflecting surface form an image of some kind of "artificial star" or slit one can, among other things, put a convergent lens in front of it. The lens has to have a focal distance smaller than the radius of curvature of the convex surface. Its diameter has to be only slightly larger. These are two necessary conditions. The lens may be simple or compound. It may have any amount of errors. Its chromatic aberration is eliminated by using monochromatic light.

The independent test of the auxiliary system is accomplished by removing the Cassegrain and placing a small plane mirror at an appropriate distance. Once this is done, the aberrations of the lens are numerically excluded.

Description of the Method.

Let C be the Cassegrain mirror to be tested, L the auxiliary lens and S a zonal screen put between the two (Fig. 1a)

Using a Foucault knife-edge apparatus in which parallax has been eliminated (E. Gaviola, J.O.S.A. 26, 166, 1936) so that knife-edge and slit are always virtually coincident and applying monochromatic light to the slit, we determine the position of the image 0 formed by the central zone of the screen along the optical axis 0 - 0'.

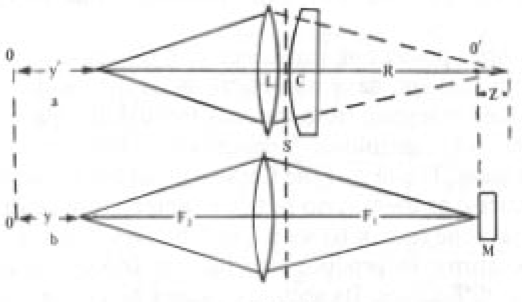


FIG. 1.

Taking 0 as the null point of the scale, we measure the distances y' of the mean positions of the images—centers of least confusion—formed by every pair of zones of the screen. These values y' will be called the longitudinal aberrations of the optical system lens plus Cassegrain. We now remove the Cassegrain, leaving knife-edge, lens and screen untouched, and place a small plane mirror M at a distance F_1 from the lens (Fig 1b) in such a way that, the slit and knife-edge being at 0, the image of the slit formed by the central zone of the screen falls again on 0. Leaving M in this position, we measure the longitudinal aberrations of the lens y for each pair of zones. If the Cassegrain were spherical we would obtain the same values as before. As it is not, we find that the differences y - y' are not zero. These differences measure the longitudinal aberrations of the Cassegrain alone. In order to calculate its curve of shape we have to compare them with the theoretical aberrations. If the convex surface of the Cassegrain could be observed from behind without the disturbing influence of the glass, it would appear as what the mirror makers call an over-corrected paraboloid.

The longitudinal aberrations of the theoretical surface—a hyperboloid of radius R and eccentricity e—would be given by:

$$Z_t = e^2r^2/2R \quad (1)$$

where r is the mean radius of each screen zone projected on the Cassegrain. The radius of curvature R of the central zone is found by measuring the distance between the surface of the small plane mirror M and the convex face of the Cassegrain.

In order to compare y - y' with Z_t we have to bring both to the same side of the lens. This is easily done if we remember that:

$$\Delta F_1 = -(F_1/F_2)^2 \Delta F_2 \quad (2)$$

If we call Z_m the measured aberration of the Cassegrain transported to the other side of the lens, we have then:

$$-Z_m = (F_1/F_2)^2(y'-y) \quad (3)$$

These are the values to be compared with the theoretical aberration (1).

If we want to obtain the curve of shape of the mirror, we use the well known formula:

$$-\Sigma_h = \Sigma zrdR^{-2} \quad (4)$$

where h is the increment in height across a zone of width d and mean radius r.

If for Z we use the measured values Z_m we obtain the curve of shape referred to the sphere. If we put $Z = Z_m - Z_t$ we obtain the resultant curve of shape referred to a theoretical hyperboloid. One can change the radius of curvature of the hyperboloid of reference simply by adding a constant, but otherwise arbitrary, amount to Z_m.

Discussion and Refinements.

While applying formulas (2) or (3) one has to remember that F_1 is constant for all zones of the screen; but not so F_2, which varies from zone to zone. If the lens L is corrected for spherical aberration for the monochromatic light used and for the image distance F_1, the F_2 and the conversion factor $(F_1/F_2)^2$ are constant. Otherwise they are not and one has to set for F_2 the value corresponding to each particular zone. When the spherical aberration is not too large, a mean value can be used for F_2.

For high precision measurements a further point has to be considered. If the convex mirror C is not spherical, the light beam reflected by it and passing a certain hole in the screen does not go exactly through the same part of the lens as when the plane mirror M is used for that particular zone. If, furthermore, the lens has bad secondary zones, a small deviation of the light beam could affect the accuracy of the determined longitudinal aberrations y of the auxiliary system because the factor $(F_1/F_2)^2$ could not be considered constant even for the neighbourhood of a single zone. This may be the case if the glass of the lens is of very poor quality. But even in this case the method can be applied with any desired accuracy. All that is necessary is to measure directly the aberrations Z of the Cassegrain by displacing the small plane mirror M with a micrometer screw parallel to the optical axis of the system.

An Alternative Method of Measuring.

Once we have determined the values y' of the longitudinal aberration of the Cassegrain plus lens system for each zone of the screen as described above, we remove the Cassegrain without changing the relative positions of lens, screen and knife-edge and place the small plane mirror M on a table that can be moved parallel to the optical axis by means of a micrometer screw and divided drum. After adjusting the mirror M properly, we measure its axial displacements necessary to reproduce the readings y' on the knife-edge side of the lens for each zone pair of the screen. These displacements, counted from the position corresponding to the central zone, measure directly the longitudinal aberration Z_m of the Cassegrain. No correction or calculation is now necessary. The light now traverses exactly the same part of the lens in the two cases. The lens may therefore be as bad as the worst without affecting the accuracy of the measurement. It is not necessary to know the values of F_1 and F_2. The radius of curvature of the central zone of the Cassegrain is found as before. The displacements Z_m of the mirror M can now be directly compared with the theoretical values Z_t given by Eq. (1). The integration is done as before.

The Main Source of Errors.

While applying this method to the Cassegrain of the La Plata reflector, with the crown part of an old lens and a small spherical mirror of short radius of curvature as auxiliary system, it was soon apparent that the main source of errors lies in the difficulty of measuring y' or y with sufficient accuracy when $\Delta y/\Delta r$ has values above a certain limit. This difficulty is not confined to the method here described. It is encountered also when testing a parabolic mirror of large relative aperture at the so-called "center of curvature," and in general whenever the longitudinal aberration of the optical system changes rapidly with the radius of the circular zone. This difficulty consists in the following. While cutting the light of a symmetrical pair of zones near the periphery with the knife-edge in the usual way, it is observed that a photometric comparison of the reduction in intensities of the two opposite parts of the zone becomes impossible. The zones are not obscured uniformly by the knife-edge even if they are chosen very narrow. Shadows enter the zones, one coming from the center and the other from the edge, and move across at different speeds as the knife-edge is made to cut more and more light. It becomes impossible to determine the correct longitudinal position of the knife-edge with sufficient accuracy.

This difficulty was pointed out—without a solution for it being given—37 years ago in a paper[1] constituting a great contribution to the theory of testing mirrors but seldom mentioned in the literature. This paper was brought to my attention after we had analyzed and solved the problem in a general way. The solution was given in a subsequent paper[2] (now known as the caustic test—Ed.). It consists in measuring not at the so-called "center of curvature," that is at the zone of intersection of pairs of symmetrical light beams upon the optical axis (zone called the center of least confusion), but at the real center of curvature of each single zone, that is, at the caustic of the optical system. The new method of measurement can be applied generally and permits attainment of the highest precision.

Conclusion.

Combining the arrangement described in this paper with the general method of surveying optical surfaces explained in the article referred to[2] it is possible to measure a Cassegrain mirror with errors of less than a hundredth of a wavelength of light per zone. This is the precision required for the Cassegrains of large telescopes.

The method can be applied to any convex surface. It permits the control of spherical as well as aspherical surfaces independently of the aberrations introduced by glass of which the lens is made.

Details of the testing and refiguring of the La Plata 82cm reflector are published elsewhere. The corrected Cassegrain has been in use since 1937.

1. F.L.O. Wadsworth, *Popular Astronomy* 10, 337 (1902).
2. "On the Errors of Testing and a New Method for Surveying Optical Surfaces and Systems," Ricardo Platzek and E. Gaviola, *J.O.S.A.* 29, 484 (1939).

TOLERANCES INVOLVED WHEN TESTING

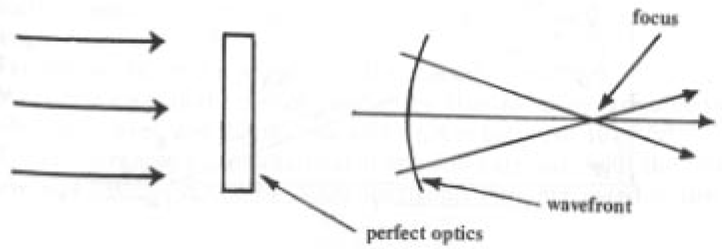
by Diane Lucas

This is a discussion of the tolerances involved when testing optics at focus or at center of curvature.

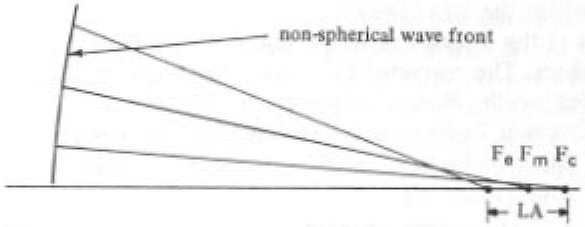
Lord Rayleigh has stated that an optical system will be very good if all the light arrives at the selected focus with at maximum a path difference of 1/4 wavelength. The question of whether this is an adequate tolerance can and has been argued, but 1/4 wavelength is the criterion in this discussion. More stringent tolerances can be scaled down from the results obtained for 1/4 wavelength.

Our eyes are most sensitive to light of a wavelength of 5600 angstroms under normal daylight illumination. This drops to 5000 angstroms at night with a dark adapted eye, so this wavelength will be used in these calculations since it results in a slightly smaller tolerance which will be equally effective at longer wavelengths. Since one inch is 4×10^9 angstroms, 1/4 of 5000 angstroms amounts to only 5×10^{-6} inch.

First let us examine the focus of a perfect optical system. Here, light from a star is bent to form a spherical wave front which converges to a point focus.



In the more usual case of non-perfect optics, the light passing through the optical system does not form a spherical wave front. Light passing through the edge of the aperture will converge to an edge focal point F_e in the diagram below, light through the center to a focal point F_c and light through the intermediate zones of the aperture between the edge and the center to intermediate focal points F_m. In the case illustrated, the best focus is to be found at a point F_m that is half way between F_c and F_e. At this point, in order to meet the Rayleigh criterion, light is required to meet with a phase difference not exceeding 1/4 wavelength.



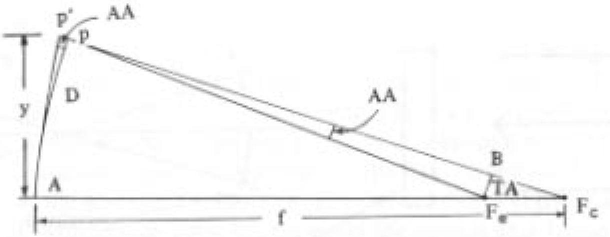
Focusing at F_c or F_e would result in a greater phase difference and lessen image quality. In this figure and the others to be given, the aberrations are greatly exaggerated in order to be easily apparent. This results in the drawings appearing distorted in some cases.

When we test at the focus, it is quite simple to measure the distance F_c to F_e with a knife-edge setup. This distance is referred to as the longitudinal spherical aberration. Conrady has given us an equation for the permissible LA or longitudinal aberration for the 1/4 wavelength limit. In a slightly altered form, this is:

$$\text{permissible LA} = \frac{4\lambda f^2}{y^2}$$

where λ is the wavelength of interest, 5000 angstroms or 20×10^{-6} inches, f is the focal length of the objective and y is the radius.

In order to use this equation to find out what the tolerance is when testing at the center of curvature, several other ways of measuring spherical aberration must be considered. We will draw the diagram again showing a wave front AP which converges to various foci falling between F_c and F_e. If we consider the wave front coincident with the objective, AF_c will be equal to f, the focal length, and AP will be equal to y, the semi-aperture. PF_e is the real path of light from the edge zone,



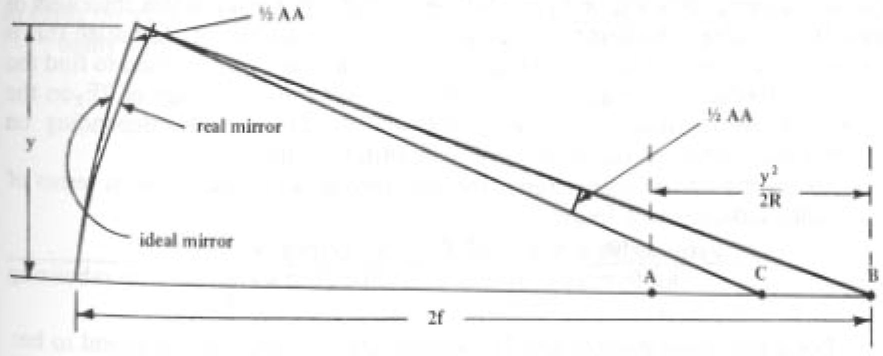
while PF_c is the ideal path, or the one the light would follow if there were no spherical aberration present. The ideal path corresponds to the ideal wave front AP'. BF_e may be regarded as the first of our new forms of spherical aberration. This is known as the transverse aberration, TA, and from similar triangles is found to be equal to LA y/f.

Another measure is angular spherical aberration, AA, shown as the angle BPF_e in the figure. Since TA is a very small quantity compared to f, tan AA is equal to TA/f. And, since AA is a very small angle, tan AA equals AA in radians. Therefore AA = TA/f = LAy/f^2, and for our 1/4 wavelength limit:

$$\text{permissible AA} = 4\lambda/y$$

AA may also be considered on the wave front as the deviation of the ideal from the real wave front (see angle P'DP on the figure); it can be used to find the longitudinal aberration at the center of curvature.

To simplify matters a little, let us first consider testing when the pinhole and knife-edge move together. The requisite knife-edge travel for a parabolic mirror is $y^2/2R$, where y is the radius of the mirror aperture and R is the radius of curvature. Our permissible error of AA, equal to $4\lambda/y$ in the wavefront, will be caused by an error of half this amount on the mirror surface; that is, a dent in the mirror of only 1/8 wavelength deep will cause a dent in the wave front 1/4 wavelength deep. In the figure below, the perfect parabolic mirror and the real mirror with its permitted aberration of ½AA is shown. A is the point where the center of curvature of the central zone is located, and B is a point at a distance of $y^2/2R$ from A where the edge zone should have its center located. In this figure the mirror is under-corrected because it is not fully parabolized.



Working backwards from the ½AA deviation on the mirror's surface, the permissible aberration in the position of B (length BC in the figure) for the 1/4 wavelength limit is found.

Permissible BC = 2 x permissible LA at focus = $8\lambda f^2/y^2$.

When testing with the pinhold stationary, this tolerance is doubled along with the knife-edge travel, and this is equal to 4 x LA at focus, or $16\lambda f^2/y^2$.

These tolerances on longitudinal aberration vary only with the f/ratio of the objective and several values for 5000 angstroms light are listed in the following table:

f/ratio	at focus	at center of curvature pinhole moving	pinhole stationary
4	.005	.010	.020
6	.012	.023	.046
8	.020	.041	.082
10	.032	.064	.128
12	.046	.092	.184
15	.072	.144	.288

When a test at the focus using autocollimated light is used, light passes through the system twice and errors in the wavefront are doubled. Testing at the focus is more definite in the respect that you are working for a "null" test where an even knife-edge cutoff or straight Ronchi bands occur.

There is another way of arriving at the result found above for testing at the center of curvature. A spherical mirror and parabolic mirror tangent at their centers of curvature with the radius R of the sphere equal to twice the focal length f of the parabola are separated at their edges by a distance E_1 equal to $y^4/8R^3$.

If we change the sphere's radius R by $y^2/4R^2$, which is a very small amount compared with R, the parabola will meet the sphere at center and edge and the maximum separation will be $E_2 = 1/4E_1 = y^4/32R^3$. Removal of this thickness of glass from a spherical mirror will result in a paraboloidal mirror. Although this is not exactly the way we remove the glass in parabolizing, E_2 can be used to find the tolerance needed. A change of E_2 on the mirror will cause a change of $2E_2$ on the wavefront, while causing knife-edge travel of $y^2/2R$ or y^2/R, depending on whether the pinhole is stationary or moves with the knife-edge.

By setting up the proper ratio, the tolerance in wavefront error in terms of knife-edge movement is found.

$$\frac{\text{Permissible LA at C-of-C}}{\text{knife-edge movement}} = \frac{\text{Tolerance on wavefront}}{\text{change in wavefront in parabolizing } (=2E_2)}$$

For a stationary pinhole and 1/4 wavelength tolerance, this is found to be:

$$\text{permissible LA at C-of-C} = 16\lambda f^2/y^2$$

which is identical to the result above.

These equations can also be used to determine when there is no need to parabolize a spherical mirror. The minimum focal length for any tolerance and diameter can be found. Set E_2 equal to the tolerance, plug in your value of diameter D and solve for minimum f. For a tolerance of 1/4 wavelength of 5000 angstroms light let $2E_2 = 1/4\lambda$. Then

$$y^4/16R^3 = 1/4(20 \times 10^{-6})$$

and since $D = 2y$ and $R = 2f$,

$$f^3 = 97.6D^4$$

For several diameters of mirrors, the minimum focal lengths found from this equation are given in the following table:

Diameter (inches)	Minimum f (inches)
4	29
6	50
8	74
10	99
12	128

These results and tolerances make it seem fairly easy to produce an optical system that will meet Rayleigh's 1/4 wavelength limit, especially if we select a longer focal length which results in a larger tolerance. Since the tolerance of 1/4 wavelength is required to cover the optical path differences due to all the aberrations of the system, and not spherical aberration alone, perhaps we should be reluctant to use the full tolerance in figuring.

Some of the basic formulas and results were found in these references:

Conrady—*Applied Optics and Optical Design*

Strong—*Concepts of Classical Optics*

Texereau—*How to Make a Telescope*

Another use of these results is to determine the minimum distance at which an artificial star or pinhole can be placed from your telescope and have the non-infinite object distance have a negligible effect on image quality. An aberration of 1/20 wavelength in the artificial star image would probably be negligible enough for anyone. The tolerances for longitudinal aberration at the focus have been scaled down to 1/20 wavelength in the first of the following tables. Using a very convenient formula that Selby gives in *A.T.M. II* for this purpose, and these longitudinal aberration figures from the table, the minimum test object distances in yards for various objective diameters and f/ratios are given in the second table.

Selby's formula

$$\Delta f = \frac{y^2\ (8f^2 + y^2)}{16f^2\ (d - f)}$$

where y = objective radius
f = focal length
Δ f = longitudinal aberration
d = object distance

f/ratio	aberration due to 1/20 wavelength
4	.001
6	.002
8	.004
10	.006
12	.009
15	.014

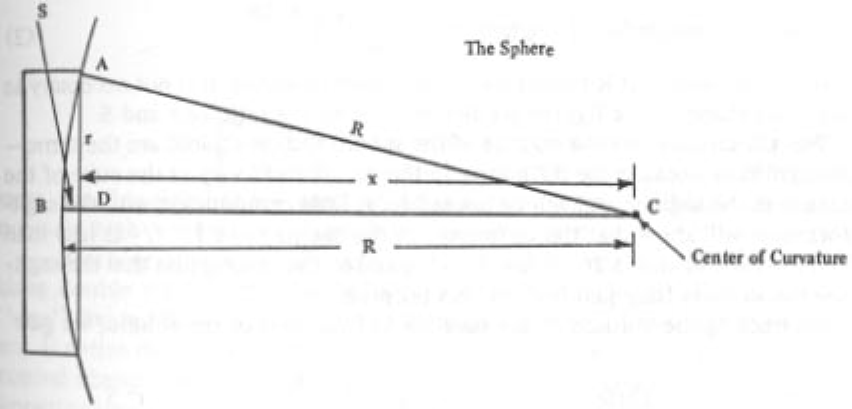
Diameter of objective (inches)	f/ratios 4	6	8	10	12	15
	distances in yards					
4	56	28	15	11	7.5	6
6	126	64	33	23	16	12
8	223	112	58	39	27	19
10	350	175	89	60	41	28
12	501	253	128	87	60	41

Chapter 3
OPTICAL THEORY

SAGITTA MATHEMATICS
by Allan Mackintosh

We may find out how much glass we have to remove when parabolizing a mirror by using the formulae for volume of segments of the sphere and paraboloid. I took them from *Machinery's Handbook*, 14th ed., pp. 160 and 162, and I shall not go through the mathematical proofs because they can be confirmed by referring to any good textbook on solid geometry.

For the sake of the record, please bear with me while I go through short proofs for the sagittae of the circle and parabola.



Without taking proofs too far, we will admit that a diameter which bisects a chord of a circle necessarily passes through it at right angles.

Then, according to Pythagoras:

$$R^2 - r^2 = x^2$$

But $x = BC - BD$, which is $R - S$.

Then $\quad R^2 - r^2 = (R - S)^2$

or $\quad \pm\sqrt{R^2 - r^2} = R - S$

and $\quad S = R \pm \sqrt{R^2 - r^2}$,

$R - \sqrt{R^2 - r^2}$ is what we are interested in.

The Parabola

The general Cartesian equation for the parabola is:

$$y^2 = 2px$$

Assuming that the parabola opens to the right and altering the notation to our familiar R, r and S terms, we may write:

$$y^2 = 2RS$$

Since p is the distance from the focus to the directrix, or twice the distance from the focus to the vertex, from the above we get:

$$S = \frac{r^2}{2R}$$

It will be noted that there are no "abouts" or "approximatelys" in the above equations so the formulae are exact for their respective figures of revolution. I apologize for taking readers through this elementary math, but it is necessary because we shall now use S as such, knowing that we can evaluate it when we wish to do so.

The formulae for volumes of spherical and paraboloidal segments are given in *Machinery's Handbook* and, after altering to our R, r and S notation, are as follow:

$$\text{Volume of spherical segment} = \pi S \left(\frac{4r^2}{8} + \frac{S^2}{6}\right) \qquad (1)$$

$$\text{Volume of paraboloidal segment} = \frac{\pi}{2} r^2 S \qquad (2)$$

It will be noted that R has disappeared in both formulae. It is not necessary as the size and shape of the figures are determined by the ratio of r and S.

We will assume that the sagittae of the sphere and paraboloid are the same—this is legitimate because the difference in the volume will vary as the cube of the difference in the sagittae and will be negligible. A little computation with the sagittae formulae will show that the difference in the sagitta for a 16″ f/4 is less than .0003″; the cube of this is 26 cu. ins. x 10^{-12}, and so the assumption that the sagittae are the same is fully justified for this purpose.

Subtracting the volume of the paraboloid from that of the sphere, we get:

$$\text{Difference} = \pi S \left(\frac{4r^2}{8} + \frac{S^2}{6}\right) - \frac{\pi}{2} r^2 S$$

$$= \frac{4\pi r^2 S}{8} + \frac{\pi S^3}{6} - \frac{\pi r^2 S}{2}$$

$$= \frac{\pi}{6} S^3 \text{ or } .5236s^3$$

Until one begins to think about it hard, this is a somewhat unexpected result—it means that the difference in the volume of any segment of a matching sphere and paraboloid with the same sagitta simply depends on the cube of the sagitta multiplied by $\pi/6$. It does not matter what the values of R and r are, provided that S is the same for each of the figures of revolution.

This is a very simple formula for those who are interested in the amount of glass that they will have to remove in parabolizing. For a 6″ f/8 the amount of glass works out to be .000054 cu. ins., but for a 16″ f/4 it works out to be .008181 cu. ins., 151 times as much glass as for the 6″. This all goes to demonstrate why the big fellas take so much longer to parabolize. The following table shows the amounts to be removed in most of the sizes to be met with by amateurs:

Total stock removal in cubic microinches.

f/	4	5	6	7	8	10	12	15
6″	433	221	128	81	54	28	16	8
8″	1023	524	303	191	128	65	38	19
10″	1997	1023	592	373	250	128	74	38
12″	3451	1767	1023	644	431	221	128	65
16″	8181	4189	2424	1526	1023	524	303	155

FUNDAMENTAL LIMIT OF TELESCOPIC RESOLUTION

by A. S. Leonard

Telescopic resolution may be described as the ability to reveal not only fine detail of high contrast, such as close double stars, but fine detail of low contrast, such as the "canals" of Mars. This requires not only high *resolving power,* but high *contrast* as well.

Resolving power is usually described as the ability of the telescope to separate close double stars. It may be defined as being a number equal to the number "one" divided by the separation of the two components, expressed in seconds of arc. It varies directly with the diameter of the objective, is increased (slightly) by central obstructions (diagonals or secondary mirrors), and is lowered by seeing, imperfections in the surface curves of the optical components, and imperfect collimation.

Contrast may be described as the ability of the telescope to show fine detail of low contrast in planetary images, or the faint companions of bright stars. As yet, there seems to be no generally accepted method of measuring this quantity. Contrast suffers much more than resolving power from seeing, imperfections in the surface curves of the optical components and imperfect collimation. Oddly enough, dust and scratches and other things that produce light losses that are distributed fairly uniformly over the optical surfaces produce relatively little effect on contrast.

Although some amateur built telescopes will show a star image which can best be described as a blob of light, many will show something that resembles, at least vaguely, the Airy diffraction pattern. For a star image such as this, the features which determine resolving power and contrast are (1) the effective diameter of the central disc and (2) the brightness of the surrounding rings, or diffuse light, relative to that of the central disc. If we are to rate a telescope for its "resolution," we should not only look for and study these features of the diffraction pattern, but we should at least attempt to measure them as well.

Methods of Measuring the Effective Diameter of the Central Disc of the Diffraction Pattern.

Although a piece of metal with a small hole, or a telescope with its aperture stopped down to 2 inches or less, will enable us to see an Airy diffraction pattern and thus make a visual comparison between the diffraction pattern produced by the *real* telescope (full aperture) and that produced by the *ideal* telescope (reduced aperture), they don't provide the means for measuring the quantities which should be measured. It might be thought that the measurement of the effective diameter of the central disc of the diffraction pattern would require the use of a filar micrometer, or some such instrument; actually this measurement can be made quite satisfactorily without a micrometer. All that is needed is a series of double stars chosen to cover a small range of separations near the limit of resolution of the telescope, and an eyepiece which gives the telescope about 40 or more power per inch of aperture. To be useful for this purpose, the two components of each double star should not differ in magnitude by more than about two magnitudes.

To make the measurement, the telescope should be trained on double stars, one after the other, until one is found which appears to be just barely separated. The *effective* diameter of the central disc of the diffraction pattern can be taken to be equal to the separation of the double star, in seconds of arc.

Unfortunately, the making of this measurement is not a completely cut-and-dried proposition. Rayleigh has given us the following formula:

$$S_R = \frac{5.5}{D} \qquad (1)$$

where S_R is the separation of the components of a double star (in seconds of arc) which is just barely resolved (separated) by an optically perfect telescope of diameter D inches (clear aperture) under conditions of perfect seeing. The Rayleigh formula is based on the assumption that the double star will be just barely resolved when the center of the central disc of the diffraction pattern of one component falls in the middle of the first dark ring (midway between the outside edge of the central disc and the inside edge of the first bright ring) of the diffraction pattern of the other component.

Dawes felt that a perfect telescope should do somewhat better than that and gave the following formula:

$$S_D = \frac{4.5}{D} \qquad (2)$$

Now, actually there is a lot of overlap of the central discs of the diffraction patterns of the two components under both these conditions and whether or not they appear to be separated is to some extent a matter of personal opinion. Beginners tend to rate as just barely separated stars at or near the Rayleigh separation. As they gain experience, however, their standards seem to change. Experienced observers usually have standards near to those of Dawes.

In order that the observer shall be able to rate himself in this respect, a fairly bright double star of 2 or more seconds of arc separation should be chosen (be sure to use an up-to-date ephemeris because some double stars move fairly rapidly). Then the objective should be stopped down, using a series of diaphragm stops having clear apertures which are circular, until a diameter is found which makes the pair appear to be just barely separated. Then, using this diameter and the stars' separation, the observer can set up "Joe Brown's formula" for double star resolution. It might be as well if this experiment were made on several different pairs of stars and then the results averaged.

For the purpose of rating a telescope for its performance on any given type of object or observation, its "equivalent diameter" is probably as practical a figure-of-merit as any. "Equivalent diameter" is defined as the diameter of the perfect telescope which, under conditions of perfect seeing, would perform equally well for the same observation. To obtain the equivalent diameter for the telescope for double star resolution, the numerical value of the separation of the closest double star which can be resolved by the telescope at full aperture should be put into "Joe Brown's formula" and the value D calculated.

Methods of Measuring the Relative Brightness of the Rings of the Diffraction Pattern.

The measurement of the relative brightness of the rings of the diffraction pattern is a problem in photometry. Although it may be very instructive to the telescope maker to look at the image of a single star as seen in his telescope at full aperture and to compare it with an Airy pattern, it will be practically impossible for him to make a reasonably accurate estimate of the difference in relative brightness of the surrounding rings from such an observation. The reason for this is that the eye is incapable of making an accurate estimate of the *difference* in brightness when that difference is as great as that between the central disc and the first bright ring of the Airy diffraction pattern. On the other hand, when the difference in brightness is small, the eye is fairly good at picking the brighter of two points or surfaces. This suggests that what is needed is another light source which is about the same brightness as the rings of the diffraction pattern and for which reasonably accurate determinations of brightness have been made by other methods.

For this purpose, a bright star which has a faint companion is just what is needed. Experiments in which artificial bright stars with faint companions were viewed under what amounted to optically perfect conditions have shown that the faint companion will be just barely visible in the rings of the *Airy* pattern of the bright star when the brightness of the center of the central disc is just about equal to that of the brightest point in the particular ring of the bright star in which it is found to lie. Since Airy's equations can be used to predict the brightness of all bright rings in the diffraction pattern, a formula may be derived which will give the relationship between the angular separation, brightness difference, and telescopic diameter:

$$\log. D = 0.292 + 0.133\Delta M - \log. S \qquad (3)$$

In this equation, D is the diameter (in inches) of the telescope (optically perfect), ΔM is the difference in brightness (in stellar magnitudes) between the bright and faint stars, and S is their separation (in seconds of arc). The base of the logarithms is 10.

Just as was found in the observations of double stars where the components were of nearly equal brightness, personal opinion will be a factor in these observations. Here again, Joe Brown will have to calibrate his eye under ideal conditions, and then set up *his* formula. (It should be the same as Eq. 3 above, except that it will probably have a different value for the constant 0.292.) Although this calibration might be done with the telescope stopped down, there are so few pairs of stars which are suitable for this work (calibration) that it may have to be done with artificial stars—a one-inch and a one-eighth steel ball, polished and set in the sunlight, will make a good artificial pair. Since the observer's eye will probably become sharper with continued use, he should re-calibrate it from time to time.

Since the purpose of measuring the relative brightness of the rings of the diffraction pattern is to determine the contrast of the telescope, we should direct our attention to the measurement of those rings which have the most effect on contrast. Of all the rings, the first is by far the most important. One reason for this is that in the diffraction patterns of most real telescopes, the first bright ring will contain well over half the light outside the central disc. Another reason is that as far as the detrimental effects (to contrast) are concerned, the brightness, or concentration, of the light in a ring may be as important as its total amount—if we must have a lot of light in the rings, it might be better to have it spread out very wide and thin than concentrated near the central disc.

In order to apply this test to the measurement of the brightness of the first bright ring in the diffraction pattern (or thereabouts in the blob of light), we should select a pair of stars for which the brightness difference is about 3.5 and 5 magnitudes. Another limitation in the selection of stars for this test is that the faint companion should not be too faint or it will be invisible, not so much because of the brightness of the rings of the bright star as because of its own faintness. To meet this requirement, the faint companion should appear in the telescope at least as bright as a 6th magnitude star would appear in a 1-inch telescope. In order to minimize the adverse effects of seeing, the star should be fairly high in the sky when the observations are made.

Unfortunately, the number of stars which can meet all these requirements is rather small. Another unfortunate circumstance is the lack of accuracy in the available data on double stars of this type. Comparisons of the data in a very recent catalogue with the best previously available data have revealed changes of more than one magnitude in the tabulated value of brightness differences for some of the pairs.

In order to rate a telescope for its contrast (by this method), various pairs of stars should be examined with the telescope (at full aperture) and note made for each as to how visible (or invisible) the faint companion is observed to be. Then, using Eq. 3 (with Joe Brown's constant in it), a value of D should be calculated for each pair. For the pairs in which the faint companion was easily visible, the "equivalent diameter" of the telescope must be definitely larger than the calculated value. For those that were invisible, the equivalent diameter must be smaller than the calculated value. From a study of all these calculations, the observer should be able to make a fair estimate of the "equivalent diameter for contrast" of his telescope.

In general the "equivalent diameter for contrast" will be somewhat less than the "equivalent diameter for resolving power." The reason for this is that seeing and instrumental errors (and central obstructions) are much more detrimental to contrast than to resolving power.

In conclusion, it should be pointed out that even though the "Airy" diffraction pattern may rightfully be regarded as the hall-mark of optical perfection, it is not necessarily the best diffraction pattern for all types of observations. A central obstruction produces a modified diffraction pattern which is superior for double star resolution; and an apodized aperture produces a modification which is superior for planetary observation. However, the Airy pattern should be regarded as a useful standard because it can be produced quite easily, and its performance is seldom equalled in actual practice.

A note of caution should be added in regard to the method of measuring the brightness of the rings in the diffraction pattern which has been presented above—it has been tried on a limited scale and appears to work fairly well; but it needs further development and at present should only be regarded as a proposed method.

LIMITING MAGNITUDES OF VISUAL TELESCOPES

by A. S. Leonard

It was back in the spring of 1957, and I had just completed construction of what I thought was the world's finest satellite tracking telescope. It had a 2-inch objective of 23-inch focal length and a newly designed wide-angle eyepiece of mine which gave a magnification of 6.8 and covered a field of 10° in the sky. The star images were razor sharp from edge to edge of the field and, according to the books, my 3.4 power per inch of aperture was just right for richest field design.

According to a formula for limiting magnitude in Dimitroff and Baker, *Telescopes and Accessories,* Harvard University Press, this telescope should show stars down to a magnitude of +10.3. I decided to try to verify this performance on stars of the North Polar Sequence. To my satisfaction, I found that the actual performance of the instrument was reasonably close to the predicted value. Then, just to see how much better my new eyepiece was, particularly near the edges of its field, than a commercially available unit, I replaced it with a 1½" Erfle. To my great surprise the Erfle showed stars, at least in the central part of its field, which were considerably fainter than what I could pick up with my own design. In order to check this finding with another commercially available unit, I tried a ½" symmetrical eyepiece. I found it to be capable of showing even fainter stars than the Erfle.

Since all three eyepieces had coated optics throughout and gave clear, sharp star images, I had to conclude that the magnifying power, as well as aperture of the objective, must have an important influence on the limiting visual magnitude of a telescope. With this benefit of hindsight, now, it is easy to understand why this should be so. What we will be able to detect in the eyepiece of the telescope will depend not only on how much light from the star the eyepiece has collected and how well the optical system has succeeded in concentrating it into a point on the retina of the observer's eye, but also on the brightness of the surrounding sky background. As most observers know, an increase in magnifying power with a given objective, results in a decrease in the brightness of the surrounding sky background. Up to some fairly high power at least, an increase in magnification results in very little decrease in brightness of the star image. With a given telescope objective, therefore, we should be able to see fainter and fainter stars as we go to higher and higher powers of magnification. At this point I decided that preliminary investigation of the matter, at least, was in order and that I should proceed with the project as best I could.

Experimental Programme.

In order to investigate this matter thoroughly, I needed to obtain data over a fairly wide range of variation of three parameters. These were (1) telescope aperture, (2) magnifying power or, better still, magnifying power per inch of aperture, and (3) star brightness. If I were to keep the aperture constant and vary the other two, I would have only as many data points as powers of magnification, or eye pieces. Either I would have to acquire a large number of eyepieces, each of a slightly different focal length, or settle for a small number of data points. Neither of these alternatives was particularly attractive to me at the time.

Another alternative would be to vary the aperture with an iris diaphragm, or a set of fixed aperture stops. With either of these alternatives, I would get as many data points as I had stars, and this would result in a maximum economy of preparation, and observing, time. Having a good sheet metal punch at my disposal, I chose the latter alternative. I made up several sets of fixed aperture stops in the form of circular wheels which could be mounted in front of the objective and rotated by a knob located at the back end of the telescope. With this arrangement, I could bring any desired aperture in front of the objective while keeping my eye on the star in question in the eyepiece.

I soon came to realize that with this arrangement, I could cover completely my desired range of variation of parameters with only one eyepiece and one power of magnification. All that was required was a sufficiently wide range of aperture stops and a proper selection of test stars. This had the distinct advantage that light losses within the optical system would remain constant throughout the full range of data acquired. This would remove one otherwise uncontrollable variable in the system.

Before I had time to start with data collection, however, the idea occurred to me that with the proper selection of aperture stops and test stars, the telescope itself could be eliminated from the system. This had the obvious advantage of allowing me to sidestep completely the question of light losses in the optical system as well as its optical quality. The equipment which I finally used to collect the data consisted of a series of about 60 circular discs, 1.5 inches in diameter, punched from rather thin sheet aluminum, and each drilled with a slightly different diameter hole. The hole diameters varied from 0.025" (No. 76 drill) to 0.500" in small steps.

The test procedure consisted of going to a suitable observing site on a clear, dark night, identifying a test star in the sky, and then trying to observe it with one of the aperture stops held in front of the eye. I tried one stop after another until the smallest one through which I could just barely see the star, was found. The stars used and other data are presented in Table 1.

Test stars were chosen which would give me a good coverage of visual magnitudes between about +3.5 and +6.3. Stars were selected from a general area of the sky which would place them fairly high in the sky at the time of night and time of year planned for making the tests. The following criteria were used in the selection of test stars: a test star must have brighter stars nearby in the sky which would serve to locate it when it was at the limit of visibility. These brighter stars should be far enough away so that there would be no danger of mistaking one of them for the test star nor of their light contributing to that of the test star and thus making it

Table 1. Data and Results

Star	Visual Mag. m	Stellar Class	Observing Site	Elevation above Sea Level	Approx. Zenith Distance	Corr. for Atmospheric Absorption Δm	Aperture Diameter D	Equivalent Magnitude m_e	Specific Magnification P/D
Delta Ursae Majoris	+3.44	A2	Wrights Lake	7000'	60°	0.15m	0.025"	11.60	40.
Epsilon Cassiopaiae	+3.44	B3	Wrights Lake	7000	60	0.15	0.025	11.60	40.
Epsilon Ursae Minoris	+4.40	G5	Mt. Vaca	2600	45	0.08	0.040	11.47	25.
Zeta Ursae Minoris	+4.34	A3	Mt. Vaca	2600	45	0.08	0.040	11.41	25.
4 Ursae Minoris	+5.00	KO	Mt. Vaca	2600	47	0.09	0.067	11.06	14.9
89 Herculis	+5.48	$F5_p$	Mt. Vaca	2600	15	0.01	0.082	10.92	12.2
Grb 2900 Draconis	+6.00	A2	Mt. Vaca	2600	42	0.07	0.1285	10.52	7.8
Pi 16°307 Herculis*	+6.36	AD	Mt. Vaca	2600	15	0.01	0.20 0.40	9.86 8.36	5.0 2.5

*Could not see this star through either of the two aperture discs listed nor with both eyes.

more readily visible. Finally, the test star should be located in an area of the sky which is devoid of other stars of comparable brightness.

In observing some of the brighter stars on the list, with which some of the smaller aperture stops were used, dark adaptation for as long as 30 minutes was required.

Results.

In order to reduce as far as possible the effects of uncontrolled variables, an attempt was made to allow for atmospheric absorption in the reduction of the data. This has the effect of placing each star in the zenith at the time of its observation.

The results are presented in Fig. 1, where the equivalent magnitude, m_e, is plotted as an ordinate against specific magnification, P/D, in power per inch of aperture, as abscissa. Because of the logarithmic nature of the stellar magnitude scale, a logarithmic scale is used in plotting values of specific magnification. Equivalent magnitude is defined as the stellar magnitude that a star would have in order to be equally visible in an optically perfect 1-inch telescope at the same specific magnification and the same observing conditions.

The data as plotted define a rather smooth curve. Since the brightness of the background illumination varies very nearly inversely as the square of the specific magnification, the curve demonstrates the steady dependence of equivalent limiting magnitude on the background illumination.

The curve as presented should be regarded as an absolute maximum which might be approached but not quite attained with any given telescope. Any real telescope has light losses in it which will generally reduce star brightness more than background illumination. This effect will be more pronounced with larger instruments and at higher specific magnifications. Sky illumination from man-made sources will have an adverse effect on the telescope's ability to reveal faint stars.

Discussion.

Arguments presented by James G. Baker (notes on "Limiting Visual Magnitudes for Small Telescopes," *Sky & Telescope,* Vol. XII, No. 10, pp. 271-273, Aug., 1953) in support of his formula for the limiting visual magnitude of a telescope:

$$m = 8.8 + 5 \log D$$

indicate that it was derived without reference to any telescopic observations. The only experimental data employed were observations made with the unaided dark-adapted eye. This formula, in effect, says that the limiting visual magnitude of a telescope is determined entirely by the area of its objective, and not at all by its magnifying power. It says that the equivalent limiting magnitude of all telescopes is +8.8 regardless of the specific magnification employed.

Let us look at the record. Table 2 presents observational data and calculated results from several noted professional observers.

The average value for equivalent limiting magnitude for the observations presented in Table 2 is 11.1. Obviously the value of 8.8 predicted by Baker's formula is seriously in error. Although the specific magnification employed in making these observations could not be calculated because of insufficient data, it would be logical to assume that it was fairly high. The fact that Curtis was able to see a star of +8.1 without the aid of a telescope shows that the human eye has the sensitivity to see such a faint light source, provided that the background illumination is reduced to a very low level.

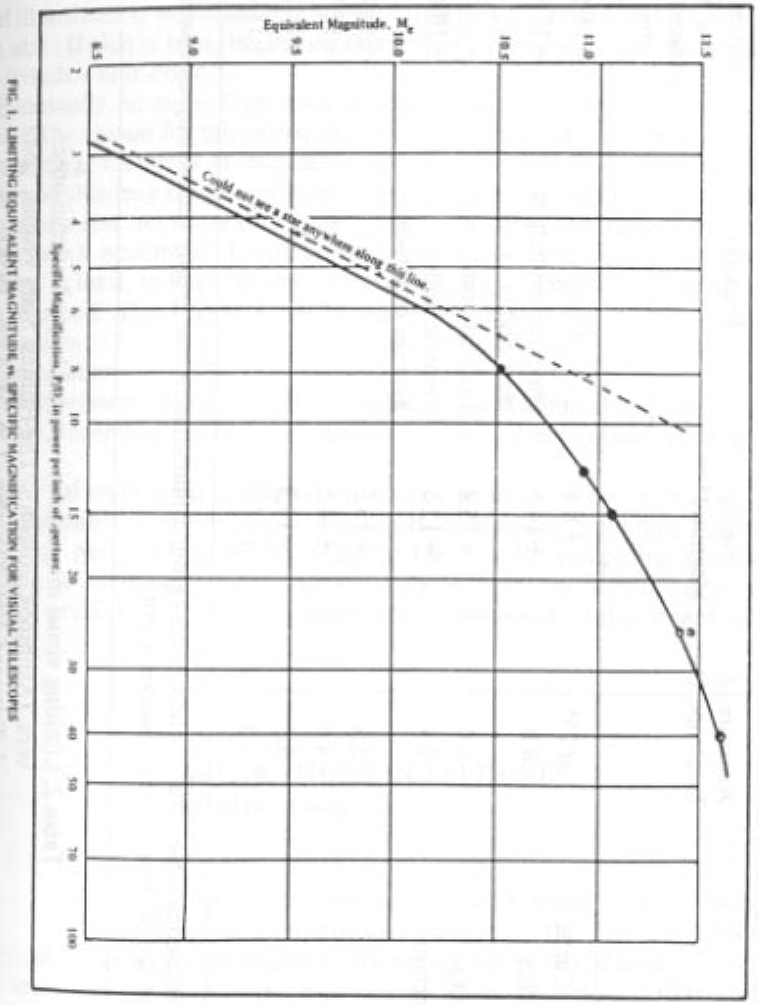


FIG. 1. LIMITING EQUIVALENT MAGNITUDE vs. SPECIFIC MAGNIFICATION FOR VISUAL TELESCOPES

Observer	Aperture of Telescope D	Stellar Magnitude m	Remarks	Equivalent Limiting Visual Magnitude m_e
Heber D. Curtis	0.25*	+8.1	Seen	+11.11
Luigi Jacchia	6.0	+14.6	Observed on half of clear nights	+10.71
Luigi Jacchia	6.0	+15.4	Faintest seen	+11.51
R. B. Lacchini	2.4	+12.5	Faintest under average conditions	+10.6
"	2.8	+13.3	"	+11.6
"	3.9	+14.5	"	+11.54
"	5.3	+14.8	"	+11.18
"	5.9	+15.0	"	+11.15

* Non-telescopic observation wherein background illumination was greatly reduced by an opaque screen located 15 feet in front of the observer's eye.

Table 2. Limiting visual magnitudes reported by professional observers. (Ashbrook, Joseph, "The Faintest Stars Visible," *Sky & Telescope*, Vol. XIV, No. 2, p. 58, Dec., 1954)

Baker's equation is apparently based on the assumption that the brightness of the night sky is so low that it will have no effect on the ability of the fully dark-adapted eye to see a faint star. Curtis's observation tends to refute this. I noticed that when making observations at the highest specific magnification (40 power-per-inch of aperture), I could still see the outline of trees against the night sky. This means that my eye is sensitive to even this low level of background illumination. It would seem reasonable, therefore, to assume that higher levels of background illumination would have an adverse effect on the ability of the eye to detect a faint star. If this is true, the curve should have a positive slope throughout its entire length—as it does.

Eventually, at some high level of specific magnification, the curve should level off. The reason for this is that above some level of this parameter, even with perfect seeing, increases in magnification will result in loss in sharpness in star images, and this may have an adverse effect on the ability of the eye to detect the presence of a star. At some still higher power, the curve may turn downward and thus provide a maximum. If this is true, it would be of interest to variable star observers, at least, to know at what value of specific magnification this maximum will be attained. This suggests that further research into this matter might yield useful results.

Conclusions.

1. Experiments have shown that the limiting visual magnitude of a telescope is strongly dependent on both the diameter of the objective and its magnifying power.

2. At values of specific magnification of up to 40 power-per-inch of aperture, at least, increases in magnifying power result in increases in limiting magnitude.

3. The previously generally accepted formula for computing the limiting magnitude of a telescope is not only seriously in error, but is misleading as well, because it predicts that limiting magnitude is completely independent of magnification.

ABERRATIONS IN TELESCOPES

by Diane Lucas

If one is concerned only with small fields of view and systems without very short radii, the third order theory of geometrical optics serves admirably to predict the behaviour of optical systems. A perfect image would be the exact pictorial replica of the object, differing only in size and position. Since in practice this ideal is never realized, the deviations or aberrations of a real image from the ideal image are described in terms of the way the real image differs. The deviations are often broken down into various types of aberrations, depending on their behaviour. For instance, spherical aberration is constant over the field of view while coma varies directly with the image distance from the optical axis. The third order errors are based on a simplification of geometrical optics and within the limitations mentioned above allow a prediction of the amount of aberration of an image that is almost exact.

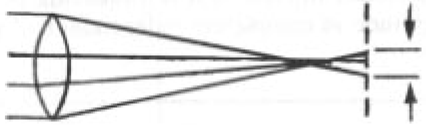
One of the first attempts to develop a systematic way of calculating these errors was a lengthy paper published in 1905 by K. Schwarzchild, a German astronomer. The equations developed in this study are based on the Schwarzchild equations. Schwarzchild treated mainly the third order aberrations, although he mentioned and described fifth order aberrations which are of importance if wider fields and shorter radii are permitted. Among more modern discussions of third and fifth and higher order errors are Herzberger's *Modern Geometrical Optics*, Buchdal's *Optical Aberration Coefficients* and a review article by J. Focke in Volume IV of *Progress in Optics* edited by E. Wolfe. However, for the purpose of gaining a basis for comparing telescopes by their inherent aberrations, Schwarzchild's equations for third order aberration coefficients are completely adequate.

First, the five third order aberrations will be described and their relation to the aberration coefficients will be given; the next section will describe the relation of the deformation to various conic sections. Then the general equations for reflecting telescopes and specific equations for various types of reflectors will be given; this will be followed by a discussion and comparison of the types given.

Third Order Errors.

There are five third order errors: spherical aberration, coma, distortion, astigmatism and field curvature. The Schwarzchild equations allow five coefficients B, C, D. E and F to be calculated from the basic dimensions and data of an optical system which will then give quantitative amounts of the errors. We will describe the effect of each of the aberrations assuming that it alone is present in turn.

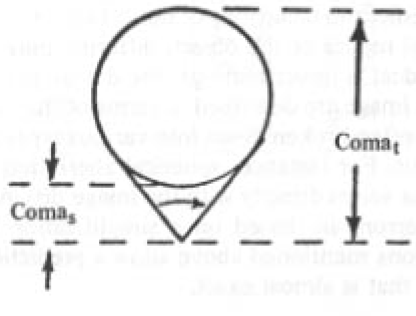
Spherical Aberration occurs when the paraxial and marginal foci do not coincide and a circle of confusion forms instead of a sharp image. The coefficient B is a measure of this and the diameter of the circle of confusion is:



$$B' = 51{,}566\ \mathbb{D}^3 B \text{ seconds}$$

where $\mathbb{D}$ is the aperture of the system. Since telescopes are designed and made to have zero spherical aberration, calculation of this quantity is usually unimportant. If spherical aberration is present, it occurs to the same degree throughout the field.

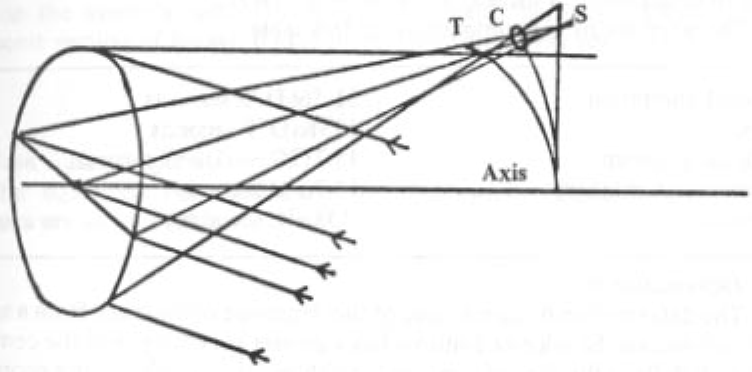
Coma is an unsymmetrical image deformation that affects off-axis images proportional to their distance from the optical axis. The radial extent of the image is called $Coma_t$ and is measured by the Schwarzchild equation:



$$Coma_t = 1351\ \mathbb{D}^2 F \text{ seconds}$$

Only in very serious examples of coma does an image patch of this shape appear (Conrady, *Applied Optics and Optical Design*, p. 743). Usually the extent is only one third of this. $\mathbb{D}$ is again the aperture of the system and α is the field diameter in degrees.

Astigmatism and Field Curvature are present if the coefficients C and D are not zero. These two aberrations are best considered together. If astigmatism is absent and only field curvature is present, the best focus is a curved surface whose radius is g and the field curvature then equals $2(C + D) = 1/g$. When astigmatism is also present there is no point focus but two line foci are formed, a radial or sagittal line focus on a "sagittal image surface" of radius g_s, and a tangential line focus in a "tangential surface" of radius g_t. The best focus when astigmatism is present is on a curved field between the two line focal surfaces; the best focus is that given by the field curvature as $1/g = 2(C + D)$. The diagram shows these surfaces for a Newtonian type telescope.



At positions other than the three surfaces, the image is an elliptical blob of light whose dimensions at a flat focal plane are:

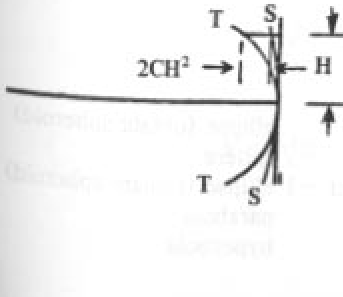
Radial astigmatism $= -15.72\ (2C + D)\alpha^2\mathbb{D}$ seconds

Tangential astigmatism $= -15.72\alpha^2\mathbb{D}$ seconds

The curvatures of the three surfaces are:

$$1/g_t = 2(2C + D)$$
$$1/g = 2(C + D)$$
$$1/g_s = 2D$$

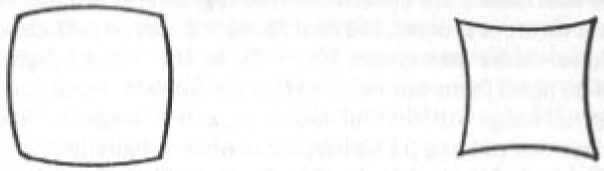
Schwarzchild defined astigmatism as the half difference of the curvatures of the tangential and sagittal image surfaces, which equals $\frac{1}{2}(1/g_t - 1/g_s) = 2C$. It can be shown that the actual distance between the tangential and sagittal image surfaces at a distance H from the axis is equal to $2CH^2$. This means that astigmatism is zero on the optical axis and increases with the square of the distance away from the axis.



Distortion does not affect the image shape but only its radial position by this amount:

$$\text{Distortion} = 0.138\alpha^3 \text{ seconds}$$

This aberration makes the image of a square appear either barrel or pincushion shaped.



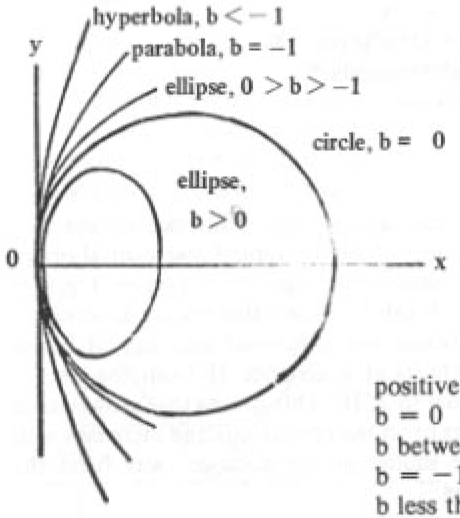
These aberrations have been given in terms of seconds of arc in the focal plane. They may be converted to inches by multiplying by $4.95f(10^{-6})$ where f is the effective focal length of the system; the field diameter in degrees, α, is related to the field diameter in inches, W, by $\alpha = 57.3W/f$.

The aberrations are summarized in this table:

Spherical aberration	$51{,}566D^{-3}B$ seconds
Coma$_t$	$1351\alpha D^{-2}F$ seconds
Radial astigmatism	$15.7(2C + D)\alpha^2 D$ seconds
Tangential astigmatism	$15.7\alpha^2 D$ seconds
Distortion	$.138\alpha^3 E$ seconds

Deformation b.

The deformation b is a measure of the departure of a surface from a sphere; a positive b means the edge of a mirror has a greater curvature than the center. The value of b defines the type of conic section ($b = -e^2$, where e is the eccentricity) as follows:



positive b	ellipse (oblate spheroid)
b = 0	sphere
b between 0 and −1	ellipse (prolate spheroid)
b = −1	parabola
b less than −1	hyperbola

The general equation of a conic section with the vertex at origin is:

$$(b + 1)x^2 - 2rx + y^2 = 0$$

or in a different form:

$$x = \frac{r}{b+1}\left(1 \pm r^2 - (b+1)y^2\right)$$

If $y << r$, which is true with most mirrors, this may be expressed in series as:

$$x = \frac{y^2}{2R} + \frac{(b+1)y^4}{8r^3} + \frac{(b+1)^2 y^6}{16r^5} + \ldots\ldots$$

In these equations r is the radius at the vertex and x and y are coordinates of points on the mirror's surface. The horizontal gap c between a sphere and any other conic section of known b may be obtained from this equation:

$$c = \frac{by^4}{8r^3} + \frac{(b^2 + 2b)y^6}{16r^5} + \ldots\ldots$$

Basic Equations for Reflectors.

The equations that determine the 3rd order aberrations in reflecting telescopes are as follows:

$$B = h_i^4\left[\frac{b_i}{r_i^3} + \frac{K_i^2}{r_i}\right]$$

$$C = h_i^2 H_i^2\left[\frac{b_i}{r_i^3} + \frac{L_i^2}{r_i}\right]$$

$$D = h_i^2 H_i^2\left[\frac{b_i}{r_i^3} + \frac{K_i\,(2L_i - K_i)}{r_i}\right]$$

$$E = h_i H_i^3\left[\frac{b_i}{r_i^3} + \frac{L_i\,(2L_i - K_i)}{r_i}\right]$$

$$F = h_i^3 H_i\left[\frac{b_i}{r_i^3} + \frac{K_i L_i}{r_i}\right]$$

In these equations the following abbreviations are used:
r_i = radius of i mirror (positive for concaves)
b_i = deformation of i mirror
s_i = distance from i mirror to object
s'_i = distance from i mirror to image
t_i = distance from i mirror to its entrance pupil
t'_i = distance from i mirror to its exit pupil
d_i = distance from i mirror to 1+i mirror
Then:

$$h_i = \frac{s_i}{s_i - t_i}, \qquad h_{i+1} = \frac{s_{i+1}}{s'_i} h_i$$

$$H_i = t_i, \qquad H_{i+1} = \frac{t_{i+1}}{t'_i} H_i$$

$$K_i = \frac{1}{s_i} - \frac{1}{r_i} = \frac{1}{s'_i} + \frac{1}{r'_i}$$

$$L_i = \frac{1}{t_i} - \frac{1}{r_i} = \frac{1}{t'_i} + \frac{1}{r'_i}$$

$$d_i = s_{i+1} - s'_i = t_{i+1} - t_i$$

$$H_i h_i (L_i - K_i) = 1$$

The Single Mirror.

In the case of a single mirror of focal length $f = r/2$ the following quantities determine the third order errors when the object is at an infinite distance:

$$s = f, s' = -\frac{r}{2}, K = -\frac{1}{r}, L = \frac{1}{t} - \frac{1}{r}, h - 1, H_i = t$$

The expressions are developed first without specifying t, and then t, the distance to the entrance pupil from the mirror, is set at zero. This gives:

$$B = h^4 \left[\frac{b}{r^3} + \frac{K^2}{r}\right] = \frac{b+1}{r^3} = \frac{b+1}{8f^3}$$

$$C = h^2H^2 \left[\frac{b}{r^3} + \frac{L^2}{r}\right] = \frac{1}{r} = \frac{1}{2f}$$

$$D = h^2H^2 \left[\frac{b}{r^3} + \frac{K(2L-K)}{r}\right] = 0$$

$$E = hH^3 \left[\frac{b}{r^3} + \frac{L(2L-K)}{r}\right] = 0$$

$$F = h^3H \left[\frac{b}{r^3} + \frac{KL}{r}\right] = -\frac{1}{r^2} = -\frac{1}{4f^2}$$

Then the aberrations in seconds of arc at the focal plane where α is the angular diameter in degrees are:

Sph. Ab. = $6448(b+1)(D/f)^3$

(If the mirror is parabolic, b = −1 and Sph. Ab. = 0).

$$\text{Coma}_t = -338\alpha\,(D/f)^2 \text{ seconds} = \frac{3W\,D^2}{32f^2} \text{ inches.}$$

Dist. = 0

$$\text{Radial Astig.} = -15.7\alpha^2\,D/f = -\frac{0.256W^2\,D}{f^2} \text{ inches.}$$

Tangential Astig. = 0

D is aperture and f is focal length, hence D/f is aperture ratio; W is the field diameter in inches.

The curvatures of the tangential and sagittal astigmatic surfaces and the field curvature are:

$1/g_t = 2/f$
$1/g = 1/f$
$1/g_s = 0$

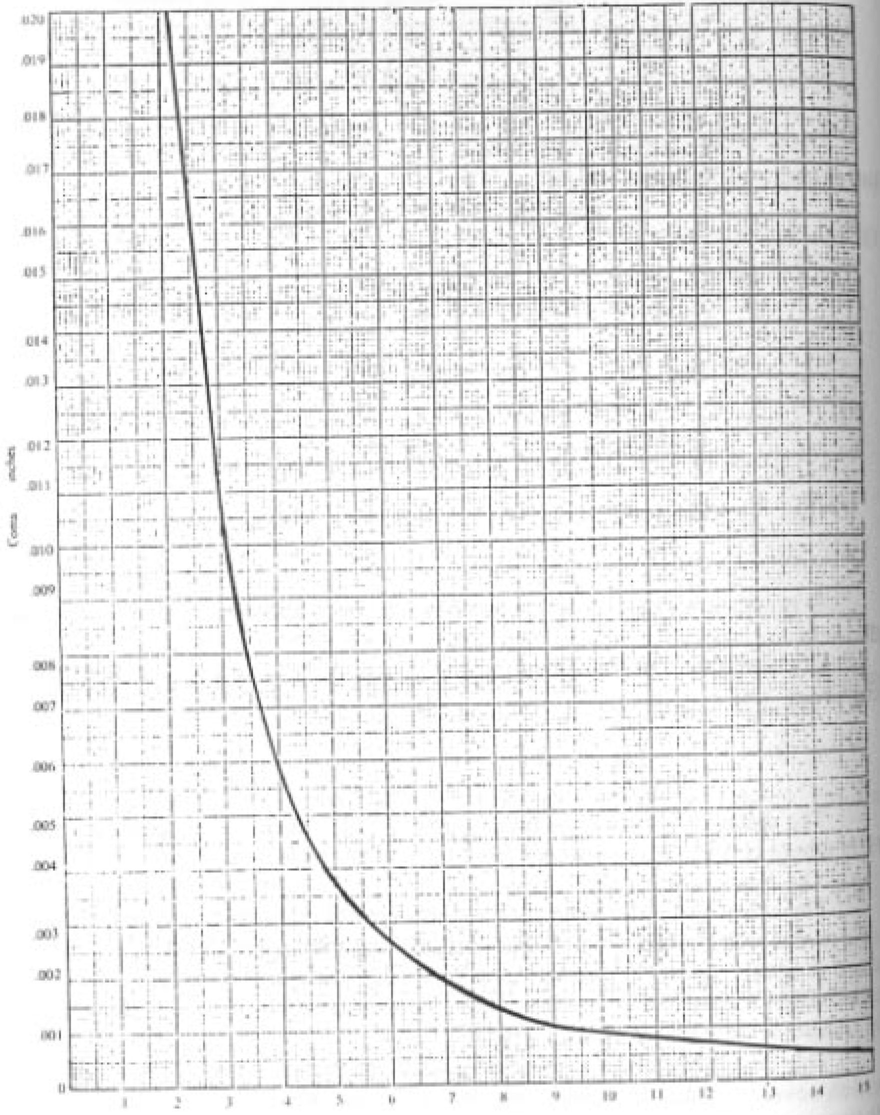
The distance between the two astigmatic surfaces or the astigmatism equals H^2/f where H is the linear distance from the axis of the image.

The Newtonian Reflector.

The only third order aberrations of this type of telescope are coma, field curvature and astigmatism. Coma is the most serious aberration of the Newtonian and since it equals $338\alpha D^2/f^2$ seconds or $3W\,D^2/32f^2$ inches, it is relatively simple to calculate its amount at any position in the field; this has been done at the edge of a 1″ diameter field and is plotted in graph Fig. 1.

This shows that short rich-field Newtonians have a serious amount of coma which severely limits their real usefulness. We can show this more plainly if we derive an expression for the maximum usable photographic field as limited by coma. Professional astronomers use a limit of maximum coma_t permissible as 0.004″, and if we use this, the maximum usable field in inches equals $W - 0.043\ (f/D)^2$. This is plotted in the graph Fig. 2. If the amount of coma were the only important factor in photography, all photographic Newtonians would be very long focus instruments. For the sake of comparison, this graph also shows the

COMA AT EDGE OF 1 INCH DIAMETER FIELD



field where the coma is less than ¼ wavelength. This gives the field where the best visual resolution is obtained. (W for $\frac{1}{4}\lambda = .0007f^3/D^3$ is derived from Conrady's *Applied Optics and Optical Design*, p. 395.)

MAXIMUM USEFUL FIELD (PHOTOGRAPHIC) OF PARABOLIC MIRROR

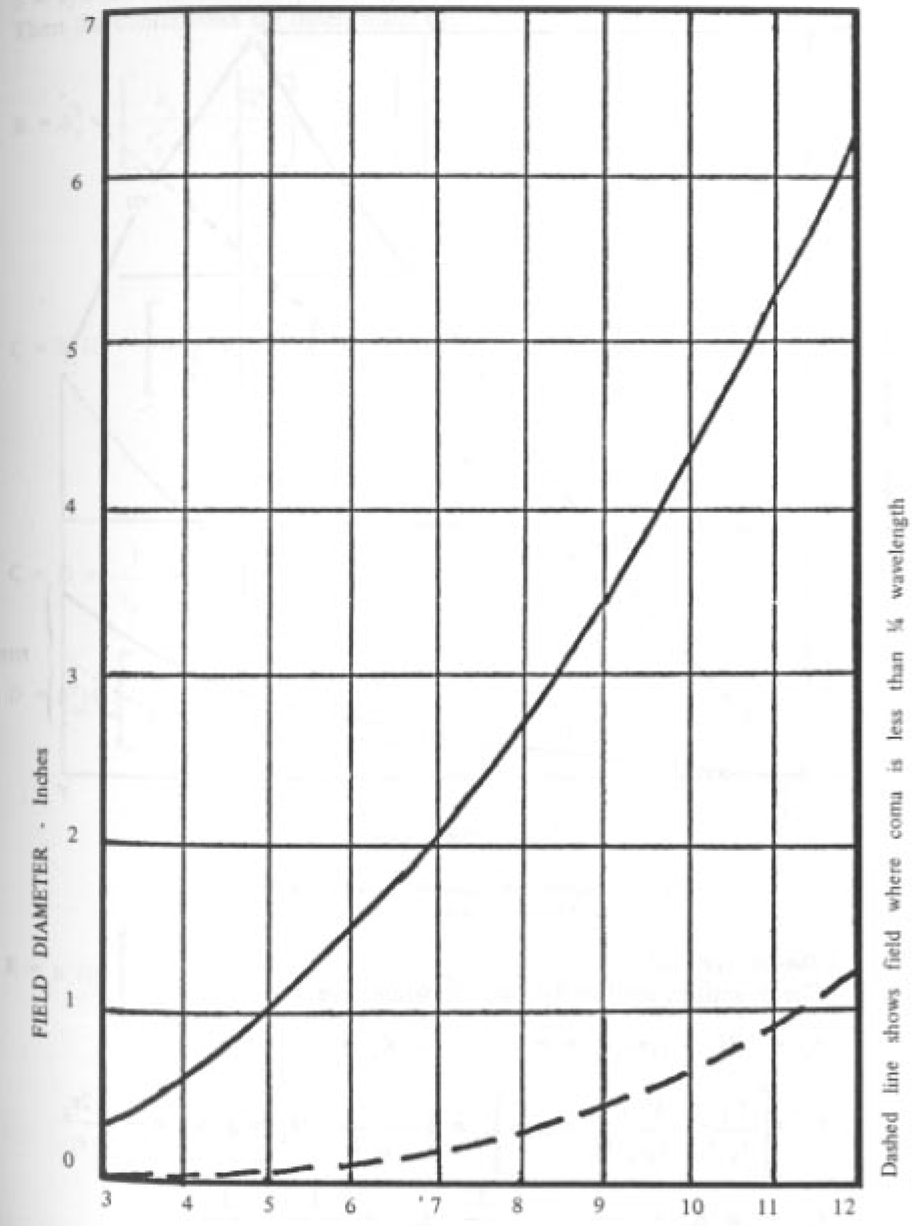


Fig. 2 FOCAL RATIO - Focal Length/Diameter

Astigmatism causes a spread of the image of $15.7\alpha^2 D/f$ seconds or $0.256 W^2 D/f^2$ inches. The graph Fig. 3 shows the plots for the amount of astigmatism and coma for Newtonians of f/3 and f/10. Astigmatism is relatively unimportant up to a field coverage of 2°, at which point it begins to play a larger role. For most purposes astigmatism in Newtonians can be disregarded.

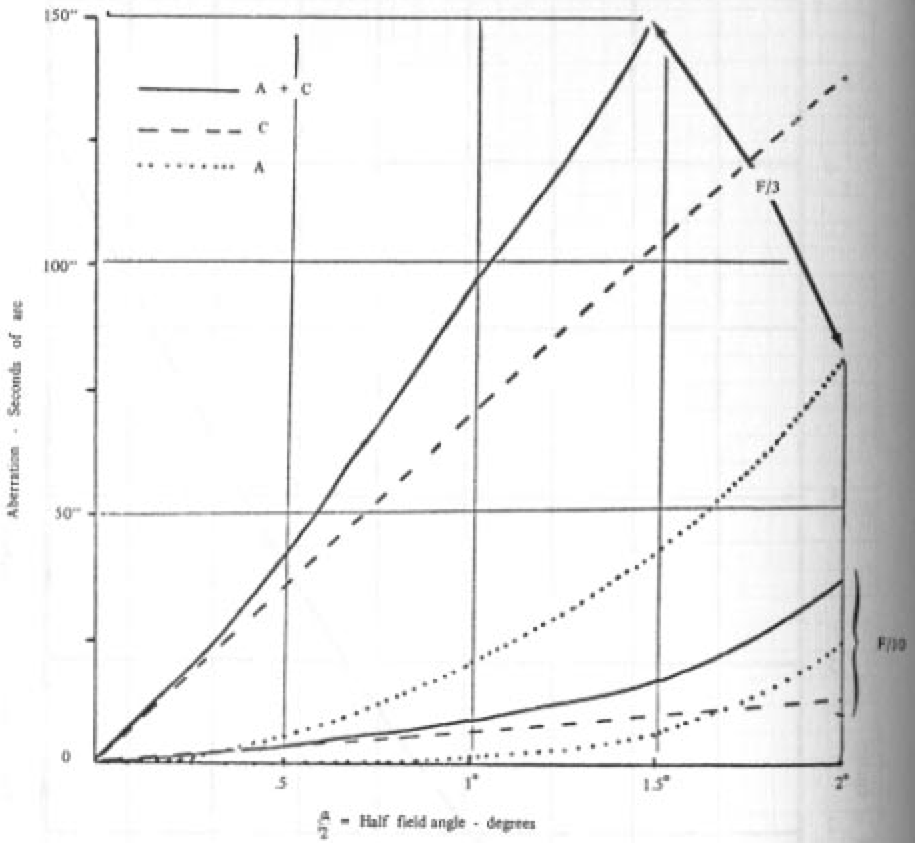


Fig. 3 Comparison of astigmatism (A) and coma (C) in Newtonian reflectors of F/3 and F/10

Two Mirror Systems.

The quantities used in the basic equations are:

$$h_1 = 1, H_1 = t_1 \to 0, s_1 = \infty, s_1' = \frac{r_1}{2}, K_1 = -\frac{1}{r_1}$$

$$L_1 = \frac{1}{t_1} - \frac{1}{r_1}, \; s_2 = d + s_1' = d - \frac{r_1}{2}, \; H_2 = d, \; h_2 = -\frac{2s_2}{r_1}$$

$$t_2 = d, \; K_2 = \frac{1}{s_2} - \frac{1}{r_2}, \; L_2 = \frac{1}{d} - \frac{1}{r_2}$$

These new abbreviations are used:

f = equivalent focal length.

$$A = \frac{s_2'}{s_2} = \frac{f}{f_1}, \; Ar_1 = aAf_1 = 2f, \; r_2 = \frac{2As_2}{A-1} = \frac{2s_2}{A-1}$$

$b = s_2' + d$ = the distance from the primary mirror to the final focus.

Then the coefficients are determined by:

$$B = h_1^4\left[\frac{b_1}{r_1^3} + \frac{K_1^2}{r_1}\right] + h_2^4\left[\frac{b_2}{r_2^3} + \frac{K_2^2}{r_2}\right]$$

$$= \frac{b_1+1}{r_1^3} + \frac{2(A-1)^3 s_2}{A^3 r_1^4}\left[b_2 + \frac{(A+1)^2}{(A-1)^2}\right]$$

$$C = h_1^2H_1^2\left[\frac{b_1}{r_1^3} + \frac{L_1^2}{r_1}\right] + h_2^2H_2^2\left[\frac{b_2}{r_2^3} + \frac{L_2^2}{r_2}\right]$$

$$= \frac{1}{r_1} + \frac{d^2(A-1)^3}{2r_1^2A^3s_2}\left[b_2 + \frac{(b-f)^2}{d^2(A-1)^2}\right]$$

$$C = D + \frac{1}{r_1} + \frac{1}{r_2}$$

$$D = h_1^2H_1^2\left[\frac{b_1}{r_1^3} + \frac{K_1(2L_1-K_1)}{r_1}\right] + h_2^2H_2^2\left[\frac{b_2}{r_2^3} + \frac{K_2(2L_2-K_2)}{r_2}\right]$$

$$= \frac{d^2(A-1)^2}{2r_1^2A^3s_2}\left[b_2 + \frac{(A+1)(b-3f)}{d(A-1)^2}\right]$$

$$E = h_1H_1^3\left[\frac{b_1}{r_1^3} + \frac{L_1(2L_1-K_1)}{r_1}\right] + h_2H_2^3\left[\frac{b_2}{r_2^3} + \frac{L_2(2L_2-K_2)}{r_2}\right]$$

$$= -\frac{d^3(A-1)^3}{4r_1A^3s_2^3}\left[b_2 + \frac{(b-f)}{d^2(A-1)^2}\right]$$

$$F = h_1^3 H_1 \left[\frac{b_1}{r_1^3} + \frac{K_1 L_1}{r_1} \right] + h_2^3 H_2 \left[\frac{b_2}{r_2^3} + \frac{K_2 L_2}{r_2} \right]$$

$$= - \frac{1}{r_1^2} - \frac{d(A-1)^3}{A^3 r_1^3} \left[b_2 + \frac{(A+1)(b-f)}{d(A-1)^2} \right]$$

Two Mirror Systems with a Parabolic Primary—Cassegrain & Gregorian.

Since the spherical aberration is zero, B is set equal to zero and with $b_1 = -1$ the value of b_2 is found to be:

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

Then the values of the other coefficients are found to be:

$$F = - \frac{1}{4f^2}$$

$$C = \frac{b - Ad}{2fs_2'} \quad \left(\cong - \frac{Ad}{2fs_2'} \text{ when } b << AD \right)$$

$$D = - \frac{d(A^2-1)}{2fs_2'}$$

$$E = \frac{d(A-1)(3b-f)}{4(s_2')^2} \cong - \frac{df(A-1)}{4(s_2')^2} \text{ when } b << f$$

The third order aberrations are then in seconds of arc:

$Coma_t = 338\alpha D^2/f^2$

Radial astigmatism $= -7.85(A^2+2A-1)\alpha^2 D/fs_2'$

Tangential astigmatism $= -7.85(A^2-1)d\alpha^2 D/fs_2'$

Distortion $= -0.34df(A-1)\alpha^3/(s_2')^2$

and the curvatures of the astigmatic surfaces and field curvature are:

$1/gt = 2(2C+D) = -(A^2+2A-1)d/fs_2'$

$1/g = 2(C+D) = -(A^2+A-1)d/fs_2'$

$1/g_s = 2D = -(A^2-1)d/fs_2'$

The astigmatism equals $2CH^2$ or $CW^2/2$ where $W = 2H$ = field diameter in inches.

$$\text{Astigmatism} = - \frac{AdW^2}{4fs_2'}$$

Two Mirror Systems with Spherical Secondary: Dall-Kirkham.

Again, since spherical aberration is zero, B is set equal to zero and since, with a spherical secondary, $b_2 = 0$, the equation for b_1 is found to be:

$$b_1 = -1 - \frac{(A-1)(A+1)^2 s_2}{A^2 f}$$

Then the aberration coefficients are:

$$F = -[A^2(1+\frac{b}{f}) + (1-\frac{b}{f})]/8f^2 \cong - \frac{A^2+1}{8f^2} \text{ when } \frac{b}{f} << 1$$

$$C = \frac{A}{2f} + \frac{(A-1)(b-f)^2}{8f^2 s_2'} \cong \frac{A}{2f} + \frac{A-1}{8s_2'} \text{ when } b << f$$

$$D = \frac{d(A^2-1)(b-3f)}{8f^2 s_2'} \cong - \frac{3d(A-1)f}{8(s_2')^2} \text{ when } b << f$$

$$E = - \frac{d(A-1)(b-f)(b-3f)}{8f(s_2')^2} \cong - \frac{3d(A-1)f}{8f(s_2')^2} \text{ when } b << f$$

The third order aberrations in seconds of arc are:

$$Coma_t = 169(A^2+1)\frac{\alpha D^2}{f^2}$$

$$\text{Rad. astig.} = -1.96 - 8As_2' - 2f(A-1) + 3d(A^2-1)\frac{\alpha^2 D}{fs_2'}$$

$$\text{Tang. astig.} = -5{,}88(A^2-1)d\frac{\alpha^2 D}{fs_2'}$$

$$\text{Distortion} = -0.52(A-1)d\frac{\alpha^3 f}{(s_2')^2}$$

The curvatures of the three surfaces of interest and the astigmatism are:

$1/g_t = -[-8As_2' - 2f(A-1) + 3d(A^2-1)]/4fs_2'$

$1/g = -[-4As_2' - f(A-1) + 3d(A^2-1)]/4fs_2'$

$1/g_s = -3(A^2-1)d/4fs_2'$

$$\text{Astigmatism} = \frac{W^2}{2} \left[\frac{A}{2f} + \frac{A-1}{8s_2'} \right]$$

Two Mirror Systems with Zero Aberration and Coma, Ritchey-Chretien and Schwarzchild.

Two extremely interesting combinations are the Ritchey-Chretien and the Schwarzchild telescopes, although the Schwarzchild is not used visually but as a camera since its focal plane is between the two mirrors. The basic equations for these are obtained by setting B = F = 0 since these systems are aplanatic; they have no spherical aberration or coma. The equations for b_1 and b_2 are obtained from the B and F coefficient equations as:

$$b_1 = -1 + \frac{2s_2'}{A^3 d}$$

$$b_2 = \frac{2f}{d(1-A)^3} - \left(\frac{A+1}{A-1} \right)^2$$

The expressions for the coefficients are then found to be:

$$C = -\frac{2f - d}{4fs_2'}$$

$$D = -\frac{d\,(2A^2 - 1)}{4fs_2'}$$

$$E = -\frac{d}{8f\,(s_2')^2}\quad [\,2f\,(f - 3b)\,(A - 1) - Ad\,]$$

The equations for the aberrations in seconds are:

Radial astigmatism $= -3.93\,(4f + 2A^2d - 3d)\,\dfrac{\alpha^2 D}{fs_2'}$

Tang. astigmatism $= -3.93\,(2A^2 - 1)d\,\dfrac{\alpha^2 D}{fs_2'}$

Distortion $= -0.17d\quad 2f\,(f - 3b)\,(A - 1) - Ad\quad \dfrac{\alpha^3}{f\,(s_2')^2}$

The field and astigmatic curvatures and the astigmatism are:

$1/g_t = -[4f + d(2A^2 - 3)]/2fs_2'$

$1/g\ = -\,[f + d(A^2 - 1)]/fs_2'$

$1/g_s = -\,(2A^2 - 1)d/2fs_2'$

Astigmatism $= -\dfrac{(2f - d)\,W^2}{8fs_2'}$

These five types of two-mirror telescopes, Cassegrain, Gregorian, Dall-Kirkham, Schwarzchild and Ritchey-Chretien, are all on-axis instruments as opposed to some of the more exotic off-axis two mirror instruments such as the schiefspiegler. Perhaps the best way to compare these five instruments will be to assemble the aberration equations in a table and then give numerical examples. To make this more useful and to reduce confusion about the signs of the quantities involved, we will let:

$p = -s_2$ and $p' = -s_2'$, and therefore $r_2 = -p'/(A - 1)$, $l = p' - d = -b$.

The quantities used to determine the aberrations will then be f, A, l, d, p, p', D, α and W which are defined as follows:

f = effective focal length (f_1 is primary focal length)

A = secondary amplifying ratio = $f/f_1 = p'/p$

l = distance from final focus to surface of primary mirror

p = distance from secondary mirror to primary focus

p' = distance from secondary mirror to final focus

D = aperture of primary mirror

α = field diameter in degrees

W = field diameter in inches (H = W/2)

Aberrations of Two-Mirror Reflectors

	Cassegrain Gregorian	Dall-Kirkham	Ritchey-Chretien Schwarzchild
b_1		$-1 + \dfrac{(A-1)\,(A-1)^2 p}{A^2 f}$	$-1 - \dfrac{2p'}{A^3 d}$
b_2	$-\left[\dfrac{A+1}{A-1}\right]^2$		$\dfrac{2f}{d\,(1-A)^3} - \left[\dfrac{A+1}{A-1}\right]^2$
F	$-\dfrac{1}{4f^2}$	$-\dfrac{(A^2+1)}{8f^2}$	
C	$\dfrac{Ad}{2fp'}$	$\dfrac{A}{2f} - \dfrac{A-1}{8p'}$	$\dfrac{2f - d}{4fp'}$
D	$\dfrac{(A^2-1)\,d}{2fp'}$	$\dfrac{3\,(A^2-1)\,d}{8fp'}$	$\dfrac{(2A^2-1)\,d}{4fp'}$
E	$-\dfrac{(A-1)\,df}{4\,(p')^2}$	$-\dfrac{3\,(A-1)\,df}{8\,(p')^2}$	$-\dfrac{[\,2f\,(f+3l)\,(A-1) - Ad\,]\,d}{8f\,(p')^2}$
$Coma_t = 1351\,\alpha^2 D$	$.338\alpha\,\dfrac{D^2}{f^2}$	$169\,(A^2+1)\,\alpha\,\dfrac{D^2}{f^2}$	

Radial astig.* $=15.7\,(2C+D)\,\alpha^2 D$	$7.8\,(A^2+2A+1)\,d\,\frac{\alpha^2 D}{p'f}$	$2\left[8Ap' - 2f\,(A-1) + 3d\,(A^2-1)\right]\frac{\alpha^2 D}{p'f}$	$3.9\,(4f+2A^2d-3d)\,\frac{\alpha^2 D}{p'f}$
Tangential astig.* $=15.7d\alpha^2 D$	$7.8\,(A^2-1)\,d\,\frac{\alpha^2 D}{p'f}$	$5.9\,(A^2-1)\,d\,\frac{\alpha^2 D}{p'f}$	$3.9\,(2A^2-1)\,d\,\frac{\alpha^2 D}{p'f}$
Distortion $=.138\,\alpha^3 E$	$-.034\,(A-1)\,\alpha^3\,\frac{df}{(p')^2}$	$-.052\,(A-1)\,\alpha^3\,\frac{df}{(p')^2}$	$.017\left[2f\,(f+31)\,(A-1) - Ad\right]\frac{d\alpha^3}{f\,(p')^2}$
$\frac{1}{g_t} = 2\,(2C+D)$	$(A^2+2A-1)\,\frac{d}{fp'}$	$\frac{8Ap' - 2f\,(A-1) + 3d\,(A^2-1)}{4p'f}$	$\frac{(2A^2-3)\,d + 4f}{2p'f}$
$\frac{1}{g} = 2\,(C+D)$	$(A^2+A-1)\,\frac{d}{fp'}$	$\frac{4Ap' - f\,(A-1) + 3d\,(A^2-1)}{4p'f}$	$\frac{(2A^2-1)\,d + f}{2p'f}$
$\frac{1}{g_s} = 2D$	$(A^2-1)\,\frac{d}{fp'}$	$3\,(A^2-1)\,\frac{d}{4fp'}$	$\frac{(2A^2-1)\,d}{2p'f}$
Astigmatism $= CW^2/2$	$\frac{Adw^2}{4fp'}$	$\left[\frac{A}{2f} - \frac{A-1}{8p'}\right]\frac{W^2}{2}$	$\frac{(2f-d)\,W^2}{8p'f}$

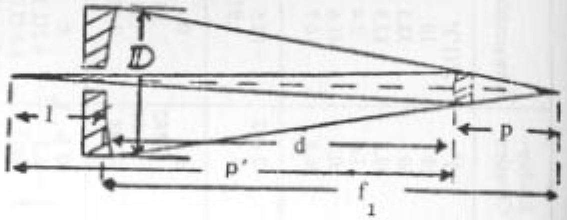
*This aberration is due to field curvature as well as astigmatism.

Aberrations of various telescopes — Examples

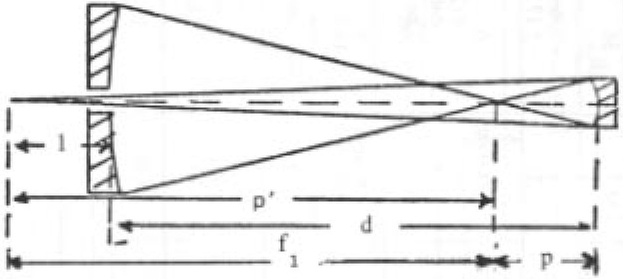
	Cassegrain	Dall-Kirkham	Gregorian	Ritchey-Chretien	Ritchey-Chretien	Schwarzchild
λ	1°	1°	1°	1°	1°	2°(1°)*
D	10	10	10	10	10	10
f	150	150	−225	150	60	33.3
f_1	37.5	37.5	37.5	37.5	37.5	83.3
A	4	4	−6	4	1.6	0.4
d	28.5	28.5	46.5	28.5	20.8	41.6
p'	36	36	−54	36	26.8	16.7
b_1	−1	.719	−1	−1.396	−2.192	−13.5
b_2	−2.78	0	−.51	−3.17	−45.5	1.97
F	−.000,011	−.000,094	−.000,005	0	0	0
C	.0100	.0032	−.0115	.0125	.0162	.0113
D	.0380	.0298	.067	.0408	.0081	−.0128
E	−2.47	−3.7	4.48	−2.84	−.348	2.47
$Coma_t$	1.5 secs	12.8 secs	.67 secs	0	0	0
RA	9.5	5.7	6.9	10.3	6.3	6.2(1.5)*
TA	6.2	4.6	10.5	6.4	1.2	8.0 (2.0)*
Dist.	−.34	−.51	.62	−.39	−.048	2.73 (.34)*
$1/g_t$	.121	.072	.088	.132	.080	.020
$1/g$	.100	.066	.111	.107	.048	−.003
$1/g_s$	.079	.060	.134	.082	.016	−.026
Astig.	.036	.011	−.039	.043	.056	.039

*Values in parentheses for a 1° field.

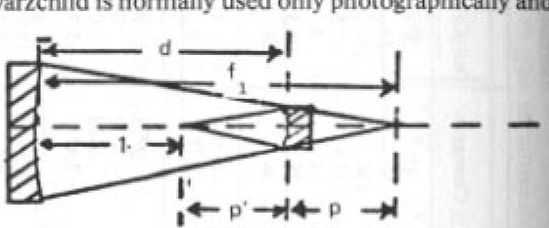
The arrangement of the optics and these dimensions in the Cassegrain type of instrument, which includes the Dall-Kirkham and the Ritchey-Chretien is then this.



In this type of instrument the only negative quantity will be the radius of the secondary. This shows the optical arrangement of the Gregorian. In this telescope p is taken as a negative number, therefore A and f are also negative and r_2 is positive.



The Schwarzschild is normally used only photographically and the focal plane is inaccessible for visual use between the two mirrors as shown here.



The deformations of the Ritchey-Chretien and Schwarzschild mirrors may be calculated by the equations given, but it is well to realize the conic sections defined by these deformations, for extremely wide aperture systems are only approximations to the fourth order curves that should be used in that case. However, for non-extreme systems these conic sections are adequate. In Schwarzschild's original paper, under a discussion of the Schwarzchild telescope, he states that the ellipsoid and hyperboloid defined by the deformations are adequate down to a focal ratio of 3:1.

In astronomical use, coma is the most serious of the third order aberrations since it distorts the image in a non-symmetrical way and decreases the apparent magnitude of the stars at the edge of the field. Coma in the Cassegrain and Gregorian telescopes equals that of an equivalent Newtonian and in the focal ratios usually found in these compound reflectors is unimportant. The coma in the Dall-Kirkham at the edge of a 1° field in the numerical example is 12.8 seconds. With a normal 1¼ inch outside diameter eyepiece of 1 inch focal length, a field of only .4 degree would be seen, however, and coma at the edge of the field would be only 5 seconds. This equals the coma of an f/5 Newtonian when the same eyepiece is used. So for general viewing the Dall-Kirkham will perform adequately although resolution on an object like the moon will be really excellent only in the center of the field.

Coma for various amplifications of the Dall-Kirkham secondary is plotted on the graph Fig. 4; coma of the Newtonian-Cassegrain-Gregorian telescopes is also shown.

In the numerical example, the Gregorian's coma appears to be less than the Cassegrain, but this is due to the effect of the longer focal length. If the effective focal lengths were equal, coma would be equal also. The Gregorian's astigmatic fields are opposite in order to the Cassegrain's and this does cause a slight difference in the astigmatism. Ordinarily, the Gregorian is about 30% longer than the Cassegrain and, except that the ellipsoidal secondary may be tested more easily in figuring, has no real advantage over the Cassegrain.

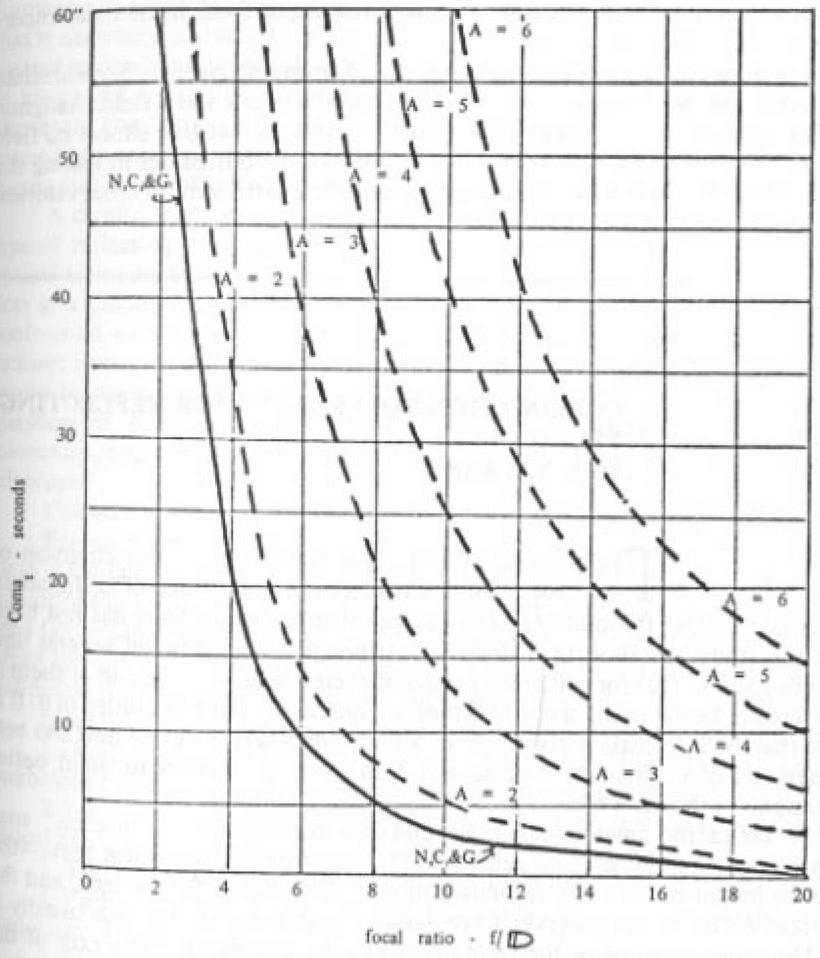


Fig. 4 Coma versus focal ratio for
—— Newtonian, Cassegrain and Gregorian
- - - - Dall-Kirkham for various secondary amplifications (A = 2, 3, 4, 5, 6)

At first glance, the astigmatism of the f/15 Cassegrain of 9.5 by 6.2 seconds, and of the f/15 Ritchey-Chretien of 10.3 by 6.4 seconds appears to be of serious amount. It must be remembered, however, that this is at the edge of the field and that the size of the elliptical blob of light caused by astigmatism and field curvature is proportional to the square of the field diameter. With the same 1 inch eyepiece mentioned above, that covers 0.4°, the radial and tangential dimensions would be reduced by $(.4)^2$ or .16 as much. This would be a 1.5 by 1 second image for the Cassegrain and 1.6 by 1 second image for the Ritchey-Chretien, and means that these telescopes would perform very well visually.

The f/6 Ritchey-Chretien is interesting since we see that a fast, coma-free telescope can be made from only two mirrors that still has only a minimal amount of astigmatism. It is for this reason that many telescopes being made today incorporate Ritchey-Chretien optics.

The Schwarzchild example, which is scaled from one given by Schwarzchild in his paper, shows its optical superiority as a camera over a wider field. Astigmatism is minimized in this design by selecting dimensions that give almost no field curvature. Few of these have been made because of the difficulties in testing the optics, although they are being used today in orbiting astronomical observatories.

COLLIMATION TOLERANCES FOR REFLECTING TELESCOPES

by A. S. Leonard

The purpose of this paper is to bring to the attention of amateur telescope makers the importance of collimation. This is one part of the building of telescopes that the writer feels has not been given the study and thought it deserves. Although I have devised several new methods (new to me) for collimating reflecting telescopes, a discussion of them is considered to be out of the scope of this paper, and so will not be included in it. It is hoped that the information given herein will inspire others to devise new and better methods of collimation, and so will help telescope makers to build better instruments with less work.

So far as the amateur telescope maker is concerned, "collimation" may mean one of two things. One relates to the alignment of all optical parts—the objective mirror or lens, any secondary mirror, diagonal, or Barlow lens, and the eyepiece. Actually, the observer's eye should be included in this, but usually is not. The other meaning of the term applies to the alignment of the axes of the telescope mounting so that the instrument will follow the stars accurately as they move across the sky, and so that the setting circles will indicate the correct values of right ascension and declination for all regions of the sky. The confusion resulting from the use of the single term for these two different meanings might be avoided by using the term "optical collimation" for the first type of adjustment

and "collimation of the axes" for the second. This paper is concerned with the first type of alignment only—optical collimation.

If a study is made of the literature on telescope making most readily available to the amateur, relatively little of it will be found to be concerned with the problem of optical collimation. To illustrate this point, out of approximately 1150 pages devoted to telescope making and allied subjects (some rather remotely allied) in *Amateur Telescope Making I* and *II*, a total of only about 7 pages (*ATM I*, pp. 43, 224, 430 and 446, *ATM II*, pp. 213, 272-274, 279-281) is given over to this subject. The situation might easily lead the beginner to think that collimation is a relatively unimportant detail of telescope making. Although Hindle, Haviland, Ellison and Lower state quite flatly that accurate collimation is essential to the satisfactory performance of some reflecting telescopes, no hint as to the accuracy of alignment that is necessary is given. This may leave the reader with the impression that these writers are unduly concerned with the problem, and that by exercising a little care in his use of any of the rather simple collimation procedures presented, optical alignment good enough for all practical purposes may be achieved. The fact that many beginners have produced reflecting telescopes which perform almost to the theoretical limits of telescopic resolution tends to substantiate this idea.

A careful study of the above-cited material suggests that the Cassegrainian type of reflecting telescope, at least, may require more accurate alignment of its optical elements than the Newtonian. Because I was contemplating the construction of a Cassegrainian telescope of short focal length and, eventually, would be confronted with the problem of collimating it, several different collimation procedures were planned and analyzed. It was soon realized that only one procedure would be necessary, but that it would have to be good enough. This raised the question of just what was "good enough"—what errors in collimation, or tolerances, could be permitted without a serious loss in the resolving power of the telescope?

Collimation Errors.

For each aspherical surface curve (paraboloid, ellipsoid or hyperboloid), there is a single straight line about which the curve is symmetrical. This is the optical axis of the surface. For a spherical curve there are an infinite number of straight lines (all passing through the center of curvature but in different directions) about which the curve is symmetrical. Since no one of these lines commands any more distinction than another, the spherical curve is considered to have no optical axis.

In addition to these lines, there are a number of points that are important:

1. Both the ellipsoid and hyperboloid have two focal points; and the paraboloid has a single one. All focal points lie on the optical axis.

2. Each aspherical mirror curve has an optical center. It is the point where the optical axis passes through the surface.

3. The important point for the spherical surface is its center-of-curvature.

4. Each optical surface has a geometrical center. It is the point on the surface equidistant from the edge.

5. In addition to these, we will use another point which we will call the center of curvature. Actually, there is no such thing as the "center of curvature" of an aspherical surface; but we will call it that and describe it as the center of curvature of the surface at the optical center.

Perfect collimation requires that the axes of all aspherical surfaces and the centers of curvature of all spherical surfaces fall on a single straight line, (as defined above) on this line. This is the optical axis of the telescope. For the best possible performance of the instrument, the geometrical center of the surface or surfaces which act as diaphragm stops should also lie on the optical axis.

Since it is humanly impossible to make any adjustment absolutely perfect, there will always be some error of collimation in any telescope. The collimation error of any optical component is the amount by which its axis or center-of-curvature fails to coincide with the optical axis of the telescope.

So far as any one error is concerned, there are only two kinds of collimation error. They are lateral displacement and angular displacement of the axis and are illustrated below (Figs. 1 and 2). Both kinds of error may be present at the same time and they may lie in entirely different planes.

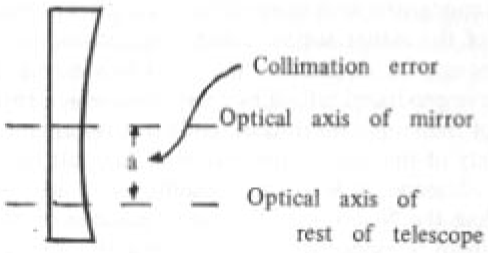


Fig. 1 Lateral error

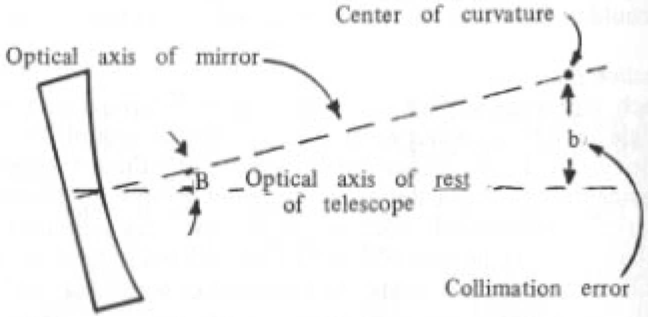


Fig. 2 Angular error

In the equations which follow, the lateral error will be denoted by the letter "a" and the angular error by the letter "B". Since most persons can visualize small distances more readily than small angles, the angular error will be multiplied by the radius of curvature of the surface curve to give a linear dimension (error) "b".

As for the causes of collimation errors, lateral error may be caused either by inaccurate original centering or subsequent lateral shifting of the mirror in its cell. Angular error may either be caused by the incorrect original adjustment of the three adjusting screws that are used to tilt the mirror, or by such insecure mounting of the mirror as to allow it to tilt in its cell as the telescope is pointed to different parts of the sky. In large reflecting telescopes, both flexure and thermal expansion or contraction of the mounting may be causes of collimation errors.

Besides these two kinds of collimation error, there is a third (shown in Fig. 3) which might be called "edge error." It is caused by the edge of the mirror not being concentric with the optical axis. The magnitude of this error is the separation between the geometrical and optical centers of the mirror face and is denoted by the letter "c". The nature of this error is such that if the mirror were to be aligned perfectly by the usual method of attempting to place its geometrical center on the optical axis of the telescope and then adjusting the three adjusting screws to make the surface of the mirror perpendicular to the optical axis of the instrument at that point, there would still be an error of collimation. It would consist of a particular combination of lateral and angular error in which both lie in the same plane with a=c and b= −c, and with the effective diaphragm stop of the system eccentric with respect to the optical axis by the distance c.

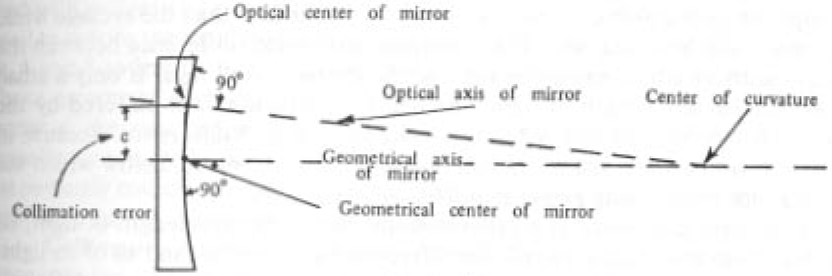


Fig. 3 Edge error

Acceptable Errors, or Tolerances.

The setting of tolerances is at best a compromise, and in some cases is no more than an arbitrary decision. As a general rule, a reduction in a tolerance (specifying greater precision) will result in better performance of the finished device; but also, it will increase the total cost or time consumed in its production. Ideally, the magnitude of a tolerance should be reduced to the point where any further reduction in its numerical value will increase the cost by more than the resulting improvement in performance is worth. In practice, however, this point may be difficult to find. Although we may be able to make a fairly accurate estimate of the increase in cost that would result from any given reduction in tolerance, we may be unable to make a reasonably accurate estimate of the increase in performance that it would bring about. Furthermore, even though we were able to tell just what improvement in performance would be realized, there might not be general agreement as to what this improvement would be worth. For these reasons a tolerance which is quite acceptable to one person may be considered either too close or not close enough to another.

In trying to arrive at optimum values for collimation tolerances, we are faced with all these problems. To start with, until we have decided just what collimation methods will be used and have tried them out, we are not in a position to say how much time and effort will be required to achieve any given accuracy in collimation. In the second place, although we can calculate just what optical performance would be obtained in a telescope which is perfect in all respects except for given collimation errors and, therefore, calculate the exact magnitude of the loss in performance these same imperfections will produce in actual practice, we cannot say just what loss in performance these same errors will produce in actual practice, because no actual telescope will ever be perfect in all other respects. Finally, different observers will place different values on high optical performance. Each one's standards will be different and may depend to a large extent on what performance he is used to getting from the telescope that he has. In order to resolve this dilemma, we will go ahead on the assumption that eventually collimation procedures capable of working to very close tolerances without the expenditure of an unreasonable amount of time and effort will be developed, and the "tops" in optical performance is really worth a lot.

An optically perfect telescope would be one which makes the effective path length identical for all rays which traverse its optical system in going from a point in the object to the image-point on the retina of the observer's eye. With any actual telescope the path length of some rays will be a little greater than the average while for others it will be a little less. When the path difference (difference between the effective path length of any given ray and the average of all rays) is only a small fraction of the wavelength of light, the loss in resolving power suffered by the telescope is directly proportional to the square of the path difference. Because of this, there will be some rather definite value of path difference, below which the resulting loss in resolving power rapidly approaches zero.

If the path difference of a ray is one-quarter of the wavelength of light, its contribution to the central disc of the diffraction pattern is nil, and all of its light-energy goes into brightening the surrounding ring-system. Such a ray definitely reduces the resolving power of the telescope; and the telescope would give better definition if that ray were to be blocked out. If the path difference is one-eighth of a wavelength, 71% of the energy goes into strengthening the central disc and 29% into the rings.

From this discussion it might appear that we should set one-eighth of a wavelength or less as the upper limit of acceptability for path differences. Experience has shown, however, that we can tolerate a somewhat higher value. If we could measure the path length of each ray in an actual telescope (the cross-section of the light path is divided into a number of small but equal areas and one ray assigned to represent each small area), we would find that only a small fraction of the rays had path differences which were over one-half of the maximum difference; and a very large fraction would be found to have path lengths which differed from the average by considerably less than one-half of the maximum. Because this type of distribution in the values of path difference is typical of most actual telescopes, one-quarter of a wavelength has become generally accepted as a practical and attainable maximum path difference, or error, to be tolerated in an optical system that is designed to give the highest possible resolution. In this case, a large fraction of the rays will have path differences well below one-eighth of a wavelength and only a small fraction between one-eighth and one-quarter.

When a search is made for the causes of optical path length in a telescope, the following are found:

1. Temperature differences in the atmosphere (seeing).
2. Errors in the surface curvature of the objective.
3. Errors in the surface curves of any secondary mirror, diagonal, prism or mirror, or Barlow lens.
4. Aberrations in the eyepiece.
5. Imperfections in the lens of the observer's eye.
6. Errors in collimation of the optical parts.

If each of these sources of error acted on the light rays in the same way and by the same amount, their effects would be directly additive and we could tolerate a maximum value of only 1/24th of a wavelength in each. Fortunately, it is very improbable (although possible) that each will act in the same way on any given light-ray. Also, through good optical design, some of these errors can be reduced to considerably less than 1/24th of a wavelength.

If we dismiss the first source of trouble, seeing, as being beyond the control of the telescope maker, or assume that he has found the perfect site and will do his observing from there, we still have a formidable group of obstacles standing in our way to obtaining really top optical performance. Even with the best optical design and with patient and careful testing and figuring of each optical surface, we will do well to reduce the maximum net error, or path difference, resulting from causes 2, 3, 4 and 5 to less than one-quarter of a wavelength. Furthermore, the natures of these errors are such that the maximum net path difference will almost always occur at the outer edge of the light-path. In optical terms, the instrument will usually turn out to be just a little over- or under-corrected. If the telescope were to be perfectly collimated and a knife-edge test made on it, the primary mirror would appear to have a slightly turned edge (either up or down).

Collimation errors are such that they will make an otherwise perfect mirror appear to have a surface curve similar to that shown in Fig. 4 (in greatly exaggerated form).

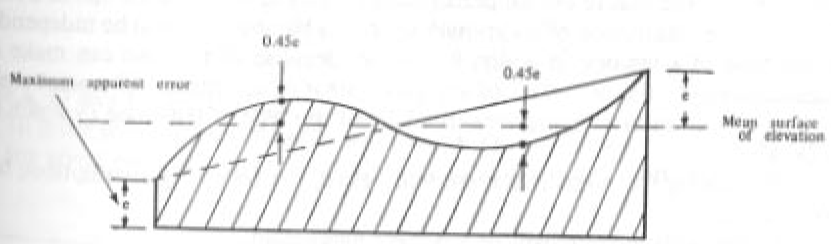


Fig. 4 Cross-sectional view of apparent shape of mirror surface (greatly exaggerated) produced by error in collimation.

The maximum error or deviation from the theoretically perfect surface curve which most nearly represents the actual surface is e. Because the light-rays traverse nearly the same path both going and coming from the mirror surface, this will result in a maximum path difference of 2e. It will be noted that collimation errors produce a maximum path difference at the edge of the mirror and furthermore, they have the effect of making the edge to be turned down on one side and up on the other. Thus, no matter whether the net effect of the other errors is equivalent to a turned up or turned down edge, on one side or the other of the mirror, the two errors are directly additive—we can't win. In view of this state of affairs, it seems wise to allocate not more than one-half of the total permissible path difference to collimation errors. This will make the maximum allowable value of e, 1/16th of a wavelength of light, and the maximum permissible figuring error (all reflecting surfaces combined) the same. This will take some doing!

Equations and Results.

In order to determine the net result of any given type of collimation error in any type of reflecting telescope, let us first consider the conventional Newtonian. With perfect seeing, perfect optics and perfect collimation, a plane wave from a star on the optical axis will be converted to a perfect spherical wave by the paraboloidal primary mirror. This will result in the formation of a perfect Airy disc on the retina of the observer's eye. If, now, the primary mirror is put out of collimation by some specified amount and the telescope re-pointed to bring the star image into the exact center of the field of view (on the optical axis of the telescope), the parallel rays from the star will no longer be converted into a perfect spherical wave. However, since the image of the star is on the optical axis of the rest of the telescope, no further imperfections, or path differences, will be introduced by the diagonal, the eyepiece or the observer's eye.

If, instead of in a Newtonian, the same paraboloid were to be used as the primary of a Cassegrainian, and if it were to be put out of collimation by the same amount, and if the telescope were to be pointed so that the star image would be formed on the optical axis of the rest of the telescope, the parallel rays from the star would make the same angle as before with the axis of the paraboloid, and the same imperfections of the spherical wave formed by the paraboloid would be present. Since the star image would be collimated perfectly with respect to the rest of the system, no further errors would be introduced. As a result the net error, so far as the observer is concerned, would be the same as in the Newtonian. From this we conclude that the loss in optical performance suffered by any telescope as a result of an error in collimation of its primary mirror (a paraboloid), will be independent of the type of telescope in which it is used. Because of this, we can make our calculations as to the net effect of any given error of collimation of a paraboloidal primary mirror without being concerned about the type of telescope in which it is to be used.

In deriving the equations presented below, the following assumptions have been made:

1. The surface curve will be a perfect paraboloid.
2. Only one type of collimation error will be present in each case and only the primary mirror will be out of collimation.
3. The image point will be so chosen that:
   a. the path difference of the central ray will be zero (this is accomplished by choosing as the focal plane the plane of best focus),
   b. the average of the path lengths of all rays reflected from each of the two halves of the mirror, formed by dividing it along any diameter, will be the same (this corresponds to taking as the image-point the point of maximum brightness in the diffraction pattern).
4. The edge of the mirror will be the effective diaphragm stop for the system.

In each case, the maximum effective path difference is 2e and occurs at the edge of the mirror:

$$2e = \frac{aD^3}{80F^3} + \frac{a^2D^2}{16F^3} \qquad (1)$$

$$2e = \frac{bD^3}{160F^3} + \frac{b^2D^2}{64f^3} \qquad (2)$$

$$2e = \frac{cD^3}{160F^3} + \frac{c^2D^2}{64F^3} \qquad (3)$$

where a, b and c are the collimation errors illustrated in Fig. 1, 2 and 3, and D and F are the diameter and focal length of the paraboloid.

The first term on the right hand side of each equation is the error due to coma, and the second due to astigmatism. These equations do not tell where on the edge of the mirror the maximum error occurs or whether it is a positive or negative quantity. Also, they do not show the effect of eccentricity of the edge of the mirror. For these reasons (and others) they cannot be used to calculate the total path difference when more than one type of collimation error is present.

If we make the assumption that the maximum acceptable path difference is the same for each type of error, the following will be true:

$$c = b = 2a \qquad (4)$$

In order to be able to calculate these quantities directly, Eq. (1) can be rearranged to give the following:

$$a = \sqrt{\left(\frac{D}{10}\right)^2 + \frac{32eF^3}{D^2}} - \frac{D}{10} \qquad (5)$$

Assuming that the maximum acceptable value of e to be 1/16th of the wavelength of light, and the wavelength of light to be 0.555 microns, the following is obtained:

$$a = \sqrt{\left(\frac{D}{10}\right)^2 + \frac{43.7 \times 10^{-6}\ F^3}{D^2}} - \frac{D}{10} \qquad (6)$$

where a, D and F are in inches.

In order to get some idea as to what precision in collimation will be required with any given primary mirror, the following table has been computed, using Eq. (6):

Values of Collimation Tolerance (a) in inches, based on a maximum path difference of 1/8th wavelength

F/D \ D	3	4	5	6	8	10	12
6"	0.006	0.014	0.027	0.045	0.103	0.19	0.30
10"	0.006	0.014	0.027	0.046	0.106	0.20	
20"	0.006	0.014	0.027	0.047	0.109		

It will be noted that with very fast mirrors (F/D = 6 or faster) the collimation tolerance is practically independent of the diameter and depends only on the focal ratio. A comparison of these values will show that in this range of focal ratios, the collimation tolerance can be expressed by the following:

$$a = 0.00022\left(\frac{F}{D}\right)^2 \qquad (7)$$

Collimation Tolerances for the Other Optical Elements of Reflecting Telescopes.
When collimation tolerances for the secondary elements (secondary mirror or Barlow lens) of compound telescopes are calculated, they are found to be not greatly different from those of the primary mirrors of the same telescopes. Eq. (7) gives at least a fair approximation for the collimation tolerances of these optics. This is true even of the diagonal flat of the Newtonian reflector for, if this part were to be shifted a short distance along the axis of either the eyepiece or the main tube, the result would be the same as if the primary mirror had been shifted laterally by the same amount.

Because the purpose in presenting this paper was more to call attention to the seriousness of the problem in reflecting telescopes than to set definite values for the tolerances, the equations and calculated values of tolerances for these parts will not be included.

Discussion.
One of the first things that is shown by both the tabulated values and Eq. (7) is the very rapid rate of reduction in the collimation tolerances as we go to faster and faster primary mirrors. This is a feature which is not fully appreciated by amateur telescope makers. The beginner's telescope is usually a 6-inch f/10 or f/12. From the table of values it can be seen that such an instrument has a fairly liberal collimation tolerance. Many of these telescopes turn out quite well and show no evidence of poor collimation.

After completing such an instrument, many telescope makers find that they would like to have a larger telescope and decide to build one. In order that it should be easy to house or transport in an automobile, they design it with a relatively fast primary mirror. They feel that since their first telescope turned out fairly well, all of the procedures that were used in its construction, including the collimating procedure, are good enough; and that with the experience gained in making the first one and with a reasonable amount of care, they should be able to turn out a larger and faster instrument which will perform almost to the theoretical limits of telescopic resolution. Unfortunately, the collimation procedure which was good enough for an f/10 or f/12 primary mirror may not be at all good enough for their faster instrument.

Another source of loss in performance in reflecting telescopes, and one which is not generally appreciated by the amateur, is what has been described as "edge error". Most of the amateur built telescopes are collimated by procedures which, if they could be executed to perfection, would result in placing the geometrical axis of the mirror, instead of its optical axis, on the axis of the telescope. This is based on the assumption that the edge error will always be zero, or at least within acceptable limits. It should be pointed out that the conventional zonal test method for the concave paraboloid does not make the optical axis of the mirror pass through it at any particular point on the surface, and is capable of producing a practically perfect parabolic figure even though the edge error is many times the acceptable tolerance.

If the mirror were to start out as a perfect sphere and if, in the figuring operations, glass were to be removed absolutely uniformly all the way round and concentrically with the geometrical center of the mirror face, the optical and geometrical axes would coincide. In actual practice, however, this is not always true. If the mirror is small and slow (f/10 or f/12), the amount of glass to be removed in figuring it is quite small. If the figuring of such a mirror is completed quickly and with the removal of a minimum amount of glass, the chances are good that edge error will be within tolerance. If, on the other hand, the mirror is both large and fast, or if a long time is spent and a large amount of glass is polished off before the figure is pronounced satisfactory, the probability that the edge error will just happen to be within acceptable limits is much lower.

In not testing for and locating the optical axis of his mirror, the telescope maker is just trusting to luck. If his mirror is small and slow, the chances are that his luck will be good. As he attempts faster and faster mirrors, his luck will get poorer and poorer. It will take more than just luck to hold the edge error of an f/3 paraboloid to within the tolerance of 0.012 inches.

Some of the reported cases of warped mirrors may be due in part to large edge errors. If the mirror is not particularly fast and if the edge error is large, the astigmatism term (second term in the right hand side of Eq. (3)) may be larger than the coma term. In that case, the most noticeable defect will be astigmatism and might easily be diagnosed as a warped mirror. Another way in which a telescope might appear to have a warped mirror without actually having one is by having two or more types of collimation error which are rather large and which are so oriented with regard to each other that the coma terms largely cancel while the astigmatism terms add.

To some, the choice of 1/8th wavelength as the maximum acceptable path difference (used in computing the tolerance for each type of collimation error) may seem unreasonably close. If only one type of collimation error were involved, this might be so; but, because of the possibility of the presence of more than one type of collimation error and in more than one optical element, these tolerances may not be close enough. In fact, it is the writer's opinion that for of a greater number of collimation errors at the same time, the working tolerance for each should be even lower than the values given.

It might be argued that in a compound telescope, such as the Cassegrainian, the optical axis of the telescope could be defined as the straight line passing through the optical centers of the primary and secondary mirrors, and that for both mirrors this would automatically reduce the lateral error to zero and make the edge error of no consequence. The trouble with this is that, unless the actual locations of the optical centers of the mirrors are known and made use of in collimating the telescope, we will have nothing at which to aim when we try to adjust the tilt of the mirrors. In other words, we will have no control at all over the tilt errors of the two mirrors and no way of holding them within any given tolerance.

NEW HORIZONS FOR TILTED-COMPONENT TELESCOPES

by Arthur S. Leonard, University of California, Davis

In the past, the field of highly corrected optical systems for wide-field photography and other applications has been the exclusive domain of lenses and the lens-designer. In correspondingly complex reflecting systems one mirror would obscure another and the photographic plate would either obscure mirrors or be obscured by them. The recent advent of tilted-component telescopes has changed all this; and the designer of all-reflecting and catadioptric telescopes is now free to lay out relatively complex systems which will provide most of the end results which previously, only all-refracting systems could deliver.

Introduction

Not so very long ago, an optical-designer friend of mine said to me, "I very much prefer to work with lenses. You can do so much more with lenses than you can with mirrors." He was, of course, referring to high-performance optical systems capable of providing wide flat fields suitable for photographic applications.

When we look into the design parameters of a typical high-performance lens system such as a modern camera lens, we will find it to contain between six and ten lens elements—as many as 20 glass surfaces. Since a large fraction of these surfaces will be cemented together in pairs, the designer will not have quite that many independent radii of curvature to work with; but with a long list of glass types to choose from and many thickness and separation distances to be adjusted, he has an impressive list of independent variables at his disposal.

When we analyze the action of such a lens system on a wave of light, we will find the wave-front encountering surface-after-surface in rapid succession as it passes through the system. Although the system as a whole has a focussing action on the light, the wave-front, in most systems, will be found to emerge from the last surface while it is still well over one-half of its original diameter. Thus, each surface in the system has an opportunity to work on the wave-front while it is still relatively large. Finally, there is no restriction as to the size of the photographic plate which will be placed behind the optical system. Clearly, the lens-designer has had many variables at his disposal which he could manipulate to achieve his objectives.

Up until recently, the designer of reflectors has had no such freedom of choice. With the Newtonian reflector optical system (see Figure 1), there is only one optically active surface which can be manipulated. All that can be done with this system is to make that surface into as accurate a paraboloid of revolution as possible. The primary mirror of the 200-inch Hale telescope is an example of this system. That giant mirror, by itself, has a field of clear definition (undegraded by off-axis coma) of only one-half inch in diameter—seven-tenths the diameter of a dime. In order to improve this situation at all, we must call in a good lens-designer—to give us a Ross correcting lens. Although the field of clear definition is much larger with this added component, it is still quite small compared with what might be obtained with a high-performance lens system of the same size.

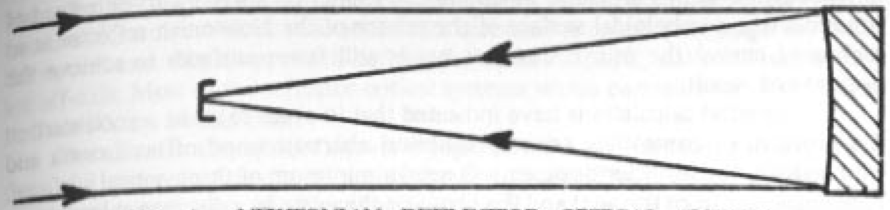


Fig. 1 NEWTONIAN REFLECTOR OPTICAL SYSTEM

With the Cassegrainian optical system (see Figure 2) the reflector designer has two optical surfaces to work with. The Ritchey-Chretien design is probably the best that can be obtained with this configuration. Since the secondary mirror in this design forms an obstruction in the center of the approach-path to the primary mirror, its presence there is detrimental to the over-all performance of the system. In order to keep this loss within acceptable limits, the size of the secondary mirror (and the associated light baffles) must be made small and the wave-front must be allowed to contract to a correspondingly small diameter before it reaches and interacts with the surface of the secondary mirror. This fact tends to make the optician's problems of producing the desired surface curve more difficult and tends to reduce somewhat the benefits which the designer can achieve from its presence in the optical system. Although the field coverage of the Ritchey-Chretien optical system is much larger than that of the Newtonian, it is still much smaller than that which could be achieved with a lens system of the same size. Also, if the focal length of the Ritchey-Chretien is made large in order to give it a large field of clear definition, that field may turn out to be larger than the area which can be devoted to the photographic plate without making it into an unacceptably large obstruction.

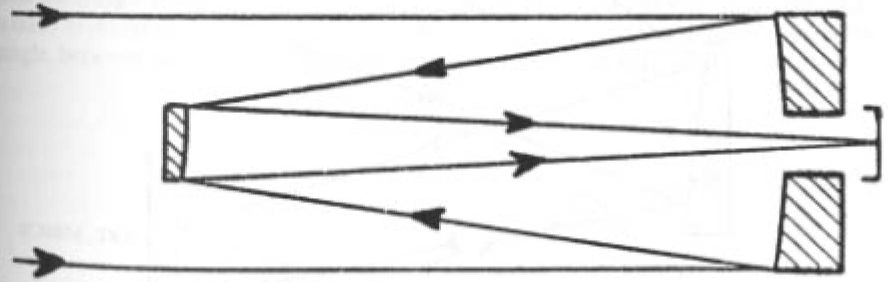


Fig. 2 CASSEGRAINIAN REFLECTOR OPTICAL SYSTEM

How Much Freedom Does the Reflector-Designer Really Need?

Lenses are afflicted with chromatic aberration and other chromatic problems. In order to do a really good job of controlling primary chromatic aberration, the lens-designer must employ three or more different kinds of glass in his lenses, and assign two or more radii of curvature just to this task. The control of other chromatic effects will require the assignment of one or more additional radii of curvature. The reflector designer, on the other hand, does not have to contend with any kind of chromatic aberration and thus, does not have to devote even one mirror surface to this problem. By employing aspherical surface curves instead of spherical (the paraboloidal surface of the mirror of the Newtonian reflector is an aspherical curve) the mirror designer needs still fewer surfaces to achieve the desired end result.

Theoretical calculations have indicated that in order to make a good start on the problem of controlling primary spherical aberration and off-axis coma and astigmatism, the reflector designer will need a minimum of three optical surfaces, each separated from the next and the photographic plate by a distance at least equal to the diameter of the wave front at the surface in question. Also, there should be adequate room for the photographic plate; and preferably, it should be possible to locate the mirror surfaces along the optical axis so that the wave front will be as large as possible when it encounters each optical surface. With additional surfaces to work with, other aberrations such as field curvature and distortion might be controlled. From this discussion it is apparent that conventional reflector optics (axially symmetrical) leaves the reflector designer one mirror short of the required minimum and inadequate room for the photographic plate.

Off-Axis Reflector Systems

Off-axis reflector systems offer a possible escape from this situation. Shown in Figure 3, is one such system. It has three mirrors and room for the photographic

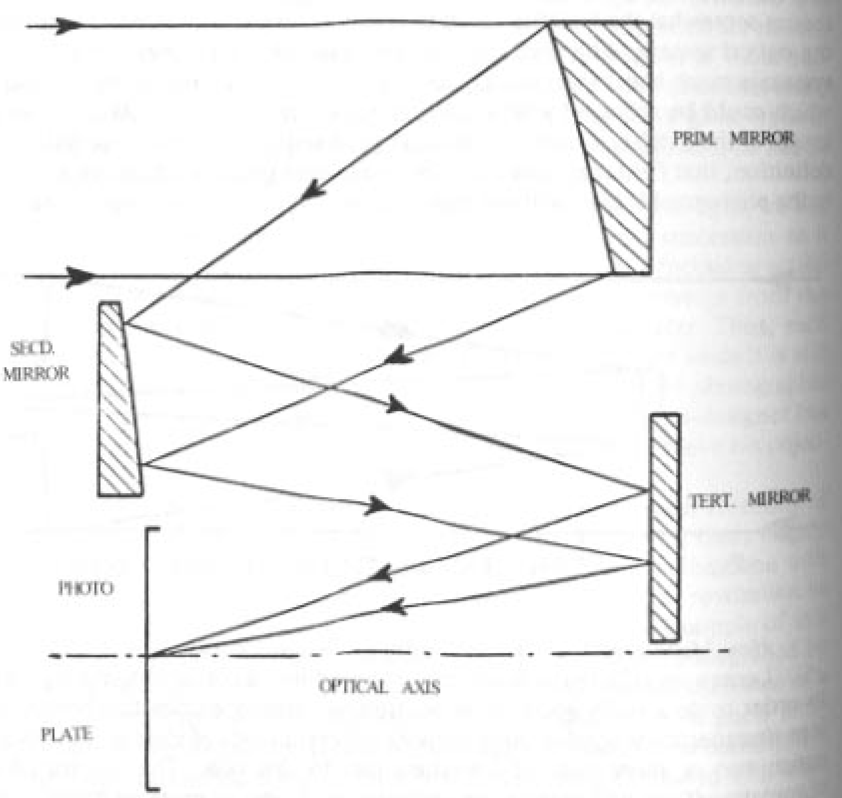


Fig. 3 WIDE-FIELD 3-MIRROR ECCENTRIC PUPIL OPTICAL SYSTEM

plate. Technically, this is not an off-axis system, but an eccentric pupil system, because if the object (located at an infinite distance) is on axis, its image will lie on the optical axis. The stop, which defines the eccentric pupil, and the cones of rays are off-axis. Most of the reflector optical systems which currently are described as "off-axis", are in this class.

The all-reflecting system shown in Figure 3 has a photographic speed of f/8, a field of 8 degrees in diameter, and is drawn to scale. The primary is a one-fifth diameter eccentric section of an f/1.6 concave mirror having a very strong hyperboloidal surface curve. The secondary is a three-elevenths diameter eccentric section of an f/2.9 convex mirror having a very strong hyperboloidal surface curve. The tertiary mirror is an eccentric section of a surface which might be described as a reflecting Schmidt plate.

I have not tried to actually carry out the design of this system, so I cannot say how well it might perform. However, I do believe that such an all-reflecting system could be designed. But actually building it would be quite another matter. It is obviously very bulky—50% wider than it is long, and yet, only f/8 effective. But the real problem would be to polish and figure the off-axis (eccentric) sections of the very strongly aspherical surface curves. There *must* be a better way to do this job.

Tilted-Component Telescope Optics

And fortunately, there *is* a better way—through the use of tilted-component optics. At the present time there are three basic tilted-component telescope systems, the Schiefspiegler, Figure 4, the Yolo, Figure 5, and the Catadioptric Herschelian, Figure 6. For someone not familiar with these designs, they might be mistaken for eccentric-pupil (off-axis) systems. They differ from eccentric-pupil systems in two important respects. First, they have no single straight line axis which is common to all components. Instead, the optical axis is defined as a series of straight lines joining the object-point, the vertices of successive components, and the image-point. Second, each component is designed and manufactured as an axially symmetrical unit and it is assembled in the system so that its axis bisects the angle between successive straight sections of the optical axis of the system.

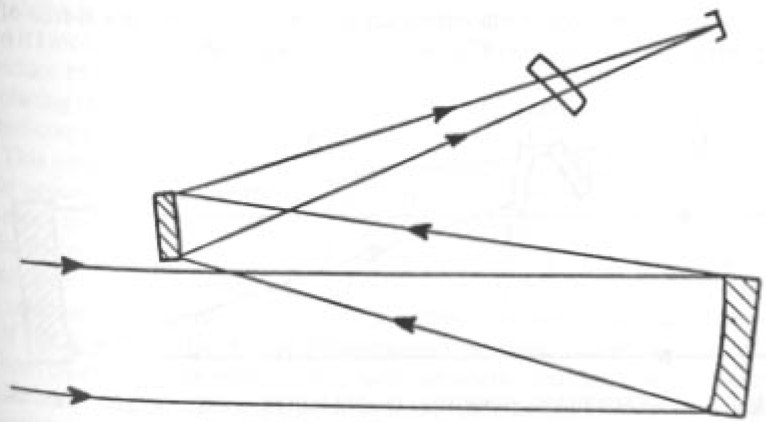


Fig. 4 SCHIEFSPIEGLER OPTICAL SYSTEM

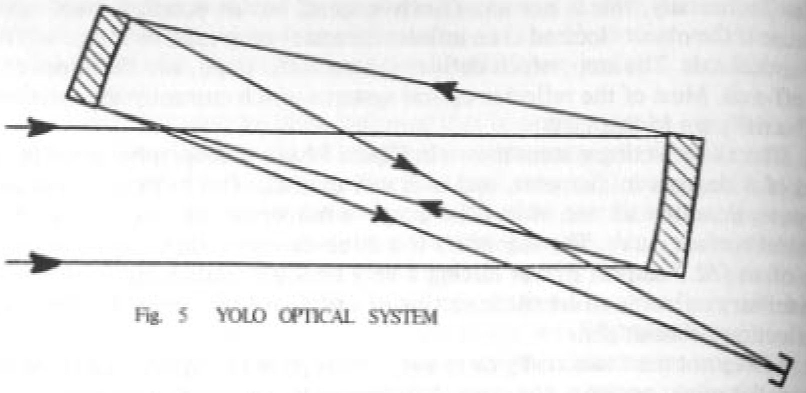


Fig. 5 YOLO OPTICAL SYSTEM

The design philosophy of tilted-component systems is to arrange to have the principal tilt-aberrations (primary coma and astigmatism) of one component cancelled by the corresponding tilt-aberrations of all the other components. Eccentric-pupil designs, on the other hand, are usually designed by arranging to have the spherical aberrations of one component cancelled by those of the other components.

One of the first questions which might be raised is, "How good are some of these tilted-component systems or, how large are the uncompensated tilt-aberrations?" Figure 7 is a spot diagram for a 10 inch, f/13.9 compound Yolo reflector. This shows all rays falling within a circle about 1/25th the diameter of the Airy diffraction pattern for that system. This means that considerably larger and faster systems could be designed without having unacceptably large residual tilt-aberrations.

All-Reflecting Systems

The Wide-Field Compound Yolo system shown in Figure 8 is an example of what can be accomplished along these lines. It is an all-reflecting optical system consisting of three concave front-surfaced mirrors arranged as shown. At least one mirror will require a warping harness; and, for the highest performance (large aperture and fast system), all three mirrors should be so equipped. When all three mirrors are given the proper aspherical surface curves, the system is free of primary spherical aberration and off-axis coma and astigmatism.

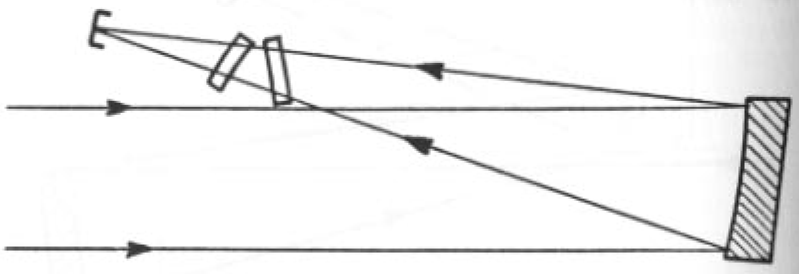
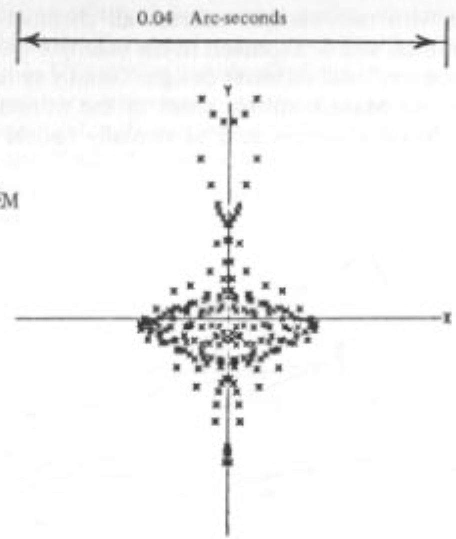


Fig. 6 CATADIOPTRIC HERSCHELIAN TELESCOPE (CHT) OPTICAL SYSTEM

Fig. 7 SPOT DIAGRAM FOR f/13.9 COMPOUND YOLO SYSTEM



The performance of this system should be superior to that of a Ritchey-Chretien of the same size and photographic speed. It should be useful for general astrographic survey work; and it should be especially good for space applications where its wide wave-length capabilities should make it most valuable.

Catadioptric Systems

A description of the Hamiltonian Reflector, Figure 9, was first published in 1814. Then, in 1899 the German mathematician Ludwig Schupmann patented a family of catadioptric telescope designs. His "brachyte" design is shown in Figure 9, and his "medial" in Figure 10. Several telescopes of the medial design have been built in recent years and they have been reported to demonstrate exceptionally high quality for visual observation. Although there are three refracting components in this design, it is virtually perfectly achromatic and free of all chromatic defects. It is also unobstructed.

The principal objection to the Schupmann medial design shown in Figure 10 is its relatively great over-all length. A rather obvious solution to this objection is to fold it twice, to give the Folded Schupmann Optical System, shown in Figure 11, and reduce its length to approximately one-third of that of the design in Figure 10. By replacing the flat with a long-radius concave mirror and applying the techniques of tilted-component optics, this system can probably be shortened even more.

This design, fine as it is, still has two minor disadvantages. First, it has a total of four optical components, whereas three should be sufficient to accomplish most of its more important objectives. Second, since the light is brought to a focus twice in this design, the various radii of curvature which it employs are somewhat shorter than would otherwise be needed and, as a result, the various uncompensated residual aberrations are a little larger than they would be otherwise.

If Hamilton's reflector and Schupmann's Brachyte design is adjusted to be free from chromatic aberration, it will have the aberration chromatic-difference in magnification. Also, the diagonal mirror of that design constitutes a central obstruction in the light path of the system. A theoretical analysis, however, shows that with two Mangin mirrors all chromatic defects can be eliminated. Thus, Hamilton and Schupmann in his brachyte design, were blocked by the restrictions of conventional reflecter designs (axially symmetrical systems) and that design fell just one Mangin mirror short of the minimum number needed to achieve that which, otherwise, would be virtually optical perfection.

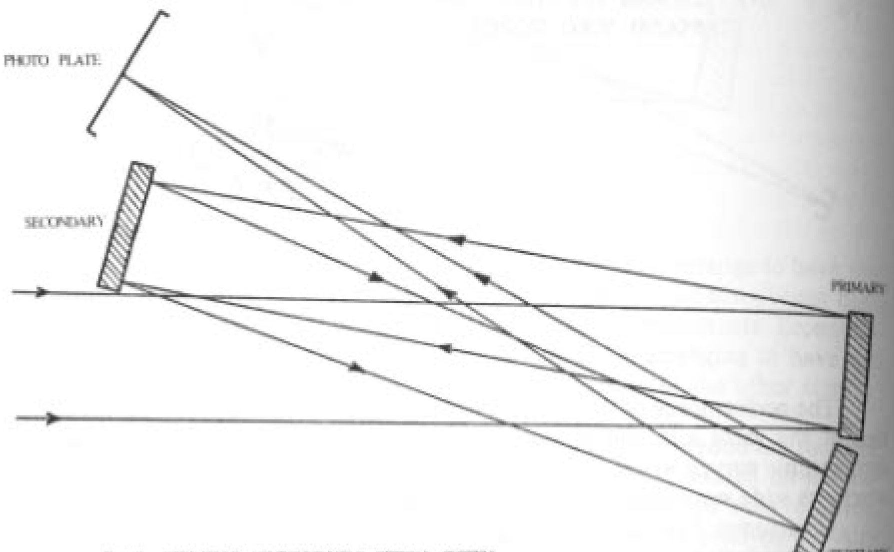


Fig. 8 WIDE-FIELD COMPOUND-YOLO OPTICAL SYSTEM

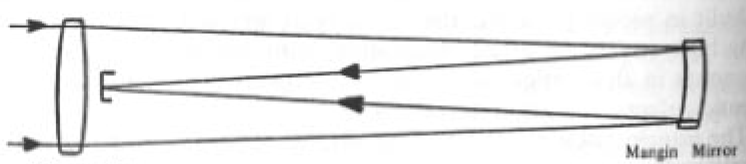


Fig. 9 HAMILTONIAN AND SCHUPMANN BRACHYTE OPTICAL SYSTEM

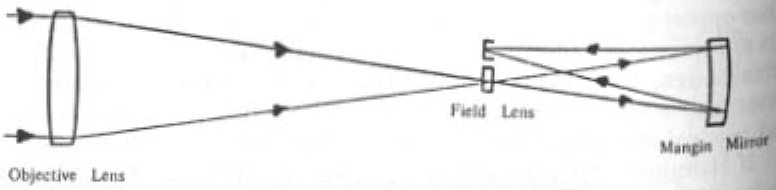


Fig. 10 SCHUPMANN MEDIAL OPTICAL SYSTEM

Here again, through the application of tilted-component optics, we can free the reflector designer of his age-old restrictions and come up with the Hamiltonian-Yolo Optical System, Figure 12. This design avoids all of the more serious types of chromatic aberration, ordinary chromatic aberration, chromatic-difference-in-magnification, and lateral color. It combines the compactness and tilt-aberration-free performance of the Yolo, the virtually perfect achromatism, closed-tube, and Mangin mirror advantages of the Schupmann medial, and the unobstructed optical perfection of both designs.

Mangin Mirror Advantages

One of the objections to reflecting telescopes is that front-surfaced mirrors usually scatter more light than do air-glass surfaces (lenses). The principal reason for this is a combination of sleeks and tiny areas of corrosion resulting from the repeated cleanings of the relatively soft aluminum surface and its exposure to insects, dust, moisture, and pollutants in the atmosphere. Mangin mirrors (back-surface aluminized on optical glass) on the other hand, are not subject to such deterioration with time because the actual reflecting surface is in intimate contact with glass, rather than being exposed to the atmosphere. Thus, these mirrors virtually last forever.

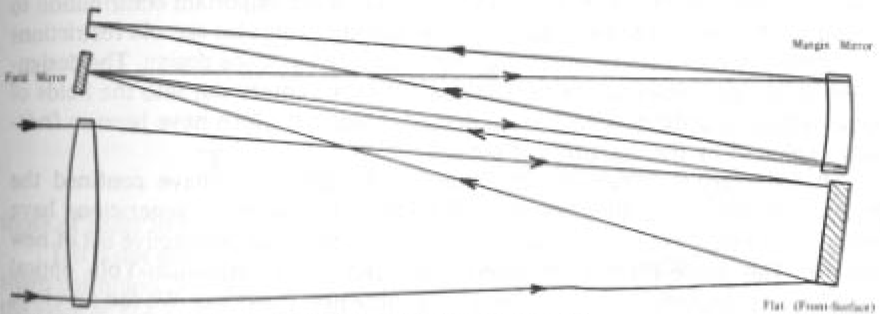


Fig. 11 FOLDED SCHUPMANN MEDIAL OPTICAL SYSTEM

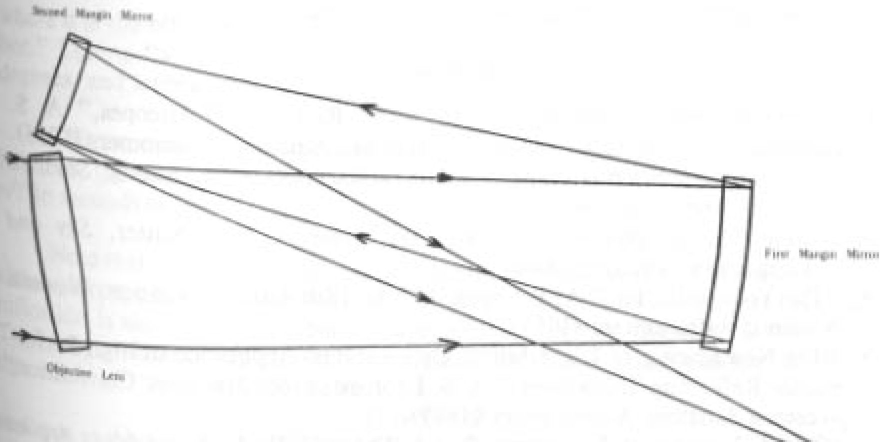


Fig. 12 HAMILTONIAN-YOLO OPTICAL SYSTEM

The Hamiltonian-Yolo design offers us a closed-tube telescope which can be built to eliminate all dust and insects from the interior of its tube and interior optical surfaces, is virtually optically perfect (no central obstruction in the light path or chromatic aberration), and the sleek-free mirror surfaces will last a lifetime; and all during that lifetime, will perform as if they had just been freshly aluminized yesterday!

Unobstructed-Reflector Philosophy

For the past several generations, students of lunar and planetary observing have known that the central obstruction in the more common forms of reflectors has a slight degrading effect on the performance of these telescopes. In an effort to realize the maximum possible theoretical performance by telescopes used in this service, a great deal of work by both professionals and amateurs has been invested in a campaign to find the best practical solution to this problem.

I believe that I am safe in saying that the total thrust to devise and develop all forms of unobstructed reflectors has come from the knowledge that a slight gain in optical performance of the more common forms of reflectors could be realized through the elimination of the central obstruction. The people who have contributed to the successful conclusion of this campaign are to be complimented for their long and dedicated efforts. I believe, also, that these people have been completely unaware of what may turn out to be a far more important contribution to optical science—the freeing of the reflector-designer from his age-old restrictions of no more than two active mirrors in any reflecting telescope design. The designers of reflecting telescope optical systems can now venture out into the fields of optics which up until now have been denied them, but which have been so fruitfully exploited by the designers of lenses.

In conclusion, I can say that the restrictions which have confined the designer of reflecting telescope optical systems for so many generations have finally been lifted. He is now free to explore and exploit an impressive list of new options. The Wide-Field Compound Yolo and the Hamiltonian-Yolo optical systems are examples of designs embodying these new freedoms. We can now look forward to having many new all-reflecting and catadioptric designs of increased sophistication and capabilities. These will include wide-field astrographs and the most nearly perfect visual telescopes that can be imagined.

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CHOICE OF FOCAL RATIOS IN NEWTONIAN TELESCOPES

by Edgar Everhart, PhD.

There are several reasons why long focus Newtonian telescopes give better images for almost all purposes than those of short to medium focus.

I. It is not generally realized how severely geometrical coma limits the field of sharp definition. We will calculate the size of the coma as seen in the eyepiece at the edge of the apparent field of view.

The usual formula for coma C in seconds of arc is:

$$C = 11d/f^2 \qquad (1)$$

where d is the off-axis angle in minutes of arc and f is the focal ratio or "f/number." Letting "a" be the half-angle of the eyepiece apparent field measured in degrees, and letting M be the magnification, it is evident that $d = 60a/M$ and

$$C = (11)(60)a/Mf^2 \qquad (2)$$

This expression is for coma in the focal plane. Since the eyepiece magnifies M times, the angular extent of coma C′ as seen visually is $C' = MC = (11)(60)\,a/f^2$ in seconds of arc, or

$$C' = 11a/f^2, \text{ in minutes of arc.} \qquad (3)$$

Note that coma as seen in the eyepiece is independent of magnification, thus although coma is very bad at the edge of a large field seen at low power, the magnification is also lower in proportion and, as seen visually, the coma is the same. Typical eyepieces have a 50° field, so the half-angle, a, is usually about 25°. With this value of "a" in Eq. (3) we get

$$C = 275/f^2 \qquad (4)$$

and this result is tabulated in Table 1.

f	C′ (minutes)	f	C′ (minutes)
4	17.2	8	4.3
5	11.0	10	2.8
6	7.7	12	1.9
7	5.6	15	1.2

Table 1. The angular extent of coma as seen visually at the edge of the eyepiece field. The eyepiece field is 50° in diameter. The result is independent of magnification.

The eye can detect as blurred, an image larger than about 2 minutes of arc. Thus an f/8 telescope, at all magnifications, has stellar images of 4.3 minutes of arc diameter at the edge of a 25° half-angle field. This comatic blur varies linearly with field angle and the images will be sharp only inside a field of about 12 degrees radius. The situation is much worse for telescopes of ratios of less than f/8. The conclusion is that short focus telescopes cannot have flawless images at any magnification over the field of the eyepiece. Only a ratio of f/10 or longer gives images which are substantially flawless to the eye to the edge of the field.

II. The linear field of the prime focal plane over which the coma is smaller than the theoretical diffraction image is quite independent of the size of the telescope and varies only as the cube of the focal ratio. Table 2 below gives the diameter of the field of substantially perfect images for various focal ratios:

f	diameter	f	diameter
4	0.055 in.	8	0.44 in.
5	0.104 in.	10	0.86 in.
6	0.185 in.	12	1.5 in.
7	0.294 in.	15	2.9 in.

Table 2. The diameter in inches of the field of good definition in the focal plane for various focal ratios.

The theory for this may be found on page 160 of Sidgwick's *Amateur Astronomer's Handbook.*

It is seen from the table that short focus telescopes require superb collimation in order that the region of good images coincides with the center of the eyepiece axis. The tolerance in collimating long focus instruments is much larger, and these will in practice be collimated well enough a larger fraction of the time.

III. A long focus Newtonian telescope can use a much smaller diagonal mirror and thus avoid some of the effect of diffraction in reducing contrast. The Cassegrainian type will lose out on this score in comparison with a Newtonian of the same focal ratio.

IV. There are a number of other considerations, such as the supposed easier figuring of long focus mirrors. It is the author's opinion that this is not nearly so important a consideration as the optical performance of the finished telescope. In any event, making a mirror is only about 1/3 of the effort of making a telescope. The mechanical parts take 2/3 of the effort.

One very real problem is that of making a very steady mount for a long focus telescope. In diameters over 6 inches, there is also the problem of arranging stools or step ladders in order to reach the eyepiece, and the difficulty in slow-motion controls from the eyepiece. There is also the awkwardly long tube to handle and transport.

Short focus instruments are easy to handle and transport and will work very well on nebulae since the objects are blurry anyway. An f/5 instrument with a 1¼" eyepiece makes a good richest field telescope and comet seeker. For many purposes the f/8 ratio is a compromise between ease of handling and mounting, on the one hand, and tolerable optical performance on the other. If, however, one is willing to make no compromise with image quality and is willing to spend the effort necessary to mount, handle and control a long tube, there is no question that an instrument of f/10 proportions is well worth the effort.

TO DESIGN A SECONDARY HYPERBOLOID FOR A CASSEGRAINIAN TELESCOPE

by A. M. Crooker, PhD.

Let the primary form its focus at F_1. Then we want to calculate the radius of curvature and the hyperboloidal figure for a secondary mirror surface placed at a distance of L_1 from F_1, so that the final image is formed at F_2, a convenient distance behind the primary, at a distance L_2 from the secondary. The equivalent focal length of the primary-secondary combination is $F.L_2/L_1$, and L_2/L_1 is called the telephoto ratio.

I. First we calculate the focal length f of the secondary required to image F_1 at F_2. Since F_1 is a virtual object

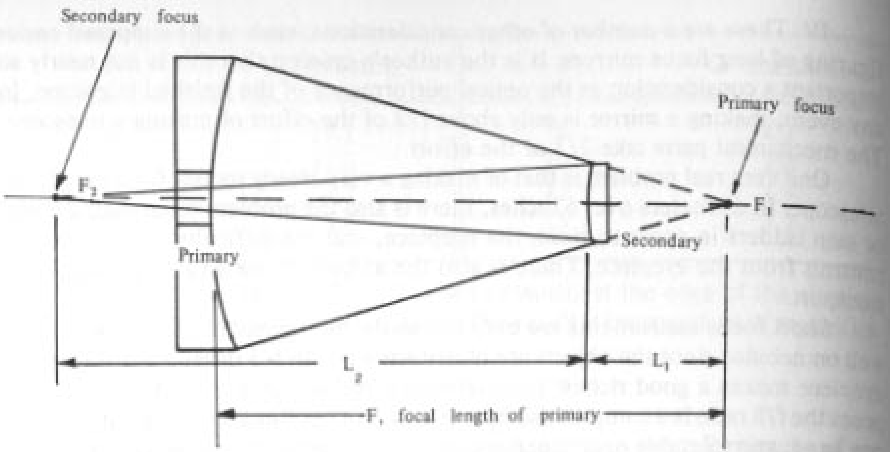
$$-\frac{1}{L_1} + \frac{1}{L_2} = \frac{1}{f}$$

This f will turn out to be negative, which just means that the mirror is convex (a dispersive element). Then the radius of the mirror is $r = 2f$.

For example, $L_1 = 320.386$ mm and $L_2 = 963.486$ mm, so that $f = -480$, i.e., $r = 960$ mm (convex).

II. We next reduce the equation to the hyperboloid in normal form:

$$\frac{x_h^2}{a^2} - \frac{y^2}{b^2} = 1$$



Calculate $2c = |L_1| + |L_2|$; i.e., add L_1 and L_2, both with positive signs.
Calculate $2a = L_2 - L_1$.

In the example $2c = 1283.872$; $c = 641.936$; $c^2 = 412081.828$
$2a = 643.1$; $a = 321.55$; $a^2 = 103394.402$
then $b^2 = c^2 - a^2 = 308687.426$
$b = 555.59646$ $b^2/a^2 = 2.985533$

As a check on the arithmetic, see that $b^2/a^2 \times a = r = b^2/a$.

III (a). If the convex hyperboloid is to be checked for "no rings" against a concave hyperboloid, then the subnormal of the concave hyperbola is calculated from the formula:

$$\text{subnormal} = \frac{b^2}{a^2}(X_h) = \frac{b^2}{a^2}(X_h + a)$$

where X is the sagittal distance measured from the center (= vertex or pole of the concave hyperboloid).

Let us calculate the subnormal form,

$$\frac{X_h^2}{a^2} = \frac{b^2 + y^2}{b^2} \text{ or } X = \frac{a}{b}\sqrt{b^2 + y^2}$$

$$\text{so that the subnormal } \frac{b^2}{a^2} \cdot X = \frac{b}{a}\sqrt{b^2 + y^2}$$

	y = 15 mm	= 30 mm	= 40 mm
b^2/a^2X	960.3480	961.3967	962.4829
add sag. $X = y^2/2R$	.1172	.4687	.8333
vertex distance (measured in Foucault test)	960.4652	961.8654	963.3162
zonal increase	.4652	1.86	3.32

III (b). The concave hyperboloid "test-glass" may be checked by fringes from a convex sphere. For the appropriate equations, use the parametric equations to a hyperbola

$$X_h = a/\cos\theta \qquad y = b\tan\theta$$

	y = 15 mm	= 30 mm	= 40 mm
θ	1.54650^0	3.09040^0	4.11789^0
$X_h = X_h - a = \frac{a(1-\cos\theta)}{\cos\theta}$	$\frac{a(.0003642)}{.9996358}$	$\frac{a(.0014543)}{.9985457}$	$\frac{a(.0025816)}{.9974148}$
X_h	.11714	.468305	.832268

Also calculate the X_s values for a spherical surface:

$$X_s = r - X_s = r - \sqrt{r^2 - y^2}$$

	y = 15 mm	= 30 mm	= 40 mm
X_s	.117195	.46886	.83370
$\Delta = X_s - X_h$	.000055	.00056	.00143
using $\lambda/2 = .000273$ mm	0.2 rings	2.0 rings	5.2 rings

Both the zonal increase and Δ expressed in rings can be graphed to interpolate their values at other values of y, the zonal radius.

MORE ON COMPUTING CASS. SECONDARIES

by Joseph Raab, Jr.

The way I get "e" (eccentricity of the hyperbola) is to use the formula:

$$e = \frac{A + 1}{A - 1}$$

where A is the amplification. The derivation of this is as follows:

We know that e of the classical hyperbola is found by using

$$e = \sqrt{\frac{a^2 + b^2}{a}}$$

We also know that ae is equal to OF, and $0 \rightarrow F = \sqrt{a^2 + b^2}$. Now in the actual telescope the distance $0 \rightarrow F$ is the same as $(f+b)/2$, and a is $(f+b)/2 - p$.

Now if we substitute the classical formula, we get

$$e = \frac{(f+b)/2}{(f+b)/2 - p}$$

This simplifies to:

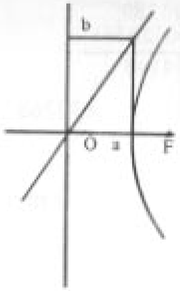
$$e = \frac{f + b}{f + b - 2p}$$

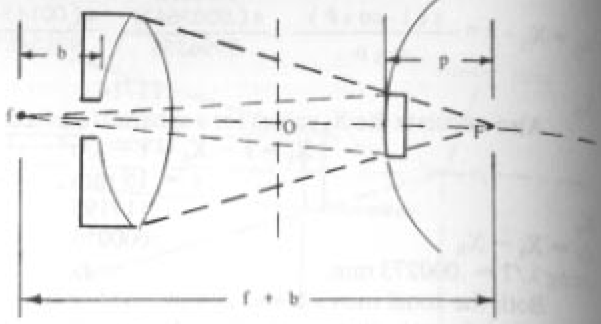
Now $p = (f+b)/(a+1)$, so if we substitute this value for p, we end up with

$$e = \frac{A + 1}{A - 1}, \quad \text{for a Gregorian } e = \frac{A - 1}{A + 1}.$$

Once we have e, it is simple to compute for the zonal aberrations from Gaviola's formula

$$z = \frac{e^2 r^2}{2R}$$



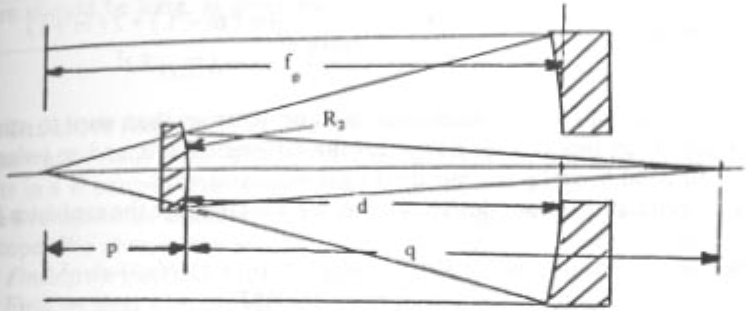


GENERAL CASSEGRAIN FORMULAS
by R. A. Buchroeder

Except for the classical Cassegrain, it is virtually impossible to find any written instructions on designing and building compound reflectors. Almost all professional instruments have conic mirrors, and this article gives complete equations, based on third order aberration theory, to calculate Dall-Kirkham and Ritchey-Chretien reflectors that use conic mirrors. So long as the primary is slower than f/2, and the secondary mirror amplification is greater than 2X, the residual higher order aberrations will be entirely negligible. For example, a 10″ f/4 — f/16 Ritchey-Chretien so calculated has a residual spherical aberration of 1/20,000 wave. A professional Ritchey-Chretien such as the 90″ f/2.7 — f/9 Steward reflector at Kitt Peak, using conic mirrors, has a residual of approximately 1/100 wave. The amateur's mirrors are likely to lie somewhere between these two extremes, and he may place complete reliance on the formulas.

The source of the equations is Woodruff & Bottema's article on page 300 of the February 1971 issue of *Applied Optics*. That article also gives equations to calculate the aberrations of any compound reflector, and the interested reader is referred to it. What we will do is to replace their measure of asphericity, the quantity "e" (which is not, incidentally, the usual geometric accentricity of the conic), by the value K+1. Thus K = (e−1). If you test a paraboloid at its center of curvature, it has a knife-edge shift of $y^2/2R$. Now in our system, the K of the paraboloid is K = −1. A sphere has K = 0, so it would show no knife-edge shift at center of curvature. All the Ks of interest will have negative values, and it turns out that the knife-edge shift of any concave mirror will be simply K times the parabolic knife-edge shift. Thus a concave mirror with, say, K = −1.25, will have a shift 1.25 times that of a paraboloid, which is to say 25% more. An elliptical mirror has its K between 0 and −1, for example the usual Dall-Kirkham will have K = −.7, and so its knife-edge shift is only 70% that of a paraboloid. With the exception of the Dall-Kirkham, the telescopes will have hyperboloidal secondary mirrors—that is, K will always be more negative than −1 (say typically −3). The usual professional way to test such a mirror is in the Hindle test, but that requires a sphere at least twice as fast as your primary. There are a number of "cheap" tests available, and the reader will only be given a method for finding the hyperboloid's asphericity and thus its two foci.

We now proceed to design a compound reflector. Study the sketch below which gives all the essentials:



f_p = focal length of primary—½ radius of curvature.
R_2 = radius of curvature of secondary, considered negative.
d = mirror separation.
p = prime focus intercept distance = f_p − d.
q = distance from secondary to Cass. focus.
m = secondary magnification = q/p.
s = q/d = (distance from secondary to Cass. focus)/(mirror separation).

Now by reference to any source on Cassegrains, one can relate the geometric parameters. You need enough clearance behind the mirror to reach the image, preferably enough to use a star diagonal as Cassegrains are uncomfortable without one. The axial obscuration ratio is just p/f_p on axis, but you should add a little more aperture. The extra amount is just the desired field of view measured in radians (divide degrees by 57) multiplied by the mirror separation, d. Usually the amateur gets this far on his own just by geometric proportions, but has difficulty in figuring out the radius of curvature on the secondary. This is found by the equation:

$$2/R_2 = 1/p - 1/q$$

where you use positive numbers for p and q, but for later use it is to be understood that R_2 is to have a negative value. Let us start an example. Let the primary mirror be 10″ f/4 (so its R = 80″), let the mirror separation be 30″, which then gives p = 40 − 30 = 10″, so that makes the distance from the secondary to the Cass. focus = 40″. Now we find the radius of curvature R_2

$$2/R_2 = 1/10 - 1/40 = .075,$$

so R_2 = 26.666666, but we shall call it minus later on. It is, of course, allowable to round off the numbers, say R_2 = −26.667.

Now we can calculate the only two quantities needed to prescribe the aspherics, m and s. We find that m = q/p = 40/10 = 4, s = q/d = 40/30 =

1.33333. The aspheric figures are calculated with the formulas:

Type	Primary $(K + 1)$	Secondary $(K + 1)$
Dall-Kirkham	$\frac{s(m-1)(m+1)^2}{(m+s)m^3}$	1
True Cass.	0	$\frac{-4m}{(m-1)^2}$
Ritchey-Chretien	$\frac{-2s}{m^3}$	$-\frac{4m(m-1)+2(m+s)}{(m-1)^3}$

Note that m and s are common to all designs; you may then want to compute the aspherics for all types to see how great the differences are, and so judge how carefully you need to make the mirrors to get what you want.

As a continuation of our design sample, we will compute the aspherics for all three types of design:

Dall-Kirkham: Primary mirror $K+1 = s(m-1)(m+1)^2/(m+s)m^3$
$= +.2929687$
so primary $K = -0.7070313$
Secondary mirror $K+1 = 1$, or $K=0$, which is a sphere.

True Cass.: Primary mirror $K+1 = 0$, so $K = -1$, which is a true paraboloid.
Secondary mirror $K+1 = -4m/(m-1)^2 = -1.777777$
Secondary mirror $K = -2.777777$

Ritchey-Chretien: Primary mirror $K+1 = -2s/m^3 = -0.4166666$
Primary mirror $K = -1.04166667$
Secondary mirror $K+1 = \text{minus } \frac{4m(m-1)+2(m+s)}{(m-1)^3}$
$= -2.1728395$
Secondary mirror $K = -3.1728395$

The above prescriptions were all ray-traced on the computer as a check on the formulas themselves, to see what sort of residual errors due to higher order aberration occurred. The computer shows that the Dall-Kirkham is good to 1/200th wave, the Ritchey-Chretien to 1/20,000th wave, and the true Cassegrain is perfect.

Making the Mirrors.

It is presumed that the reader will use the knife-edge tests and the formulas:
desired longitudinal reading = z
$z = Ky^2/2R$ for both source and knife-edge moving together.

Mathematically, the way to keep the design radius from changing as you figure is to knock down the edge of the mirror, but this is rarely done owing to the risk of ruining the figure due to a turned-down edge. Opticians generally deepen the center, and to get the right final radius it is advisable to start with a spherical radius that is long by $Ky^2/2R$. If all you did was to directly aspherize, the depth of the stock removed in the middle would be $Ky^4 8R^3$, which is approximately the

difference between the spherical curve and the aspheric. Professionals use Offner Null lenses to figure their primaries, but these are too much work for the ATM, so we are left with the simpler tests.

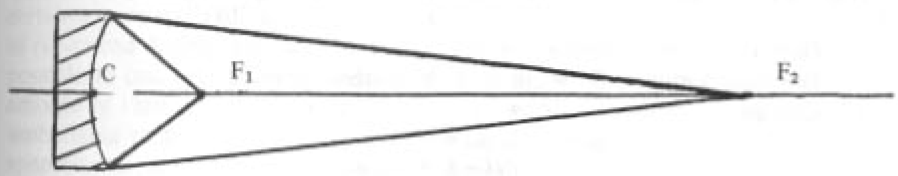
The secondary mirror will always be hyperbolic in these telescopes, except for the obviously simple mirror of the Dall-Kirkham. Our opticians figure convex hyperboloids by removing stock mainly at the 70% zone. Despite the high K values, the amount of stock removed on a secondary is always much less than on a primary mirror, and the 70% zone is the minimum stock removal form. In order to start with a radius that should end up with the design value, again the starting sphere should be long, as given by:

$$R_{(start)} = \frac{R_{(design)}}{1 + (Ky^2/4R^2)_{design}} \quad \text{remember K is negative}$$

The above formula differs from the one for the primary because we are using the minimum stock removal method. Disregarding the above formulas sometimes results in a ½ percent error of radius on a fast mirror, an amount that is negligible in the average small amateur telescope, but consequential to the large professional telescope. We always take account of it in our work.

Finding the Foci.

First we deal with the ellipse of the Dall-Kirkham. The sketch below shows the situation:



R = the mirror's radius, F_1 is its short focus, and F_2 is its long focus. A source at one will be perfectly re-imaged at the other when you have the correct figure, so it is a good null test. K was calculated from the D−K formula, and is negative. For the mathematician, if the eccentricity of the conic is E, then $K = -E^2$. The steps to find the two foci are as follows:

1. Calculate $m = R/(K+1)$, remember K is negative.
2. Calculate $n = m\sqrt{K+1}$.
3. Calculate $o = \sqrt{m^2 - n^2}$.

The short conjugate $CF_1 = m - o$, use positive values of m and o. The long conjugate $CF_2 = m + o$.

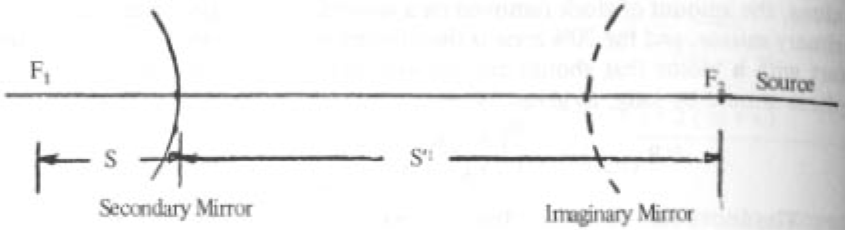
If you end up with negative values for the two conjugates, check your math for error.

Example.

Let $R = 100$, $K = -0.7$
then $m = 333.333$
$n = 182.574$
$o = 278.886$
and $m - o = 54.447$
$m + o = 612.193$

For telescopes with unusually high secondary magnifications, you'll find that the long conjugate may be so far away as to be impractical for testing, and then it is best to go ahead and knife-edge it. The shift sought is just K times the shift for a paraboloid, and of course is always less than a paraboloid would have.

Hyperbolic Secondary.



Given: R = design radius, *negative.*
K = value calculated with the equations, K is always more negative than −1.
1. Calculate $m = R/(K+1)$, positive.
2. Calculate $n = -m + \sqrt{m^2 - mR}$,

but since R is negative, both quantities under the root sign are positive and additive.

Then the short conjugate $S = n$.
The long conjugate $S' = 2m + n$, both items positive.

Example.

$$R = -50,\ K = -3$$
$$\text{gives } m = -50/(-3 + 1) = +25$$
$$\text{and } n = -25 + \sqrt{25^2 - 25(-50)} = 18.3013 = S$$
$$\text{so } S' = 2 \times 25 + 18.3013 = 68.3013.$$

The way a Hindle sphere works is that it is concentric with the left-hand focus, and since it must not hit the secondary mirror, its minimum radius is obviously longer than S. If its radius were longer than S + S', it would be hard to get the light in and the knife-edge at it as it comes out. Thus the Hindle sphere has a value somewhere between these two extremes; ideally its radius is about equal to the focal length of the primary mirror, at which point its diameter would be about the same as the primary. Usually this is uneconomical, so one of a shorter radius is used, with a consequent increase in central obscuration due to the necessity of enlarging the hole in the Hindle sphere to get the light through. It is possible to use a folding flat, but it is harder to align. One can also use a smaller Hindle sphere put off to one side to examine parts of the secondary rather than the whole thing at once. This is quite a mess, but often required in large telescopes. As to errors on the conjugates, the accuracy of the short conjugate is more important than that of the long conjugate and the ATM should be certain his two conjugates are precise when he gets his null!

Derivations of the various equations used are omitted for the sake of brevity. However, the reader will perhaps take comfort in knowing that none were conjured

up specially for this article, but have been used in our shop and proved time and again on actual optical instruments.

TOLERANCES (SAGITTAL AND OTHER)

by Diane Lucas

When starting out to make any telescope, one of the first things to consider is just how closely the given radii must be obtained. Most of us probably didn't come within more than a few inches of our aim with our first f/8. This was not too disastrous, however, since it meant at most drilling a few more holes in the tube and moving the diagonal and eyepiece holder; unless, of course, you were smart enough to wait until the mirror was all finished to drill the holes. The important thing was achieving a usable figure on the mirror.

For anything more complicated than a Newtonian, the problem of attaining a certain accuracy of radii and figure arises. Since there is an ever increasing number of ray-traced designs available, it would probably be advisable to come as close as possible to one set of specified design figures as can be attained in a reasonable amount of time with a reasonable amount of work. This should reduce the final aspherizing required, if nothing else. For accurate radii, a good tool would be a spherometer, and an understanding of its possible sources of error and their effect on radius measurement is useful. To use a spherometer, once we have it made, we need to measure its diameter (y) and the sagitta (s) of the surface to be measured. Then we find the radius of curvature (R) with the spherometer formula:

$$R = \frac{s}{2} + \frac{y^2}{2s} \qquad (1)$$

1. Errors in sagitta measurement are the major causes of error. From the spherometer formula, the following is derived showing the error in radius dR_s caused by a sagitta error ds.

$$dR_s = ½\left(1 - \frac{y^2}{s^2}\right) ds \qquad (2)$$

Obvious sources of error here would include an inaccurate indicator, lack of care in making measurements, etc. This formula can be used to show the effect of increasing spherometer diameter, 2y, in the accuracy. Let us consider a 10" spherometer and a 10'3/4" spherometer, both measuring a radius of 18.2".

For 2y = 10 and s of about .7, dR_s is 25 ds.
For 2y = 10.75 and s of about .8, dR_s is 21.4 ds.

For a longer radius of R = 100, the advantage of the larger diameter may be more apparent.

For dy of 10, dR_s is about 800 ds.
For dy of 10.75, dR_s is about 700 ds.

The system favors the shorter radii, which is where Maksutov tolerances are most stringent. With a 10.75" spherometer, measuring a 18.2" radius and a ds of .001", the radius error will be .021". With a .0001" indicator carefully zeroed and checked for accuracy, we might have an error in sagitta of only .0002" to .0003", which in this case would cause a radius error of .004" − .006". Maximum accuracy could be obtained by using a spherometer with y equal to the R that needed measuring, then $dR_s = ds$. This would lead to some impossible situations, with a spherometer diameter of 200".

2. Errors in y. A possible source of error here is an inaccurate measurement of y. This formula gives the effect on R of an error dy in y as dR_y.

$$dR_y = \frac{1}{s} dy \tag{3}$$

For example, if dy is .001" and s is .5", then dR_y will be .002". With the same spherometer and dy, if s is .1", the error dR_y will be .010".

The more accurately y is measured, the less worry there is about its contributing error. If 2y is measured within .0002", dy will be only about .0001" and in the above two cases the error dR_y will be reduced to .0002" and .001" respectively.

3. Effect of an off-center indicator. If a .0001" indicator is used, the old $y^2/2R$ equation can be employed to find how far off center the indicator may be placed. If a sagitta error of .0001" is permitted, the eccentricity of the indicator will be:

$$y = .0002R \tag{4}$$

The case is worse for short radii. For R of 10" this equation will give a y of .014" (about 1/64"). For R of 20", it will be .064". If the indicator is off center by an appreciable amount, it should be possible to measure the amount and compensate for it.

4. Temperature effect. Besides the obvious effect of dust and dirt under the feet of the spherometer, in extreme cases temperature could also cause an effect. Steel expands 6.36×10^{-6} inches per degree Fahrenheit. If a measurement of 2y for a 10" spherometer were made at 65°F. and the spherometer later used at 75°F., there would be an error of .00064" in 2y, or dy of .0003", and from Eq. (3) dR_y = .0003/s. If a long radius is measured, s may be .1" or less, and the error dR_y will be .003" or more.

If the radius measured is short, as for an s of .5, the error will be only .0006". These effects would probably be the only temperature effects worth considering.

5. If a two ball footed spherometer is used, the spherometer equation is:

$$R = \frac{s}{2} + \frac{y^2}{2s} \pm r \tag{5}$$

where r is the radius of the bearing ball used. Since two balls are used

$$dR_s = 2dr \tag{6}$$

where dr is the error in ball radius from the value used. Since bearing balls can be obtained as uniform as desired, this error can probably be ignored, unless your bearing balls have flats worn on them.

The total possible error in radius determinations will be the sum of all the contributing errors. This analysis should give an indication as to the area where extra care should be taken. My own approach is to pick a good design and work radii and thickness as closely as a good spherometer and skill will allow, without worrying about gnats' eyebrows, and then finish aspherizing by autocollimation.

T.C.T.'s (TILTED COMPONENT TELESCOPES)

by A. S. Leonard

Reports from many (but not all) experienced observers indicate that for planetary observation increases in aperture above some moderate size yield very little improvement in performance. The reason for this appears to be a combination of the fact that even a small loss in the optical quality of a system will result in a rather large loss in a telescope's ability to show faint planetary detail and the fact that as the aperture of the telescope is increased, the loss in the optical quality of the system due to astronomical "seeing" increases. The net result is that there is some size above which the potential gain in performance which should be obtained from a further increase in aperture is just about wiped out by a corresponding increase in the loss of optical quality due to seeing.

Quite a number of experienced amateur observers who have used both reflectors and refractors of the highest quality have expressed the opinion that 6 inches is just about the optimum aperture for planetary work. The quality of their work seems to leave little room for doubt about their observing ability or the optical quality of their telescopes. At the sites where these observers had their telescopes set up, the seeing was probably just about the same as that at the average amateur's observing site. Dr. J. A. Anderson of the Mount Wilson Observatory, with the benefit of the very good seeing at Mt. Wilson, has raised this optimum aperture to 10 inches.

Another way of explaining this is as follows: a wave-front of light from a distant planet is accurately flat at the time it reaches the top of our atmosphere. By the time it has passed through our atmosphere and arrived at the observer's telescope, it is pretty badly wrinkled. However, there are a few small patches in it here and there which are still fairly flat. Since for planetary observation we can tolerate very little deviation from perfection, we must limit the size of the piece we take to the size of the largest reasonably flat area that we are likely to find occasionally in the wave-front. After we have taken this section of the wave-front into our telescope, we must handle it in the best possible way—our telescope must be as nearly optically perfect as possible. We will not get the same result by taking in a larger section of the wave-front, which will contain larger imperfections to start with and then passing it through an imperfect instrument which will add its imperfections to the total.

In order to locate areas in the design of the reflecting telescope open to improvement, let us raise the question, "What, if anything, is wrong with available reflector designs?" This requires a definition of what we mean by "wrong" and, ultimately, this must be resolved by setting some sort of standards, or "tolerances".

Many years ago Rayleigh stated that if the effective total path length of the longest and shortest ray in an optical system did not differ by more than one-quarter of a wave-length (¼λ) of the light traversing the system, the optical performance of the system would be practically the same as a perfect system. Stated in another way, this means that no path length should deviate from the mean by more than $1/8\lambda$.

Some authorities on optics have expressed the opinion that this is not a high enough standard for a telescope intended for use on lunar and planetary detail, and others feel that it is too strict. Actually, the quality of the image produced by an optical system will depend not only on the amplitude of the maximum path difference, or error, but also on the fraction of the total light which is subject to this error and on its location or distribution within the cross-section of the beam of light. Since a detailed discussion of this subject is outside the scope of this paper and since the Rayleigh tolerance appears to be a good, practical working compromise, it will be taken as the standard for the rest of this discussion.

It should be pointed out that Rayleigh stated quite clearly that the *total* path difference should not exceed $\frac{1}{4}\lambda$. This means that the total of *all* the errors in the optical path should not exceed $1/8\lambda$. In the case of an astronomical telescope which is being used for visual observation, this includes all the errors in the line of sight in the Earth's atmosphere ("seeing") and in the observer's eye, as well as those in the telescope. Practical experience has shown that from most of the observing sites that are available to the amateur telescope maker and with most of the sizes of telescopes that he is likely to build, seeing usually uses up all, or practically all, of the Rayleigh tolerance (and sometimes a lot more). This means that if the telescope maker is to have an optical system which meets this standard, he must build his telescope to a much closer tolerance than $1/8\lambda$. Since there are quite a number of places in the telescope, or steps in its construction, where optical errors may be introduced, he should strive to keep each individual error smaller. This means that wherever possible, he should strive to make each error vanishingly small. Since this is rather vague, we will quite arbitrarily choose a value of $\pm 1/100\lambda$, and then try to determine what this leads to. As far as the figuring of the mirror is concerned, most amateur telescope makers will find that this is an unreasonably close tolerance. It is suggested that in this particular operation the amateur sets his own tolerance (somewhat to match his skill at mirror making). But for other errors, which can be either detected or predicted, and for which reasonable solutions for their reduction are available, it is felt that the $1/100\lambda$ tolerance should be used.

Six Things Wrong with Reflecting Telescopes.

In order to show the possibilities for improvement in the performance of the reflecting telescope, let us apply this standard to a typical instrument—an f/7.5 8-inch Newtonian reflector—and list the things that are "wrong" with it:

1. Need for parabolization. Its mirror needs to be parabolized to within about 3½% of the calculated value. It is probably safe to say that not more than one such mirror in one hundred is parabolized to this degree of accuracy. The reasons for this are that with the test methods readily available to the amateur telescope maker, it is not practical to test such a paraboloid to this high degree of accuracy, and he could not figure it this accurately without the expenditure of an unreasonably great effort.

2. Collimation. In order to keep the errors due to imperfect collimation from exceeding $1/100\lambda$, this mirror must be adjusted in its mounting to within 25 seconds of arc. Here again, with the collimation methods employed by most amateurs, very few telescopes will be found to be aligned with this degree of accuracy.

3. Mirror sag. For a standard 8-inch mirror blank supported at three points 0.7 of its radius from its center and with the telescope pointing straight up, the maximum error (in the form of 3 high and 3 low spots at the edge of the mirror) will be about $\pm 5/100\lambda$. This method of support has been used very successfully for the testing of optical flats because with it there are three diametral lines across the face of the glass blank for which there is practically no sag. These lines come to the edge of the blank midway between the high and low spots and are the lines along which the optical flats are tested. This method of support is not particularly beneficial for telescope mirrors because, unfortunately, the whole surface of the telescope mirror is not just three narrow bands across its face.

4. Eyepiece errors. Aberrations chargeable to the eyepiece may or may not exceed $1/100\lambda$ in the center of the field of view of this telescope, depending on the type of eyepiece used. With a good, first quality orthoscopic ocular, there should be little loss in performance in the center of the field from the eyepiece; but there seems to be little doubt that *one* of the reasons for the reflector's reputation for being "not quite so good as the refractor" has been due to the use of eyepieces which, when used with an f/15 objective (typical refractor), introduce relatively little error, but which introduce a really significant error with an f/7.5 system. Also, for objects some distance from the center of the field of view, even the orthoscopic ocular will be in trouble with the f/7.5 objective of the reflector.

5. Thermal effects. Thermal effects may be divided into two groups: those which produce convection currents in the air in the optical path and those which change the surface curve of the mirror. Temperature measurements made with very small thermocouples on an 8-inch pyrex mirror which was mounted in a thin sheet-metal tube and set out-of-doors before sunset on what was a good night for observing, have shown differences in temperature between the mirror and the tube of as much as 5°F. as long as 3 hours after dark. This temperature difference was due to the relatively large heat capacity of the mirror and the falling air temperature which is typical of many observing sites on many nights. The relatively warm mirror will produce convection currents in the air within the tube and these will be very detrimental to the performance of the telescope. To give an idea of how serious these can be, it takes a temperature difference of only 0.0061°F. in a column of air 5 feet long at sea-level density to produce an effective difference in path length of $1/100\lambda$. Lining the tube with cork or closing the front end with a window will have relatively little effect on those convection currents which will be confined to the space within the tube.

Changes in the figure of the 8-inch mirror brought about by the steady drop in its temperature under these same night-time conditions will not be nearly so detrimental to its performance, but may easily exceed $1/100\lambda$. As we go to larger telescopes, the thermal effects in the glass become relatively more serious; so for very large telescopes, the changes in figure may constitute a greater loss in performance than the convection currents in the air from the relatively warm mirror.

6. Central obstruction. The centrally located secondary mirror of the Newtonian reflector (and also of the Cassegrainian and Gregorian designs) produces a very appreciable loss in performance when it comes to observing faint planetary detail and the faint companions of bright stars. This loss in performance is of a different nature than the other five because it does not introduce any change in effective path length for the various rays. Therefore, it cannot be judged by the same criterion ($\pm 1/100\lambda$ path difference) as the others.

The central obstruction brings about changes in the light distribution within the diffraction pattern which result in the telescope losing some of its ability to show detail of low contrast in planetary images. Since the telescopic image is no more than a mosaic of overlapping diffraction patterns formed on the retina of the observer's eye, and since all diffraction patterns formed by any given telescope within the central part of its field of view are of the same size and geometry, the quality of the telescopic image will depend almost entirely on the quality of the individual diffraction pattern.

The diffraction pattern consists of a bright central disc surrounded by a series of concentric rings, each successive ring being fainter than the one just inside of it. The apparent brightness of any point in the image is, therefore, the sum of the brightness of the central discs of all the diffraction patterns whose centers lie within a radius equal to the radius of the central disc of the diffraction pattern, plus the brightness of the *first* bright rings of all diffraction patterns whose centers fall within a circular band around the point corresponding to the *first* bright ring of a diffraction pattern whose center lies at the point in question, plus the brightness of the *second* bright rings, etc., etc. From this explanation, it can be seen that only a few diffraction patterns will contribute the brightness of their central discs to any given point in the image while successively greater numbers will contribute the brightness of their successively fainter rings. The net result is that the ratio which counts is the ratio of the *total light* in the rings, and not the ratio of *apparent brightness,* which has been stated erroneously by other writers on this subject.

The ideal diffraction pattern would be one which consisted only of a small bright central disc—no rings. In actual practice the diffraction pattern will have rings. Now if the diffraction pattern must have rings, it would work best if the light of the rings were spread out uniformly around the central disc (all rings of the same brightness). The reason for this is that the eye is particularly sensitive to *steep* contrast gradients (abrupt changes in surface brightness) even though the ratio of the surface brightness of the two adjacent areas may be very nearly unity. With a diffraction pattern of this energy distribution, abrupt but small changes in brightness of the object would still be represented faithfully in the image by fairly abrupt changes in surface brightness, but of a somewhat lower magnitude.

In actual practice, the first ring is *much* brighter and contains more light than any of the others. This is very unfortunate because the light of this ring falls in just that part of the image where it will be most effective in reducing the contrast gradient. This means that as far as the telescope's ability to show detail of small brightness difference on planetary surfaces is concerned, the ratio of the total light in the central disc of the diffraction pattern to the ratio of the total light in the first bright ring is the most important.

With a clear circular aperture, this ratio turns out to be 11.6. With a central obstruction of one-quarter of the diameter of the aperture (typical reflector design) this ratio is only 4.6. This is a change of 2.8 to 1. If we compare the light in the central disc to the total light in all the rings, the ratio goes from 5.16 for a clear aperture to 2.65 for the obstructed aperture. This is a change of 1.95 to 1.

The center of the light path is the worst place possible to have an obstruction. An obstructive *ring* having a mean diameter (half the sum of its O.D. and I.D.) of 0.47 times the diameter of the aperture neither increases nor decreases the light in the first bright ring, but it increases the light in most of the other rings at the expense of the light in the central disc. When the diameter of the obscuring ring is

increased to about 0.7 the diameter of the aperture, it decreases the light in the first ring by a maximum amount and increases the light in the other rings by a greater amount. Finally, an obstruction added at the outer edge of the aperture decreases the light in the central disc and in each bright ring by the same fraction.

As a check on calculations such as these, Horace E. Dall of England set up and performed a series of tests in the laboratory in which central obstructions of various diameters were introduced into the light-path of a small telescope, and its ability to show detail of fairly high contrast was evaluated. He found that with central obstructions as small as 1/5 the diameter of the aperture, the loss in performance could be detected. These experiments check the theoretical calculations fairly well, but it is felt that if he had used a target of very low contrast, he might have been able to detect the loss in performance down to even smaller central obstructions.

It should be pointed out that both the theoretical calculations and the laboratory experiments referred to above were carried out under ideal conditions—everything in the optical system was practically perfect. In actual practice this is seldom the case. Even if the telescope is practically perfect (which it seldom is), the seeing is usually far from perfect. What then? Recent experiments in which central obstructions of various different sizes were placed in front of a 4-inch and a 6-inch refractor, and these telescopes were used on astronomical objects on nights of average seeing, have indicated that under average conditions the loss in performance chargeable to a central obstruction may be considerably greater than predicted by theory for ideal conditions.

Another very good reason for the amateur's trying to eliminate the central obstruction of the typical reflector (if at all possible), is that amateur telescopes frequently turn out to be "just a little sour". Although this "sourness" may be due to a combination of several, or all, of the first five defects mentioned above, a detailed analysis of the optical errors in the system will usually show the "sourness" to be confined largely to the outer part of the light path. By stopping down the aperture of such a telescope only a relatively small amount, most of those parts of the wave-front (of the light traversing the system) which are subject to serious aberrations, will be eliminated. If the telescope is unobstructed, this procedure will usually turn it into a really fine instrument (optically). But if it has a central obstruction, this same procedure will make that obstruction relatively larger and, although the loss in performance from the other aberrations may be reduced very greatly, the loss from the central obstruction will be increased. The net result will seldom amount to very much.

The moral to all this is: the center of the light path is the heart of your telescope. Don't cut it out!

No single one of these six defects of the reflector is really very bad (if any one of them were really bad, it would have been proven so long ago), but taken altogether, they do add up to definitely inferior performance. At one time or another each one of these has had the finger of suspicion pointed at it, but up to now nobody seems to have been able actually to pin anything on any single one of them. If a telescope had only one of these things wrong with it, it would be rather conspicuous, but with five other things, plus seeing, wrong with it, it is very difficult to prove any of these charges.

Some telescope owners have tried placing an off-axis diaphragm stop in front of their Newtonian reflectors. In most cases they have been amazed and perplexed at the improvement in performance (for the aperture used) that they have obtained with this device. The reason for this very great improvement in performance is that the device completely eliminates loss No. 6 and reduces very greatly losses Nos. 1, 2 and 4. The fact that it has gained this reputation is good evidence that taken together, losses 1, 2 and 4 do account for a significant loss in performance for the average reflector.

Possible Ways of Eliminating or Reducing the Loss in Performance from the Central Obstruction.

If the optical performance of the reflecting telescope is to be raised to that of a theoretically perfect instrument, something must be done about the central obstruction of the common types of reflector. The central obstruction must either be eliminated entirely or at least reduced very considerably in size. One possible design change which will permit a very significant reduction in the size of the diagonal of the conventional Newtonian reflector is to move the diagonal out to near the focal plane of the primary mirror. Since the individual cones of rays will be quite small here, the diagonal need only be as large as the desired field of view in the focal plane. If the telescope is equipped with a good finder and is intended primarily for planetary observation, its diagonal can be quite small.

Since each cone of rays will be diverging after being reflected by the diagonal of this design, the cones of rays must be intercepted by a positive element (a convex lens or a concave mirror) located at the side of the telescope tube in order to bring the rays back together again to form an image which can be viewed with an eyepiece. Horace Dall has reported using a high-quality lens-type erecting system for this purpose with very satisfactory results. The Johnsonian reflector, invented by Lyle T. Johnson, uses a concave mirror which has an ellipsoidal figure to intercept and re-focus the rays at the side of the main tube of the telescope. It may be considered to be a folded Gregorian reflector with the field being located at the focal plane of the primary.

If the effective focal length of the system is made fairly large (and this can be done quite easily in both of these designs), the loss in performance from eyepiece aberrations will be reduced very greatly. Neither of these designs, however, will tend to reduce the loss in performance from the other four defects listed above for reflectors. Satisfactory collimation will be a particularly difficult problem in both of these designs.

When we look into the possibilities of eliminating the central obstruction altogether, we find several very promising leads. The first of these is the Herschelian telescope—the original unobstructed reflector. This might be described as an off-axis section of the Newtonian reflector. Following this idea, we might lay out designs which would, in effect, be off-axis sections of the Cassegrainian and Gregorian reflectors. Since all of these optical systems employ one or more aspherical surface curves, we might classify these designs under the general heading of "off-axis sections of axially symmetrical systems which employ aspherical surface curves".

Another very promising unobstructed telescope is the Wright off-axis Maksutov. This is an off-axis section of an axially symmetrical system which employs only spherical surface curves. Other designs along this line are possible. These designs have a distinct advantage over those of the first classification because an off-axis section of a spherical surface curve is still a perfect sphere. We might, therefore, classify these under a separate heading "all-spherical off-axis designs".

Finally, we have a whole new group of designs which are based on the principle that in a multiple-mirror system in which more than one mirror is tilted through an angle of appreciable size, it may be possible to adjust the various angles of tilt and the relative orientation of the various tilt lines so that one or more of the tilt-induced aberrations of one mirror are completely cancelled out by the corresponding aberrations of one or more of the other mirrors. Although some of these designs employ only spherical surface curves, the method of their design is quite different from that of the "all-spherical off-axis designs". Furthermore, they have no axis parallel to the line of sight and about which all the surfaces of the system are surfaces of revolution. It seems logical, therefore, to give them a separate classification: "unobstructed tilted-mirror systems".

Off-Axis Sections of Axially Symmetrical Systems Which Employ Aspherical Surface Curves.

All the optical systems of this group have much in common; they all look good on paper and probably can be made to perform quite well provided that you can make the off-axis aspherical mirrors. Only the Herschelian will be discussed in detail here but most of that which is said about it will apply to the other systems as well.

In the Herschelian, the field of best definition lies in a plane which is nearly perpendicular to the line joining the focal point and the center of the face of the off-axis mirror. This means that the eyepiece should be pointed right at the mirror (not down the optical axis of the system). With moderately high f/ratios (f/10 and higher), the aberrations for those parts of the image which lie some distance from the center of the field of view are not at all serious. This is in contradiction to what some authorities have stated, but their calculations were based on the assumption that the eyepiece would be pointed straight down the optical axis.

The most obvious way to make the off-axis aspherical Herschelian mirror is to start with a spherical mirror of the desired focal length and gradually work it into the correct shape by local polishing with a small sub-diameter tool. This can be done, but it is difficult, requires a good null-test method (the autocollimation method which uses an optical flat the diameter of the mirror), and you may end up with a blotchy surface. Although this may be done by a *real expert*, it is no job for a novice.

A second possible method of making the Herschelian mirror is by thermal warping. Andre Couder of France has reported making a large paraboloid by heating the back of the mirror electrically (just a little and in just the right places) during the polishing operations and polishing with a full-diameter lap to produce an accurately spherical surface curve. After the mirror was polished out, the heat was turned off and the mirror changed its shape from a sphere to a paraboloid (to within the desired tolerance). Perhaps this method (thermal warping during polishing operations) could be developed to the point where it would produce a satisfactory off-axis section of a paraboloid.

A third possible method of producing the Herschelian mirror is by controlling the warpage, or distortion from grinding stresses. When glass is ground in the usual manner, rather deep cracks (which are usually invisible to the unaided eye) are left on the surface of the glass, and these cracks have tiny slivers of glass driven into them by the abrasive. This puts the whole surface of the glass under compression. The coarser the abrasive, the larger are the slivers, and the greater is the compressive stress.

Experiments wherein a mirror had originally been polished spherical, later had its back ground with various sizes of abrasive in concentric zones (coarsest in the center and graded off to finest at the outer edge), have demonstrated that a certain amount of parabolization can be produced in this way. Perhaps this method could be developed to the point where it could produce a satisfactory off-axis section of a paraboloid; or it might be employed to effect a final correction in a mirror that had been figured only approximately correctly by another method.

A fourth possible method of producing a mirror for the Herschelian reflector is by warpage, or distortion of the mirror by means of a mechanical pressure applied by a warping harness. Preliminary calculations and experiments have shown that by applying bonding and warping forces to a mirror which has been ground and polished with an axially symmetrical surface curve, it can represent a reasonably good (within acceptable optical tolerances) approximation to an off-axis section of a paraboloid. To assist in getting the correct curve, the mirror should be ground wedge-shaped before its front surface is polished. A thickness ratio of about 2 should be good, with the thickest part of the mirror nearest the optical axis.

The warping harness will have pressure pads which press at various points distributed over the back of the mirror and clips which reach around and pull back against the face of the mirror around the edge. In order to be at all practical, the warping harness must be designed so that the pressure at all those points can be applied simultaneously and in the correct amounts by tightening a single screw. Fortunately, this can be accomplished quite easily by a rather simple system of levers which connects pairs of pressure pads or clips and which in turn are connected by other levers. The whole problem in this method is to determine just how much pressure should be applied where.

At the present time it is difficult to predict with any certainty which of these various methods will turn out to be the most practical. It may even turn out that the difficulties encountered with each of them will prove to be greater than the telescope is worth. However, the Herschelian reflector is basically such a simple instrument and it offers the prospect of such good optical performance that it would seem that a determined effort should be made to explore these possible methods of making the mirror in greater detail.

In conclusion it should be pointed out that at best these methods offer only a means for the elimination of the central obstruction. They do not help appreciably with the other five defects of the reflector. If really top performance is to be obtained with telescopes of this classification, a lot of work will have to be done on the other problems as well.

All-Spherical Off-Axis Designs

One way to make an off-axis optical system and yet not to have to figure an off-axis section of an aspherical curve (a paraboloid, ellipsoid, hyperboloid or Schmidt correcting plate) is to go to an optical system which employs only spherical surface curves. The reason for this is that an off-axis section of a sphere is still a sphere.

If we were to make a survey of published reflector optical systems for the purpose of finding those which employ only spherical surface curves and which

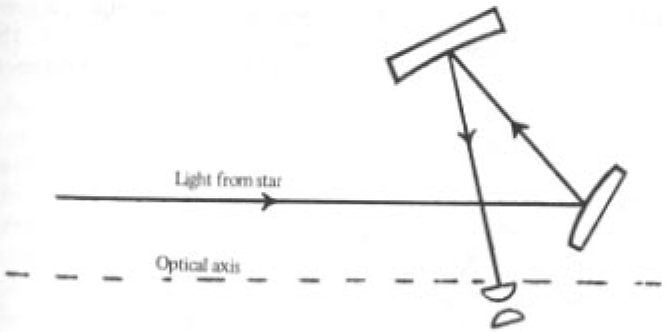
might lend themselves to off-axis telescope designs, we would find the following:

1. Maksutov reflector.
2. Modified Maksutov reflector (employs a concave spherical mirror and a Maksutov-type correcting plate located in the cone of rays not far from the focal point).
3. The Questar system.

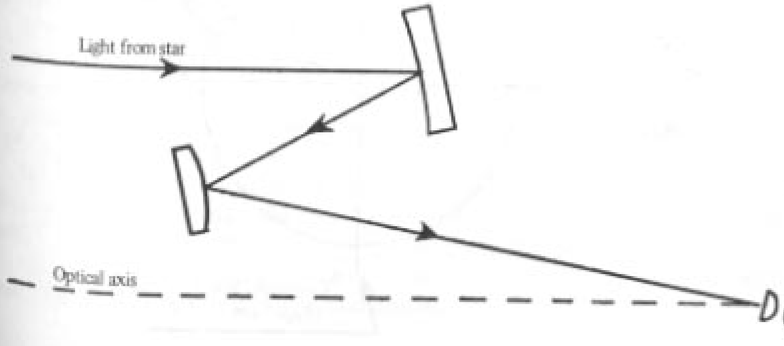
An example of the off-axis Maksutov system is the Wright off-axis Maksutov reflector (see *A.T.M. III*, pp. 574-580). An example of the Modified Maksutov design is J. S. Hindle's design (see *Sky & Telescope*, Feb. 1953, pp. 107-108, and *Scientific American*, Feb. 1954, pp. 102-106). I have not heard of an off-axis reflector which employs the system of the Questar reflector but know of no reason why it should not work well.

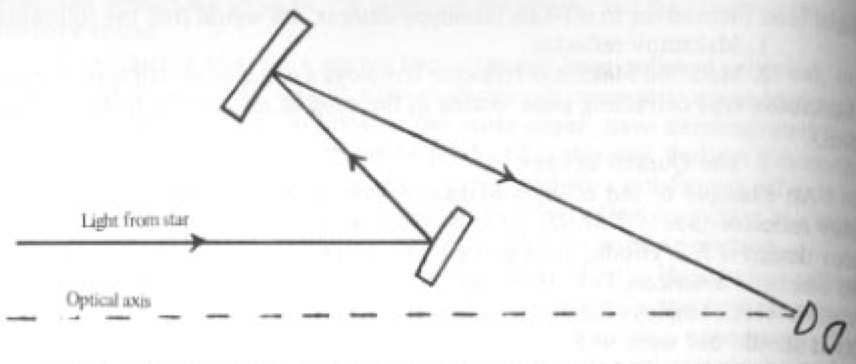
Although it should be quite possible to make all three of these systems work quite well, each contains a lens, or correcting plate, which will turn out to be rather difficult to produce within the desired accuracy (the correcting plate of the off-axis Questar design will be *very* difficult to produce within the desired accuracy). Also, the collimation of these systems to within reasonably close tolerances will prove to be very difficult.

When we look for off-axis designs which employ only spherical mirrors in their objective systems, we find three theoretically possible designs which employ only two mirrors. The first might be described as an off-axis all spherical Cassegrainian. It looks something like the following:



The second and third look like this:





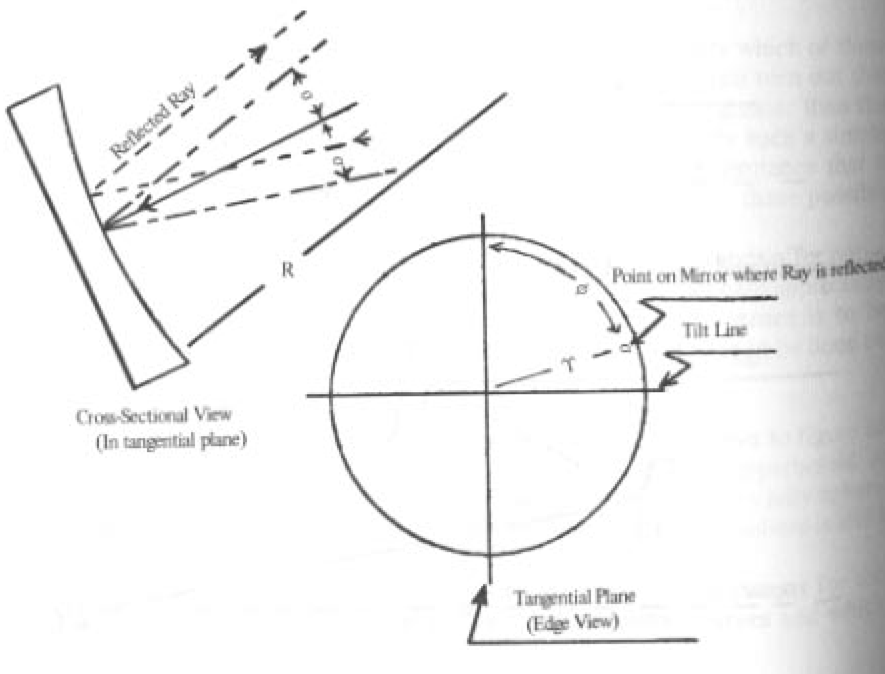
None of these designs appear to be at all competitive with some of the most promising of the other unobstructed reflector designs.

When we look into the possibility of using three spherical mirrors, we find that there may be six or eight theoretically possible designs. One or more of these may turn out to be somewhat competitive with some of the more promising designs of other types. Although none of them appear to hold really exciting prospects, it is felt that they should be investigated more completely in order to make sure that something really useful is not being overlooked.

Unobstructed Tilted-Mirror Systems

The design of optical systems covered by this classification is based on the following general principles:

1. When a mirror or lens in an otherwise perfect system is tilted, a wave-front error, or aberration, is introduced into each ray traversing the system. The magnitude of this error, in terms of path length, may be expressed as follows:



The Geometry of a Tilted Mirror

Wave-front aberration (general expression):

$$W = C_1 \sigma \frac{r^3}{R^2} \cos\phi + C_2\sigma^2 \frac{r^2}{R} \cos 2\phi + C_3\sigma^3 \frac{r^3}{R^2} \cos 3\phi$$

where the Cs are constants which depend on the amount of divergence or convergence of the cones of rays.

2. Because of the cyclic nature of the individual terms (proportional to $\cos\phi$, $\cos 2\phi$, etc.), it is possible by tilting n elements (mirrors or lenses) in a system (each one tilted through the correct angle and oriented in the correct direction), to make n-1 (or possibly more) of the terms cancel out completely.

3. By applying a properly designed warping harness to one or more of the mirrors of the system, acceptable control or cancellation of one or more of the terms not eliminated by the combination of optical elements can be effected.

4. In order that the sum of all the residual uncompensated terms in the system shall not exceed acceptable optical tolerances, the length of the system must be made no less than some definite value (which will be a function of the diameter and the design of the system).

Actually, the complete expression for the wave-front aberration contains many more terms. The three terms given above are merely the first and largest of an infinite series. The first order term given is the first of a series of "first order coma" terms. (The other terms in this series are much smaller and are not included here). The second term is the "first order astigmatism." The third is the principal "second order coma." In most systems that will be designed by these methods, only the first two terms will be larger than acceptable optical tolerances and will need to be controlled or eliminated. They will be roughly of the same size. The third term will be in the order of 1/100th as large. Succeeding terms will be even smaller.

When we look into the problem of designing a warping harness which will be capable of deforming a mirror in such a way as to cancel out one or more of the terms in the aberration equation, we find the coma term to be very difficult to handle. At best, a warping harness for the control of coma will be a rather complicated device and very probably it will introduce other aberration terms, or residual errors, of appreciable size. In other words, we will not be able to compensate a very large amount of coma with a warping harness without getting in return unacceptably large residual errors. For a telescope of 6 to 8 inches in aperture and moderately long focal length, however, we may be able to build a warping harness which will be reasonably simple in design and yet not introduce an unacceptably large amount of residual error.

The design of a warping harness for the control or elimination of astigmatism, on the other hand, turns out to be a relatively simple matter. A rather large amount of astigmatism can be eliminated from the system by such a warping harness, and without introducing an unacceptably large amount of residual error. This has already been proved by very sensitive tests in the laboratory.

When we look for proven or proposed designs which might be placed in this classification, we find only the sun telescope and the neo-brachyte. I suspect the reason no other designs have been proposed up to this time is that these two have been designed largely by a process of trial and error, or at least without a knowledge of *all* the principles stated above.

To start out with the simplest designs (on paper) first—there appear to be only two possible one-mirror designs. They are the harness-warped Herschelian and the sun telescopes. Since there is only one mirror in each of these systems (the diagonal in the Herschelian and the flats in the coelostat of the sun telescope can't introduce any tilt aberrations [in theory], and therefore don't count), either both the coma and astigmatism must be eliminated with a warping harness or the system must be designed to make the sum of these two terms no greater than acceptable tolerances.

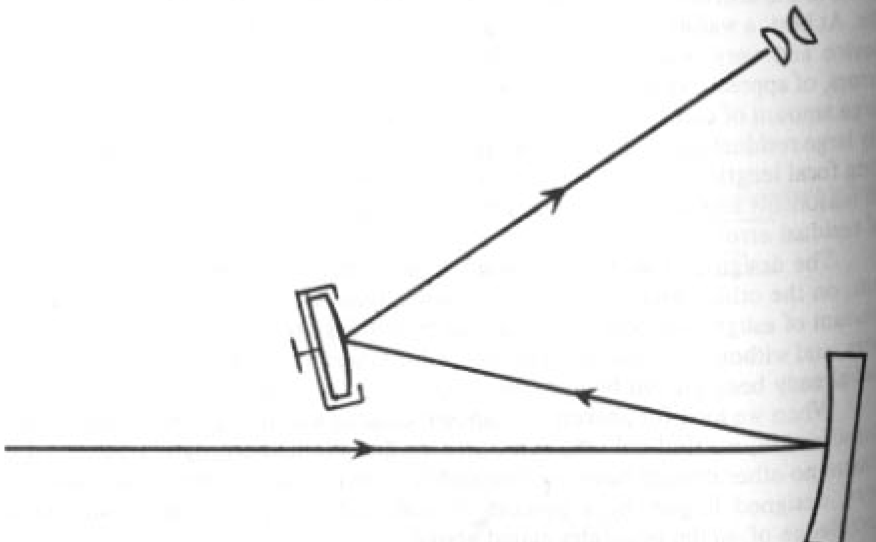
The harness-warped Herschelian will employ a warping harness on the one mirror in the system and it must be designed to eliminate both coma and astigmatism. It will probably be a rather complicated device. As has been explained previously, its use will probably be limited to rather small apertures and moderately long focal lengths.

Since the sun telescope does not employ a warping harness, no compensation for the coma and astigmatism resulting from the tilt of the objective mirror can be effected. Satisfactory design of this type of instrument is based on making its focal length sufficiently large and the angle of tilt correspondingly small. Thus, although no provision is made to compensate the tilt aberrations, they can be kept within acceptable optical tolerances.

Two-Mirror Systems

Since, with two mirrors in the system, only one tilt aberration term (in general) can be made to cancel out through adjustment of the tilt of the mirrors, a warping harness will be employed in most of the designs. Since the design of a warping harness for the elimination of astigmatism is much simpler than one for coma, these systems will, in general, be designed to have the coma eliminated by the proper adjustment of the tilt angles of the two mirrors, and the astigmatism eliminated by a warping harness.

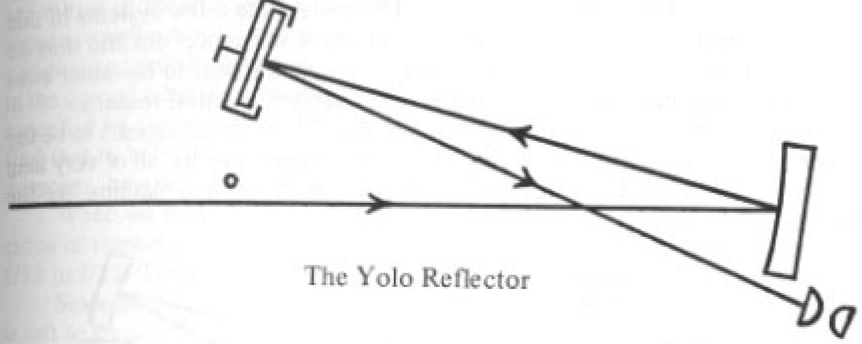
The neo-brachyte, or neo-bra, (see *The Strolling Astronomer*, Dec. 1952) looks something like the following:



The Neo-Brachyte Reflector

It has a concave primary mirror and a convex secondary with a warping harness on the secondary. At first glance, it might be mistaken for an off-axis Cassegrainian; but it is not, because it has no axis and its design is based on the elimination of first order coma by the proper adjustment of the tilt angles of the two mirrors. The warping harness is designed to eliminate the not first order astigmatism of the system.

When we look into the possibility of designing other optical systems along these lines, we find three more possible combinations (using only two mirrors and a warping harness for the astigmatism), only one of which appears to be practical. The (Yolo) reflector, which is a totally new design, is illustrated below.



The Yolo Reflector

It has a concave primary and a concave secondary with a warping harness on the secondary. Its design is based on the elimination of first order coma by the proper adjustment of the angles of tilt of the two mirrors and the elimination of the total first-order astigmatism with the warping harness. The construction of a 9″, f/16 model of this design has proved to work excellently.

In the course of designing these systems, it was noted that when one mirror is concave and the other convex and the angles of tilt are adjusted to make the coma terms cancel out, the astigmatism terms for the two mirrors are of opposite sign and tend to cancel each other. This suggested that by a suitable choice of focal lengths, it might be possible to design a two-mirror system by these methods in which both the coma and astigmatism would cancel out. When this was done, the systems turned out to be identical to the two-mirror, all-spherical off-axis systems described previously, and which had already been found to be rather impractical. (For a Yolo reflector design, see Chap. 10.)

Three-Mirror Systems

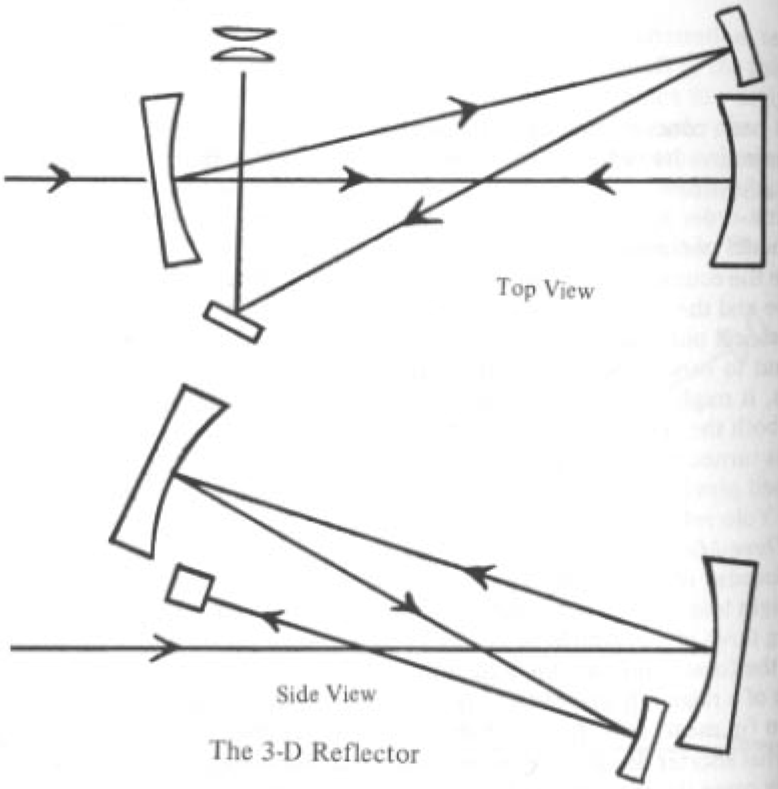
Because of the possibility of cumulative figuring errors, collimation problems, light loss from so many reflections, etc., some question as to the advisability of using three mirrors might be raised. The addition of a third mirror to the system brings the focal point back up to the forward part of the telescope, thus permitting the use of a relatively low and steady mounting and a more comfortable observing position (in most cases) for the observer. The use of three mirrors makes possible somewhat shorter designs and the elimination of the warping harness. It is felt that in many cases the advantages of the use of the third mirror will outweigh its disadvantages.

There appear to be a very large number of possible three-mirror designs.

They may be divided into two groups: those in which the centers of curvature and the centers of the faces of all three mirrors lie in a single plane which contains the line of sight, and those in which the three mirrors and their individual optical axes are skewed with respect to each other and the line of sight. Systems of both groups may contain concave mirrors only, both concave and convex mirrors, or even mirrors and lenses.

Optical systems of the first group have a common tangential plane for all three elements, and all tilt angles are perpendicular to this plane. In most of these designs the tilt angles of the three elements will be adjusted to make the coma terms cancel out and the astigmatism will be taken care of by a warping harness on one of the mirrors (usually the smallest one in the system). The design of most of these systems is rather a simple operation. There are quite a few systems in this group in which both the coma and astigmatism terms will cancel out and thus do not require a warping harness. Most of these, however, appear to be rather awkward-looking and may not be very attractive for various practical reasons.

Of all the three-element skewed systems, the 3-D reflector appears to be the most promising (see Chap. 10). It contains three concave mirrors, all of very long radius of curvature, and requires no warping harness. It looks something like the following:



The 3-D Reflector

It appears that the skewed systems can be designed shorter (more compact) and can be carried up to larger apertures (30 to 40 inches) than either the Yolo or any of the single-plane systems without having their residual tilt-aberration terms exceed reasonable optical tolerances.

When we consider the tilted-mirror systems from the standpoint of avoiding some of the other defects of the reflecting telescope, we find them very promising indeed. Both the Yolo and the 3-D employ only concave mirrors and although theoretically the surface curves should be paraboloids and hyperboloids, they are of such very long radius of curvature that they will be very close to spherical. This means that very little, if any, parabolization will have to be done on any of the mirrors and the test of these mirrors will be very nearly null and thus very sensitive. Thus these designs should be able to avoid defect No. 1.

When we look into the problem of mirror sag, we find that since the secondary mirror in these designs is not much smaller than the primary, we can, by the simple expedient of thinning down the secondary mirror blank a little before fine grinding and polishing and by orienting the three mounting points for each mirror in the correct relative positions, arrange to have the sag error of the primary largely cancelled by the sag of the secondary and ternary mirrors (in the 3-D). Thus we find that in both the Yolo and the 3-D designs defect No. 3 can, for all practical purposes, be eliminated quite easily.

When we look into the question of eyepiece losses, we find the overall focal ratios of these systems (for fairly compact designs) to be in the range from about f/12 to f/15. Thus eyepiece errors should be practically non-existent.

Since all these systems are unobstructed, only defect No. 5 (thermal effects) is left to be dealt with.

In conclusion it can be stated that a number of small but significant defects have been found in the optical system of the reflecting telescope. These can easily account for the reflector's reputation of being not quite so good as the refractor for planetary observation. A number of new and interesting designs of reflectors based on new principles have been proposed. These offer the prospect of providing reflecting telescopes with optical performance equal to that of the best refractors, and putting the reflector on an equal footing with the refractor for planetary observation.

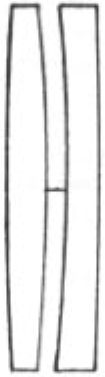
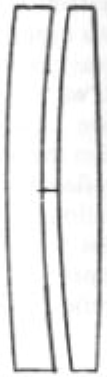
LENS DESIGN
by R. A. Buchroeder

If for no other reason but that it is the most commonly used form of lens, the air-spaced doublet deserves attention. Despite its simplicity, there are certain misunderstandings about it. For example, in D. H. Jacob's *Fundamentals of Optical Engineering* (McGraw-Hill, 1943, p. 189), we find the incorrect claim that if spherical aberration is corrected at two wavelengths, then coma must be uncorrected. It is, in fact, possible to eliminate coma while simultaneously eliminating spherochromatism, as a simple computer study will show.

In the archives of history, we find certain novel doublets that seem to have been forgotten. For example, Herschel designed a doublet that was corrected for spherical aberration at two distinct conjugate pairs. There is also reported to be a doublet that could be turned either way and still be corrected. Of more practical value, doublets that could cover two separate spectral regions with excellent correction in both have been designed with one element reversed and re-spaced. It is somewhat amusing that none of these "novelties" are susceptible to automatic design with our modern lens-design programs. There is still much to be learned by studying the behavior of the air-spaced doublet, and it is the purpose of this preliminary report to show some of the things that can be accomplished.

Most modern doublets are designed with two common glasses: borosilicate crown BK-7 and flint F4 (or F2 in Europe). For our study, the glass choice is not critical. However, in applied design, lower cost elements can be more economically fabricated with glasses that give equi-convex or flat surfaces. Optically, there is little distinction among the preferred glasses. We will be concerned with only two basic forms: the Fraunhofer and the Steinheil, and all shall be corrected for coma unless otherwise specified.

The Fraunhofer and Steinheil Designs.

(left)
Fig. 1 Simple
Visual f/15
Baker type

(right)
Fig. 2 Steinheil
Visual f/15
Simple Aplanat

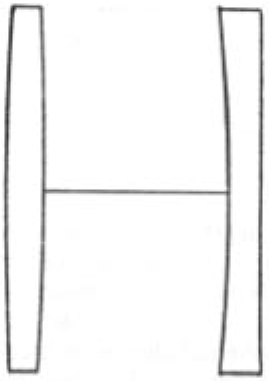


Fig. 3 Visual f/15
Zero Spherochromatism

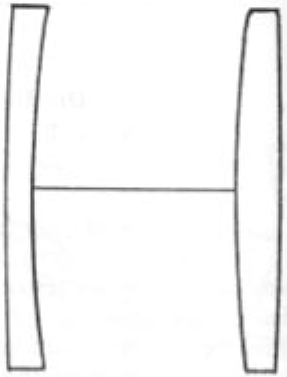


Fig. 4 Steinheil
Visual f/15

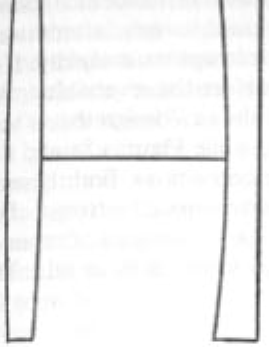


Fig. 5 Good
Visual f/15
Flat flint

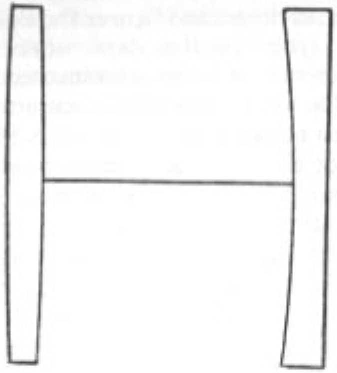


Fig. 6 Simplest
f/15 visual
equiconvex flat

Figure 1 shows a conventional air-spaced doublet disclosed by J. G. Baker, *Telescopes and Accessories,* the Blakiston Company, Philadelphia, (1945). The inner radii have the same value, and the lens is coma free. Figure 2 shows the Steinheil counterpart of the Fraunhofer lens. Both have residual spherochromatism that cannot be corrected simultaneously with coma as long as the air gap or glass types are kept fixed.

Figures 3 and 4 show the same lenses now corrected for spherochromatism as well as coma. Note the increased gap. The spherochromatic correction was obtained through the influence of high-order spherical aberration, and the balance is sensibly perfect. The secondary spectrum of these widely spaced lenses is greater than in the close doublets; however, the spherochromatism degrades the lenses of Figures 1 and 2 to the point where their color blur is about the same as that of the lenses in Figures 3 and 4. The only drawback of the wide doublets is that they introduce lateral color, but for visual use the amount is insignificant.

Figure 5 shows a design in which the goal was to simplify fabrication by putting a flat surface on the flint. The crown assumed the form it wished, and while spherochromatism was not eliminated, the design was superior to that of the lenses in Figures 1 and 2. Coma is negligible but not fully corrected.

Figure 6 shows the greatest simplification possible: the crown is equiconvex and the flint is flat. This design has some coma that is no longer insignificant and is not recommended except for apertures smaller than perhaps 6 inch.

For lab. specialty work, it is not uncommon for the optician to take a lens with an equiconvex crown and flat flint and aspherize the back surface to eliminate spherical aberration. This lens will show coma unless it is very slow, but the optician will have a satisfactory lens without having to go to a designer. At the turn of the century and well into the present, the old craftsmen undoubtedly made their instruments this way, which probably accounts for the residual (and, to a professional, inexcusable) coma noted in some of their work.

Figures 7a and 7b are actually the same lens, but with the crown reversed and re-spaced in the second figure. The Boyden 13-inch refractor at Harvard has a lens of this type. In the days when photographic emulsions were strictly orthochromatic, a violet achromat recorded an image most rapidly. However, the visual observer prefers a green achromat. Therefore the reversible crown lets both have their choice at the lowest price. Figure 7 shows a design that is very well corrected for both spherochromatism and coma, while Figures 8a and 8b show one that is more compact at the expense of these corrections. Both types would give satisfactory performance in general use. The widely spaced settings, of course, give some lateral color. The implication in this type of design is that one can often squeeze more usefulness out of his optics by such tricks as this. The problem somewhat resembles that of zoom design.

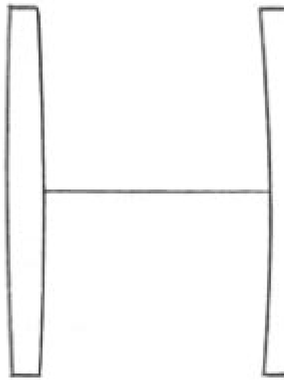


Fig. 7a Long reversible
f/14.7 Photographic mode

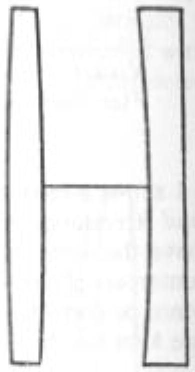


Fig. 7b Long reversible
f/16 visual mode

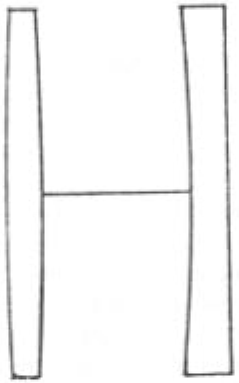


Fig. 8a Short reversible
f/14.05 photographic mode

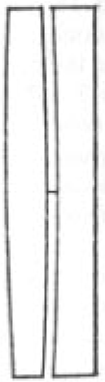


Fig. 8b Short reversible
f/16.03 visual mode

Apochromatic Designs

Secondary spectrum has always been the main problem with refractive optics. Eighty years ago, when the glassmakers were first producing unusual glass types,

designers were optimistic that new glass could be developed that would allow apochromatism to become general. This dream has not been realized despite the enormous number of glasses now available. It would seem that all glass is similar, for despite the modern achievements with phosphate crown and borate flint, the optical quality of today's designs is not greatly superior to those of Dennis Taylor's at the turn of the century. The latest attempts in the glassmaking art are directed at producing a glass with the properties of crystalline fluorite. If this could be achieved, apochromatism could indeed be applied to almost any situation. Unfortunately, efforts to date have produced only the FK-20 and FK-51 glasses, both of which are exceedingly expensive and subject to fine parallel striation that disqualifies them from a number of important situations. It is doubtful that suitable glasses will soon be developed, but hopefully efforts will be unceasing.

To show what can be done with a doublet, we have designed both a semi-apochromatic lens (Figs. 9 and 10) with SSK4 and KzFSN4 and a full apochromat (Figs. 11 and 12) with SSK3 and KzFSN4.

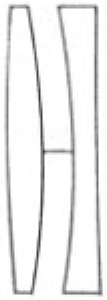


Fig. 9 Crown front
f/20 semi-apochromat

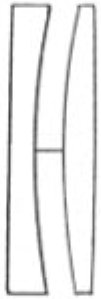


Fig. 10 Fint front
f/20 semi-apochromat

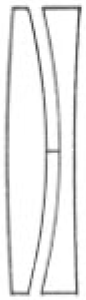


Fig. 11 Crown front
f/20 full apochromat

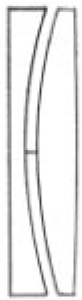


Fig. 12 Flint front
f/20 full apochromat

Actually, the semi-apochromat is a full apochromat in the red; the advantage is that its elements are weaker and therefore its corrections are superior to those of the full apochromat in the visual. The borate flint used is optically inferior to its predecessor, KzFS1, which has been avaliable for at least thirty years. However, the KzFSN4 has largely superseded the theoretically superior glass because it is far more durable. The SSK glasses are preferred by virtue of their high index of refraction, which minimizes the monochromatic defects of the doublet. Both the full and semiapochromatic lenses here are corrected for coma and spherochromatism; the full apochromat would benefit by aspherization on its rear surface in sizes larger than 4 inch. Figure 13 shows a normal achromat of the same speed for comparison of shape.

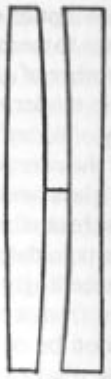


Fig. 13 Common visual f/20 doublet

Note by Ed. The above paper was included in the Applied Optics Research Report of the Optical Sciences Center of the University of Arizona for October 1971. It is reproduced here by kind permission of Dr. A. B. Meinel, Director of the Center, and Dr. Buchroeder.

CLOSED FORM THIRD ORDER ABERRATION EQUATIONS FOR DESIGNING MAKSUTOV AND TWO-LENS CATADIOPTRIC TELESCOPES

by Robert D. Sigler

Introduction

Third order aberration equations are an effective design and evaluation tool for Schmidt and conic mirror telescopes (Cassegrains, Newtonians, etc.). For these designs, the aberrations are well approximated by third order terms such as the Seidel coefficients. This is still true when the paraxial power and thickness of the Schmidt plate is ignored.

When the relatively thick correcting element of the Maksutov has been split into two relatively thin correcting lenses such as in the case of two-lens designs, third order theory using the thin lens approximation is sufficiently accurate to provide a useful design tool. However, when similar thin-lens equations are applied to Maksutov systems, the results depart significantly from the true third order aberrations as given by the summation of the contributions at each surface or by ray tracing. This is due to the thickness and large angles of incidence at the corrector.

In this article, relatively simple thin lens equations of a normalized or non-dimensional character will be developed which allow the capabilities of two-lens designs to be readily explored. A similar, thick lens equation will also be developed to explore the Maksutov systems.

First Order Properties

The following equations describe the first order characteristics (radii, spacings, etc.) of the mirrors of conic or catadioptric telescope systems. The definitions of all symbols used are given in the Appendix.

$$R = \frac{M - E}{M + 1} \quad (1) \qquad E = M - (M + 1) R \quad (3)$$

$$T = \frac{1 + E}{M + 1} \quad (2) \qquad S = \frac{M(1 - R)}{1 - M} \quad (4)$$

The Seidel Aberration Coefficients

The Seidel aberration coefficients B, F and C can be used to represent the third order monochromatic aberrations of any system. Distortion will be ignored as it is usually small and not considered a serious error in most photo-visual systems. The relative Petzval curvature will be given by J. From these coefficients, we can find the monochromatic characteristics of the image.

Angular diameter of the spherical aberration blur circle $= \frac{\Sigma B y_1^3}{2}$ (5)
Angular length of the tangential coma patch $= \Sigma 3 F y_1^2 \phi$ (6)
Angular diameter of the astigmatic blur circle $= \Sigma C y_1 \phi^2$ (7)
Radius of Petzval image surface $= fp/\Sigma J$ (8)
Radius of best image surface $= fp/(4fp\Sigma C + \Sigma J)$ (9)

Our goal will be to find the Seidel coefficients for the complete telescope and, fortunately, the contribution to the coefficients from each element can simply be added together, provided that the contribution of the aperture stop is kept track of. The aperture stop is assumed to be at the primary mirror. The coefficients of the total system are:

$$\Sigma B = \Sigma B_{lens} + \Sigma B_{mirrors} \quad (10)$$
$$\Sigma F = \Sigma F_{lens} + \Sigma F_{mirrors} \quad (11)$$
$$\Sigma C = \Sigma C_{lens} + \Sigma C_{mirrors} \quad (12)$$
$$\Sigma J = \Sigma J_{lens} + \Sigma J_{mirrors} \quad (13)$$

Since the two-lens designs are the easier to evaluate, let us turn to them first.

The Two-Lens Telescope System

First, considering the contributions of the mirrors of any compound, two-mirror telescope, the following equations can be derived from K. Schwarzchild's work (*Astron. Mitt. Koig. Sternwarte,* Gottingen, 10, 1905), but using considerably different notation:

$$\Sigma B_{mirrors} = \frac{1}{8fp^3}\left\{1 + bp - \left[b_s + \left(\frac{M+1}{M-1}\right)^2\right]\frac{(M-1)^3(1-R)}{M^3}\right\} \quad (14)$$

$$\Sigma F_{mirrors} = \frac{1}{8fp^2}\left\{\frac{2}{M^2} + \left[b_s + \left(\frac{M+1}{M-1}\right)^2\right]\frac{(M-1)^3 R}{M^3}\right\} \quad (15)$$

$$\Sigma C_{mirrors} = \frac{1}{8fp}\left\{\frac{4(m-R)}{M^2(1-R)} - \left[b_s + \left(\frac{M+1}{M-1}\right)^2\right]\frac{(M-1)^3}{M^3(1-R)}\right\} \quad (16)$$

$$\Sigma J_{mirrors} = 1 + \frac{1}{s} \quad (17)$$

Usually, in Maksutov and two-lens designs, the goal will be to find designs with all spherical surfaces, so the above equations can be simplified by setting $b_p = b_s = 0$.

$$8fp^3\Sigma B_{mirrors} = 1 - \frac{(M+1)^2(M-1)(1-R)}{M^3} \quad (18)$$

$$8fp^2\Sigma F_{mirrors} = \frac{2}{M^2} + \frac{(M+1)^2(M-1)R}{M^3} \quad (19)$$

$$8fp\Sigma C_{mirrors} = \frac{4(M-R)}{M^2(1-R)} - \frac{(M+1)^2(M-1)R^2}{M^3(1-R)} \quad (20)$$

In all cases, we will naturally want to set the spherical aberration sum to zero, and if we can also get the coma sum to zero we will have an aplanat. If we can make the sum of B, F and C zero, the result will be an anastigmat. The contribution of the corrector(s) to the Petzval sum has been ignored because the conditions for chromatic correction imply that the total corrector be afocal or have a very long focal length.

For two-lens designs, the following chromatic corrections can be made:

(1) For zero longitudinal color errors, the lens pair should have no net power and should have the same relative dispersion ($K_1 = -K_2$ and $L_1 = -L_2$).

(2) For zero lateral color, the lenses should be the same distance from the aperture stop (implies the lenses are in contact).

(3) For zero secondary color, the lenses should have the same partial dispersion.

These three conditions imply an afocal lens pair in contact and of the same glass type, usually a light crown like BK-7.

Starting from Conrady's thin lens or G-sum equations (*Applied Optics and Optical Design*, Dover, 1957), the following can be derived:

$$\Sigma B_{lens} = \frac{K_1^3}{4(N-1)^2}\left\{\frac{N+2}{2N}\left[(Q_1+1)^2-(Q_2-1)^2\right] - (2n+1)(Q_1+Q_2)\right\} \quad (21)$$

$$\Sigma F_{lens} = \frac{-(N+1)(Q_1+Q_2)K_1^2}{4N(N-1)} + d\Sigma B_{lens} \quad (22)$$

$$\Sigma C_{lens} = \frac{-d(N+1)(Q_1+Q_2)K_1^2}{2N(N-1)} + d^2\Sigma B_{lens} \quad (23)$$

These equations, when normalized to the primary focal length are:

$$8fp^3\Sigma B_{lens} = \frac{2}{L_1^3(N-1)^2}\left\{\frac{(N+2)}{2N}\left[(Q_1+1)^2-(Q_2-1)^2\right] - (2N+1)(Q_1+Q_2)\right\} \quad (24)$$

$$8fp^2\Sigma F_{lens} = \frac{-2(N+1)(Q_1+Q_2)}{L_1^2 N(N-1)} + D\,8fp^3\Sigma B_{lens} \quad (25)$$

$$8fp^2\Sigma C_{lens} = \frac{-4D(N+1)(Q_1+Q_2)}{L_1^2 N(N-1)} + D^2 8fp^3\Sigma B_{lens} \quad (26)$$

In order to investigate the properties of various telescope design families, it is convenient to hold some configurational parameters constant. Convenient parameters are E, N and frequently the ratio D/R and sometimes Q. The following terms can be grouped together for a given design family:

$$A_1 = \frac{N+2}{N(N-1)^2} \quad (27)$$

$$A_2 = \frac{2(2N+1)}{(N-1)^2} \quad (28)$$

$$A_3 = \frac{1-(M+1)^2(M-1)(1-R)}{M^3} \quad (29)$$

$$A_4 = \frac{2(N+1)}{N(N-1)} \quad (30)$$

$$A_5 = \frac{2}{M^2} + \frac{(M+1)^2(M-1)R}{M^3} \quad (31)$$

$$A_6 = \frac{4(M-R)}{M^2(1-R)} - \frac{(M+1)^2(M-1)R^2}{M^3(1-R)} \quad (32)$$

Using the above, we can write the Seidel sum for the complete two-lens telescope as:

$$8fp^3\Sigma B = \frac{A_1}{L_1^3}\left[(Q_1+1)^2-(Q_2-1)^2\right] - (Q_1+Q_2)\frac{A_2}{L_1^3} + A_3 \quad (33)$$

$$8fp^2\Sigma F = \frac{-A_4(Q_1+Q_2)}{L_1^2} + D8fp^3\Sigma B lens + A_5 \quad (34)$$

$$8fp\Sigma C = \frac{-2DA_4(Q_1+Q_2)}{L_1^2} + D^2\,8fp^3\,\Sigma B\,\text{lens} + A_6 \tag{35}$$

When, as is usually the case, we want the sum of the spherical aberration and the coma to be zero (i.e., an aplanat), the last two equations can be further simplified to:

$$8fp^2\Sigma F = -(Q_1+Q_2)\frac{A_4}{L_1^2} - DA_3 + A_5 = 0 \tag{36}$$

$$8fp\Sigma C = D^2A_3 - 2DA_5 + A_6 \tag{37}$$

Obviously, this third order thin lens approximation breaks down when $Q_1 = -Q_2$, but the possible number of valid solutions is almost limitless. Just as an example of one design family, consider the case of an aplanat with $Q_1 = Q_2$ (i.e., the radii of the corrector elements are matching so that one lens can be contact tested against the other). Here we can write:

$$L_1 = \frac{(DA_3 - A_5)(2A_1 - A_2)}{A_3A_4} \tag{38}$$

$$Q_1 = \frac{(A_5 - DA_3)}{2A_4}L_1^2 \tag{39}$$

If we fix the value of E at 0.4 (making the focus about one primary diameter behind the primary vertex), N at 1.517 (the index of BK-7 at the d sodium line), D/R at 0.95 (so the secondary can be mounted to the second corrector element), and allow M to be a running variable, we can solve for the required values of Q and L as a function of M.

Table 1 is a list of the solutions obtained for this family of two-lens aplanat telescopes. Note that an anastigmat solution exists at M = 3.5.

In general, an anastigmat is obtained from a family of aplanats when:

$$D = \frac{A_5 - \sqrt{A_5^2 - A_3A_6}}{A_3} \tag{40}$$

Also, if the rear surface of the second corrector element is desired to be the secondary by aluminizing a spot on it, then the following condition must be satisfied:

$$L_1 = \frac{S(1-Q_2)}{N-1} \tag{41}$$

Table 2 is a list of the aberration values predicted by these thin lens approximation equations and the aberration values obtained from ray tracing (the exact value of the third order contribution) for a two-lens design that is known from extensive analysis to be a near anastigmat. This example is the two-lens telescope design configuration C in Chap. 10. As can be seen, the agreement is quite good.

The Maksutov Telescope System

As was pointed out earlier, the thin lens approximations do not work well for Maksutov systems. However, the only term that is really inadequate is the expression for spherical aberration as we will shortly show. If this term can be corrected, we will have a usable design tool for the Maksutov system. But first, let us present the thin lens equations as a starting point. The following are derived from Conrady's G-sum equations with the object at infinity and a remote stop (assumed to be at the primary):

$$\Sigma B_{lens} = \frac{K^3}{2}\left[\left(\frac{N}{N-1}\right)^2 - \frac{(2n+1)(Q+1)}{2(N-1)^2} + \frac{(N+2)(Q+1)^2}{4N(N-1)}\right] \tag{42}$$

$$\Sigma F_{lens} = \frac{-K^2}{2(N-1)}\left[\frac{(N+1)(Q+1)}{2N} - N\right] + d\Sigma B_{lens} \tag{43}$$

$$\Sigma C_{lens} = \frac{K}{2} - \frac{dK^2}{(N-1)}\left[\frac{(N+1)(Q+1)}{2N} - N\right] + d^2\Sigma B_{lens} \tag{44}$$

From the condition of zero primary axial color (as stated by D. D. Maksutov and others, but in different notation), the power of the corrector is given by:

$$K = \frac{-4N^2H}{fp(N+1)(Q^2-1)} \tag{45}$$

Using this, equations 42, 43 and 44 can be rearranged as:

$$8fp^3\Sigma B_{lens} = \frac{-256N^6H^3}{(N+1)^3(Q^2-1)^3}\left[\left(\frac{N}{N-1}\right)^2 - \frac{(2n+1)(Q+1)}{2(N-1)^2} + \frac{(N+2)(Q+1)^2}{4N(N-1)}\right] \tag{46}$$

$$8fp^2\Sigma F_{lens} = \frac{-64N^4H^2}{(N+1)^2(N-1)(Q^2-1)^2}\left[\frac{(N+1)(Q+1)}{2N} - N\right] + D8fp^3\Sigma B_{lens} \tag{47}$$

$$8fp\Sigma C_{lens} = \frac{-16N^2H}{(N+1)(Q^2-1)} - \frac{128DN^4H^2}{(N+1)^2(N-1)(Q^2-1)^2}\left[\frac{(N+1)(Q+1)}{2N} - N\right] + D^2\,8fp^3\Sigma B_{lens} \tag{48}$$

The thin lens approximation to the total Maksutov system is obtained by adding the above three equations to equations 18, 19 and 20 (or 14, 15 and 16 if the mirror is aspheric).

As the focal length of an achromatic Maksutov corrector is very long, its contribution to the Petzval sum can be ignored and the relative Petzval radius is given by equation 17. Let us once again combine terms:

$$A_7 = \frac{256N^8}{(N+1)^3(N-1)^2} \tag{49}$$

$$A_8 = \frac{128(2N+1)N^6}{(N+1)^3(N-1)^2} \tag{50}$$

$$A_9 = \frac{64N^5(N+2)}{(N+1)^3(N-1)} \tag{51}$$

$$A_{10} = \frac{32N^3}{(N+1)(N-1)} \tag{52}$$

$$A_{11} = \frac{64N^5}{(N+1)^2(N-1)} \tag{53}$$

The thin lens approximation to the total Maksutov system is then:

$$8fp^3\Sigma B = \frac{H^3}{(Q^2-1)^3}\left[-A_7 + A_8(Q+1) - A_9(Q+1)^2\right] + A_3 \tag{54}$$

$$8fp^2\Sigma F = \frac{H^2}{(Q^2-1)^2}\left[-A_{10}(Q+1) + A_{11}\right] + D8fp^3\Sigma B_{lens} + A_5 \tag{55}$$

$$8fp\Sigma C = \frac{-16HN^2}{(N+1)(Q^2-1)} + \frac{2DH^2}{(Q^2-1)}\left[-A_{10}(Q+1) + A_{11}\right] + D^2 8fp^3\Sigma B_{lens} + A_6 \tag{56}$$

Table 3 is a comparison for the previous equations and the exact third order contribution (from ray tracing) for a Maksutov-Cassegrain telescope that is known to be well corrected. This example is the Sigler-Maksutov design from the August 1973 issue of *Sky and Telescope.* As was expected, the spherical aberration predicted by equation 46 was erroneous. Short of ray tracing, something must be done to obtain a more accurate algebraic expression for the third order spherical aberration. This can be done by going back to the surface contribution expression for spherical aberration (see Conrady) which included the effects of corrector thickness. Up to this point, thickness has only been considered in the expression for zero color.

The thick lens spherical aberration expression in terms of the surface curvatures is:

$$\Sigma B_{thick} = \frac{(N-1)}{2}\left\{\frac{c_1^3}{N^2} - Y\left[Yc_2N^2 - c_1(N^2-1)\right]\left[Yc_2 - c_1\frac{(N-1)}{N}\right]^2\right\} \tag{57}$$

$$\text{where } Y = \frac{y_2}{y_1} = \left[1 - \frac{tc_1(N-1)}{N}\right] \tag{58}$$

Using equation 45, the definition of H, and the following two equations:

$$c_1 = \frac{K(Q+1)}{2(N-1)} \tag{59}$$

$$c_2 = \frac{K(Q-1)}{2(N-1)} \tag{60}$$

equation 57 can be re-written as:

$$8fp^3\Sigma B_{thick} = \frac{-32N^4H^3}{(N+1)(N^2-1)^2(Q^2-1)^3}\left\{(Q+1)^3 - Y\left[YN^2(Q-1) - (N^2-1)(Q+1)\right]\left[YN(Q-1) - (N-1)(Q+1)\right]^2\right\} + A_3 \tag{61}$$

$$\text{where: } Y = \left[1 + \frac{2N}{(N+1)(Q-1)}\right] \tag{62}$$

Using the parameters from the example in table 3, the value of the equation is 0.0161, or essentially the same as that obtained from ray tracing. Reviewing the data in table 3, we can see that only equation 46 was seriously in error. A little residual astigmatism or coma won't hurt too much but residual spherical aberration is the "kiss of death." Once the value of the spherical aberration is determined (using equation 61), equations 47 and 48 (using the thick lens value of $8fp^3\Sigma B$) describe the coma and astigmatism accurately enough for design purposes. Finding the residual higher order contributions (usually almost exclusively fifth order and almost exclusively due to the corrector) is a job for ray tracing. A fifth order thick lens expression for ΣB is very complex and the thin lens approximation (such as that given by H. A. Buchdal in *Optical Aberration Coefficients)* is inaccurate enough to be worthless in designing Maksutov telescope systems. The fifth order is usually not large and if small enough, can be ignored completely or we can aspherize one of the surfaces (usually one near the aperture stop) or try small perturbations of the parameters to eliminate it. An important point to make here is that once we have a design correct through the third order we are 90% of the way to having a great telescope design.

In table 4 is a family of aplanatic Maksutov Cassegrain telescope designs based upon the solutions of equations 61, 55, 56 and 17. One of the degrees of freedom required to give aplanatic solutions was to allow D to become a variable as a function of M. Clearly, aplanatic designs with values of M greater than about 3.0 are not feasible as the corrector is required to be inside the primary-secondary space and thus, the anastigmatic solution at M = 4.0 is not valid. The useful range for these designs appears to be $2 \geq M \leq 3$.

Table 1. Thin lens and surface contributions (ray tracing) compared for a 12½", f/10 two-lens telescope design. Configurational data:

$b_p = b_s = 0$

$Q_1 = Q_2 = 0.2728$	$R = 0.6655$	$D = 0.6878$
$M = 3.098$	$L_1 = 2.2689$	$N = 1.517$ (BK-7)

Aberration	*Thin lens equations*	*Ray tracing*
$8fp^3\Sigma B$	0.0104	0.0083*
$8fp^2\Sigma F$	−0.0913	−0.0938
$8fp\Sigma C$	0.2457	0.2323
ΣJ	−1.0245	−1.0288

* The residual third order spherical aberration is cancelled by this design's residual fifth order term (due almost exclusively to the correctors). Here the fifth order contributions of the afocal correctors are 70 times smaller than the third order terms. For moderate focal ratios, the fifth order contributions are generally very much smaller than the third order for spherical aberration, coma and astigmatism.

Table 2. A family of aplanatic two-lens Cassegrain designs with matching radii on the correctors.

Common configuration data:

$E = 0.4$ $Q_1 = Q_2$ $N = 1.517$ (BK-7) $R/D = 0.95$ $b_p = b_s = 0$

M	R	L_1	Q_1	$8fp^3\Sigma C$	ΣJ
1.0	.300	3.33681	1.4886	2.8366	1.000
1.5	.4400	4.4581	1.7717	1.9475	.4048
2.0	.5333	3.5088	.7792	1.3717	−.0714
2.5	.6000	2.6100	.3667	.8974	−.5000
3.0	.6500	2.0239	.1890	.4691	−.9048
3.5*	.6889	1.6371	.1081	.0655	−1.2959
4.0	.7200	1.3680	.0670	−.3237	−1.6786
5.0	.7667	1.0205	.0303	−1.0775	−2.4286
6.0	.8000	.8071	.0158	−1.8144	−3.1667

* This magnification ratio gives an anastigmat. When this data, as given, was scaled to 12½" clear aperture (f/10 overall) and then ray traced, the result was a design that is nearly diffraction limited over 1° without any retouching or tweaking up of the design!

Table 3. Thin lens and surface contributions (ray tracing) compared for an 11", f/8 Maksutov-Cassegrain telescope.

Configurational data:

$b_p = b_s = 0$

$Q = 52.130$	$N = 1.517$ (BK-7)	$R = 0.6304$
$D = 1.0574$	$M = 2.3386$	$H = 31.8402$

Aberration	Corrector thin lens eq. 46, 47, 48	Corrector surface contribution	Mirrors eq. 18, 19, 20, 17	Mirrors surface contr.	Summation thin lens **	Summation surface contr.
$8fp^3\Sigma B$	−.8680	−.5537	.5568	.6006	−.3112	−.0469*
$8fp^2\Sigma F$	−.15229	−.9942	1.1011	1.1025	−.4218	.1084
$8fp\Sigma C$	−2.4216	−1.7205	2.1260	2.0173	−.2956	.2968
ΣJ	—	.0288	−.5487	−.5489	−.5487	−.5201

* The fifth order spherical aberration contribution (determined from ray tracing) exactly cancels this third order residual for marginal rays.

** Most of this error is due to the error in thin lens value of the spherical aberration. When the thick lens value (eq. 60) is used, the aberration sums give .0161, −.0725 and .0739 for the spherical aberration, coma and astigmatism respectively.

Table 4. A family of aplanatic Maksutov-Cassegrain telescope designs.

Common configuration data:

$E = 0.4$ $N = 1.517$ (BK-7) $H = 35$ $b_p = b_s = 0$

M	R	Q	D	$8fp^3\Sigma C$	ΣJ
1.0	.3000	48.0	1.0647	.6524	1.0000
1.5	.4400	57.5	1.5592	.0182	.4048
2.0	.5330	57.6	1.1732	.3762	−.0714
2.5	.6000	56.2	.8337	.4774	−.5000
3.0	.6500	54.8	.6200	.3769	−.9048
3.5	.6889	53.7	.4862	.1715	−1.2959
4.0	.7200	52.9	.4004	−.0922	−1.6786
5.0	.7667	51.6	.2865	−.3878	−2.4286

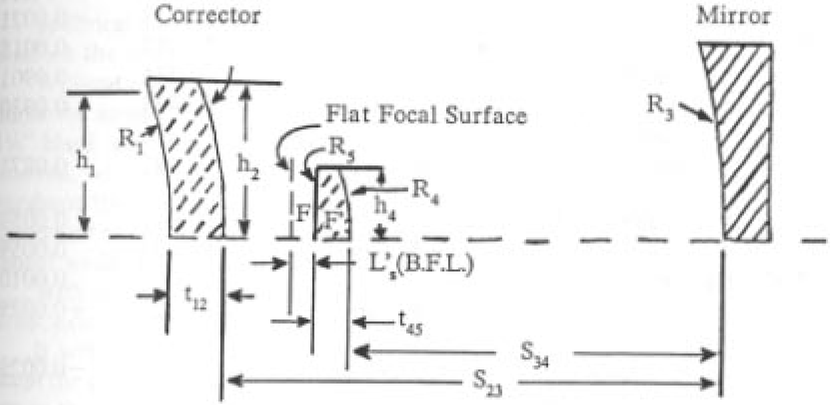
Appendix

A_1 = A refractive index constant (= 8.6737 at N 1.517)
A_2 " " " 30.1846 "
A_4 " " " 6.4186 "
A_7 " " " 1684.5888 "
A_8 " " " 1476.4832 "
A_9 " " " 219.3512 "
A_{10} " " " 85.8488 "
A_{11} " " " 156.9824 "
A_3 = spherical aberration contribution of the mirrors
A_5 = coma contribution of the mirrors
A_6 = astigmatism contribution of the mirrors
B = Seidel coefficient for spherical aberration
b = conic constant (0 for a sphere and −1 for a parabola. Subscript p means primary and s means secondary)
C = Seidel coefficient for astigmatism
c = radius of curvature. For light proceeding from left to right (object to image), a center of curvature to left of the surface is negative and a center of curvature to the right is positive.
d = distance between corrector and primary
D = corrector distance ratio
E = back vertex distance ratio (distance from primary to image plane divided by fp). Negative when image is in secondary-primary space.
F = Seidel coefficient for coma
f = focal length (subscript o means effective system focal length, and subscript p means primary focal length). A concave mirror has positive focal length and a convex mirror has negative.
H = Maksutov corrector thickness ratio (fp/t)
J = product of Petzval curvature and fp
K = power of the element (1/fp)
L' = corrector element focal length ratio (f/fp)
M = secondary magnification ratio (fo/fp). Magnification ratio is negative for a Gregorian.
N = refractive index of corrector glass
Q = corrector element bending: $Q = (c_1 + c_2)/(c_1 - c_2)$ equals 1 for convex-plano and 0 for equal convex.
R = primary to secondary separation divided by fp
S = secondary focal length divided by fp
t = corrector element axial thickness
y = ray height at surface
Y = ratio of ray heights on a Mak corrector (y_2/y_1)
ϕ = semi-field of view angle

Chapter 4
TELESCOPE DESIGNS AND DESIGNING

FLAT-FIELD PRIME-FOCUS MAKSUTOV CAMERA

by Jacques Labrecque



Geometrical setup of the camera

Table 1. Physical Dimensions (inches).

		C.A.=8.34	C.A.=10.50
h_1	semi-aperture of the corrector	4.17	5.25
h_2	back semi-aperture of corrector	4.28	5.39
R_1	radius of curvature of 1st lens surface (concave)	−11.180	−14.087
t_{12}	central thickness of corrector	0.792	0.998
R_2	radius of curvature of 2nd lens surface (convex)	−11.640	−14.666
S_{23}	separation of lens and mirror	36.40	45.86
R_3	radius of curvature of mirror	58.65	73.90
S_{34}	separation of mirror and field-flattener	29.621	37.322
R_4	radius of curvature of f-f (convex)	10.320	13.003
t_{45}	central thickness of f-f	0.391	0.493

R_5	back surface of f-f (flat)	flat	flat
l'_5	separation of R_5 and focal plane (B.F.L.)	0.0715	0.0901
h_4	semi-diameter (semi-diagonal) of f-f	1.73	2.18
	half field angle	3°.5	3°.5
h_4	– – – – – – – – – –	1.96	2.47
	half field angle	4°.0	4°.0

Table 2. Aberrations and Their Tolerances.

LA'_m	marginal spherical aberration	−0.0013	−0.0016
LA'_z	zonal spherical aberration	+0.0013	+0.0016
tol (LA')	tolerance (spherical aberration)	0.0060	0.0060
$Coma's_m$	sagittal coma at 4° off axis (marginal)	0.0000	0.0000
$Coma's_z$	sagittal coma at 4° off axis (zonal)	0.00013	0.00016
$L'_F - L'_C$	chromatic aberration (marginal)	−0.0009	−0.0011
$L'_f - L'_C$	chromatic aberration (paraxial)	−0.0017	−0.0021
tol (FC)	tolerance, chromatic aberration	0.0015	0.0015
l'_5	back focal length	0.0715	0.0901
l'_s	on axis projection of sagittal focus (astigmatism)	0.0738	0.0930
l'_t	on-axis projection of tangential focus (astigmatism)	0.0691	0.0871
$l'_s - l'_t$	true astigmatic difference	0.0047	0.0059
D.L.C.	disc of least confusion (astigmatism)	0.0007	0.0059
tol D.L.C.	tolerance on D.L.C.	0.0010	0.0010
$X'_s = l'_s - l'_5$	sag of sagittal astigmatic focus relative to back focus	+0.0023	+0.0029
$X'_t = l'_t - l'_5$	sag of tangential astigmatic focus relative to back focus	−0.0023	−0.0029
E.F.L.	equivalent focal length	28.02	35.30
E.F.R.	equivalent focal ratio	f/3.36	f/3.36

Comments. Having been interested in Maksutov optics for a number of years, I had the opportunity to design my own systems with the help of computers.

Computers afford the opportunity to optimize a system very rapidly and the only danger lies in becoming lost in a pile of printed paper.

A prime focus camera being needed at the Dominion Observatory for satellite research, it was deemed useful (and also agreeable for a TN) to design and build it from scratch. The instrument is of medium speed (f/3.3), covers a reasonable field (8°) and should be relatively easy to make. The glass for both corrector and field-flattener is BSC-2 and the blanks are easily obtained from International Glass.

After some experimenting with a Schmidt camera, it became obvious that the curved focal surface was a great nuisance, hence the reason for adding a plano-convex field-flattener to a Maksutov. It might be pointed out that a plano-convex field-flattener is not necessarily the best solution, but due to time and expediency it was not possible to go through all the combinations.

Although the instrument made had a 10.5-inch entrance aperture (C.A.), the computer's data are given for an entrance aperture equal to 8.34 inches also. Figures quoted relate to the latter dimension although the tables give figures for both. By interpolation, one may scale down, if desired. The figure clarifies the geometrical setup.

The photographic plate is well enough separated from the flat surface of the field-flattener not to cause trouble in mounting and also to minimize the effect of dirt on its last surface.

It became obvious during design that the field-flattener, henceforward to be called f-f, helped to reduce coma but tended to destroy the excellent achromatism of the initial Maksutov. The chromatism introduced is, all the same, negligible and should not cause trouble in photography. I would not be surprised at all if the residual chromatism were not more than half that of the equivalent Wright (short) camera. The sagittal coma (coma'$_s$) at 4° off-axis was made null but some zonal coma of very negligible importance, creeps in.

Astigmatism ($l'_s - l'_t$) is small and no effort was made to correct it as the biggest spot for the disc of least confusion at 4° reaches only .0007 inch (17 microns).

Spherical aberration (LA') is some three times inside the Rayleigh limit and therefore the central part of the field is almost of *visual* quality.

Without really trying for it, the second surface (R_2) of the meniscus became almost the same radius as the convex surface of the blanks on the glass list (the 11¼" blank excepted). Therefore, a minimum of center thickness needs to be removed, and only the periphery of R_1. Care should be taken, all the same, not to overshoot the already large central thickness (t_{12}) of the design; approach the central part of the blank with carbo no bigger than 120 and be careful to check the original wedge of the blank. This may save labor and gnashing of teeth later on.

With regard to the tables, all subscripts "5" have been dropped for the sake of clarity, except for the back focus (l'_5).

It will be seen from Table 2 that all aberrations are well within tolerance except the chromatic, where the paraxial value is slightly outside. This is of no concern as that part of the central beam is necessarily occulted by the plate-holder.

Even at double the given size the performance would be good, although for an instrument with a C.A. equal to 20 inches I would certainly try to bring the DF (yellow-blue) focus difference smaller at the expense of the CD (red-yellow). The D.L.C. due to spherical aberration in the central part of the field is 0.0002 inch (5 microns); certainly very hot for photographic sharpness. Tolerances for fabrication remain the same as for a Mak-Cass. system. The plano-convex field-flattener, being close to the final image plane, does not need to be too exact and should be quite easy to make. R_4 may diverge from 10.320 by ±0.020".

The mirror deserves a word: it should be a regular sphere but if faint zones show up under the Foucault test, it would not be tragic as only 8.34 or 10.5-inch circles are used for each point image. Get R_3 as close as possible.

For illumination over a field of 8°, the mirror should be 12.5 inches diameter for the C.A. = 8.34" and 16.0 inches for the C.A. = 10.5". These dimensions give *full* illumination.

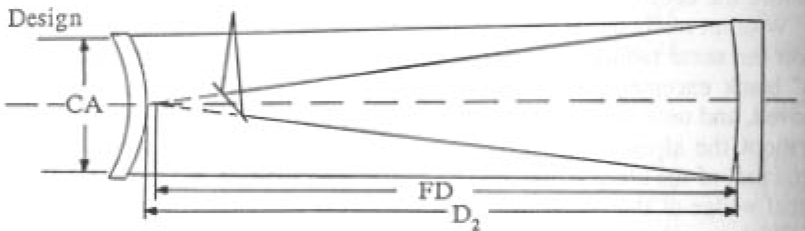
The plate-holder may be held by a long magnesium tube screwed to the center of the corrector; but as the f-f adds weight, it would be preferable to have a spider of four strong piano wires to reinforce it in the vicinity of the photographic plate.

It should be possible to have the system temperature-compensating with invar rods screwed to the mirror cell at one end and on an auxiliary ring, in the plane of the focus, at the other. Rods of the same material as the tube holding the photographic plate would connect the auxiliary ring to the corrector cell.

The f-f may be mounted on an integral part of the plate-holder, details of which one may have to solve.

The foregoing system is equivalent to a Schmidt, but with a flat field and no deep aspherics to figure, and it is about two-thirds the length. The astigmatism is certainly less than the equivalent Wright camera.

NEWTONIAN-MAKSUTOV FOR VISUAL USE
by Harrison Sarrafian



C.A.	clear aperture of corrector lens	11.0	
R_1	radius of curvature of 1st lens surface	−21.017	
d_1	center thickness of lens	1.113	
R_2	radius of curvature of 2nd lens surface	−21.655	
B.A.	back aperture of corrector lens	11.203	
	corrector lens glass, Borosilicate Crown	n_d = 1.517,	V=64.5
d_2	separation of lens and primary mirror	63.350	
R_3	radius of curvature of primary mirror	−123.000	
D_m	diameter of primary mirror	12.5	
$(D_m)_o$	diameter of primary mirror illuminated by on-axis rays	11.422	
FD	distance of focal point from primary mirror	62.591	
EFL	effective focal length	60.3	
EFR	effective focal ratio	5.5	

Comments. In order to achieve best image quality in a visual telescope, the designer should select a focal length as long as possible while still permitting the lowest desired magnification to be realized with available oculars. The lowest observed image quality will be superior with a long focal length instrument for the following reasons:

1. Eyepiece aberrations will be reduced since the eyepiece is working at the same f/ratio as the main instrument. The effects of astigmatism and curvature of field inherent in the ocular will be reduced since the depth-of-focus is greater with the narrower cones of light. The contribution due to the residual spherical aberration of an eyepiece is especially sensitive to f/ratio. In the third order approximation it varies as the cube of the relative aperture of the telescope. Thus, an eyepiece will introduce almost exactly twice the amount of aberration at f/4 as it will in an f/5 telescope.

2. Large, long focus eyepieces "interface" with the observer's eye much more satisfactorily. A large eye relief permits comfortable viewing, and a large ocular contributes a favorable psychological effect. On the other hand, a short focus eyepiece always gives the observer the sensation of peeping at the object through a pinhole. In addition, it is virtually impossible to keep the eye lens of an ocular with less than about 3/4" of eye relief uncontaminated with oils deposited by the observer's eyelashes. That is, of course, ruinous to definition (perhaps our pinhole analog of the short focus eyepiece should include a layer of waxed paper!)

3. The residual aberrations of the telescope itself are lower at high f/ratios. This is primarily a consideration in the case of the Newtonian reflector which has a large amount of coma at the faster f/ratios (third order coma increases with the square of the reciprocal of the f/ratio). Since good correction can be realized in a Maksutov at fairly fast f/ratios, however, this consideration is of somewhat lesser importance.

In summary of the three considerations outlined here, I decided to design a Maksutov-Newtonian telescope which would perform more satisfactorily as a visual instrument than the usual f/4 designs available. Of course, the Cassegrainian forms are excellent as visual instruments, but their use is generally restricted to medium and high powers. However, I suspect that this instrument will be capable of better performance at high powers when used with a good Barlow lens than the Mak-Cass. designs. This is because the Cassegrainian forms generally have very fast primary optics which are extremely sensitive to collimation errors and have substantially larger amounts of spherical and chromatic aberration. Also I understand that Cassegrainian systems with sizeable secondary amplifications suffer from the amplification of residual roughness on the primary mirror which is difficult or impossible to detect by the usual test methods (Texereau has some good pictures of this roughness on mirror surfaces). The effect of such roughness, especially when highly amplified, is to scatter light out of the Airy disc into the surrounding diffraction rings and also to lower contrast on fine planetary detail.

If one is designing a visual telescope capable of use at the lowest powers (i.e., richest field), he should not select an f/ratio below f/5 since 1½" Erfle eyepieces which are readily available will provide richest field magnification at about this f/ratio. An f/4 telescope would invite serious eyepiece problems as Dr. Everhart points out. It is surprising to note that longer focal length will not require a larger diagonal; quite the contrary, a larger unvignetted angular field will be obtained with a given diagonal size in the slower system. If anyone does not believe this, equations will prove it.

I finally decided on a focal length of 60 inches in the 11" size, which makes magnification with most eyepieces come out in nice round numbers. This results in a focal ratio of about 5.5. A 1½" Erfle will provide richest field at 40x while a comfortable ½" orthoscopic or Ploessl Eyepiece will provide plenty of magnification for planetary work when used with a Barlow lens amplifying about 4x. If one desired the "ultimate" in a lunar and planetary telescope, he could insert a Barlow immediately ahead of a very small diagonal mirror. In this way it should be possible to reduce the obscuration ratio to 10% or even less, and of course there are no spider supports to cause diffraction problems. This Barlow-diagonal combination could be substituted, when desired, with a larger diagonal for variable or deep-sky work. Perhaps the best all-round compromise would be a 2.25 inch minor axis diagonal which would fill the field of a giant Erfle with unobtrusive vignetting at the margin of the field, while obscuring only 20% of the aperture diameter, thus providing good contrast on planetary detail.

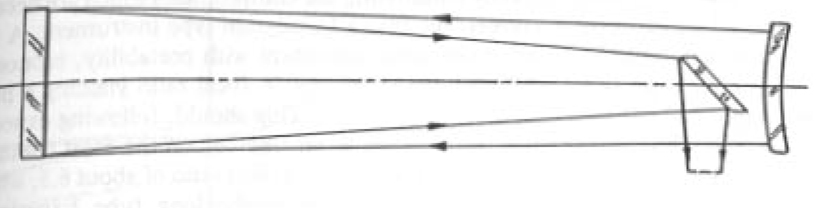
This design was carefully ray-traced to achieve optimum performance. The effect of the increased focal length is quite evident in the smallness of the residual aberrations. Longitudinal zonal spherical aberration, LZA', is 0.00077" (the marginal and paraxial rays come to a common focus). The permissible value for LZA' at this ratio is 0.01678" according to the Rayleigh tolerance, thus the residual spherical aberration is 22 times smaller than the Rayleigh tolerance. With reference to chromatic aberration, the C and F rays have been brought to a common focus near the 70% zone, although this may have been "gilding the lily" in a sense since the total amount of residual color is quite small; nevertheless, I made this adjustment in order to have an optimum design. As a result, the residual chromatic aberration for all light between the C and F lines is only about 1/10th of the Rayleigh tolerance. As for coma, I calculated the value of OSC' to be .00039, less than one-sixth of the permissible amount which, according to Conrady, is 0.00250. Visually it will be impossible to see any coma under any circumstances since it will be beyond the resolving power of the observer's eye. Photographically, one can expose a plate at prime focus over 5 inches in diameter and have what Conrady considers "extremely sharp definition" to the edge of the plate (as far as coma is concerned). If one machines a plate-holder with a surface conforming to the surface of best focus, as is done on a Schmidt camera, it may be possible to achieve excellent definition over a plate this large, or even larger.

It should be pointed out to the prospective builder that the corrector for this telescope can be ground easily from a standard 11¼" molded blank, despite the longer radii. The sagittae are about 1/8th inch less for a 11¼" blank and so a total of only about 1/8" stock need be removed from the center thickness in grinding both sides to the new radii. This leaves a more than ample surplus for fine grinding of about 0.140", assuming that the original blank was 1 3/8" thick.

One additional advantage to the longer focal length is that the tolerances on the corrector become less severe. The corrector thickness may deviate from the design by as much as about 0.080" before the Rayleigh tolerance is exceeded. R_1 and R_2 may vary together as much as ±0.8", but they cannot vary separately more than about 0.030". The reader should be cautioned about these figures since, when each of these perturbations was introduced into the design, it was assumed that all other dimensions were at their correct value. Moreover, a telescope will perform at its best only when the residual aberrations are held to a small fraction of the Rayleigh limit, and the builder is well advised to work to close tolerance in order to realize the capabilities of this design.

WIDE-FIELD NEWTONIAN-MAKSUTOV CAMERA

by John D. Lytle



R_1	radius of 1st surface, corrector	−22.875
d_1	clear aperture	10.00
R_2	radius of 2nd surface, corrector	−23.681
t_1	thickness, corrector	1.3183
d_2	C.A., rear surface of corrector	10.25
R_3	radius of mirror	−134.801
t_2	distance, corrector to mirror	−69.025
d_3	clear aperture of mirror	13.35
t_4	distance mirror to diagonal	64.000
R_4	radius of diagonal	flat
d_4	C.A. of diagonal	4.8
	Glass for corrector	611588
E.F.L.	equivalent focal length.	66.03
	Dimensions in inches.	

Comments. It is not by free choice that most back-yard astronomers own modest instruments. Even within the small-aperture domain (2" to 12"), the cost of a specific type of telescope may increase with the square of the aperture. Beyond about 12", the aperture-cost curve may become cubic or even quartic. As a result, few amateurs can afford to buy or properly house even a 12" instrument. This limitation seems to have motivated many of the more serious among us to squeeze more performance per inch of aperture from our telescopes than do a number of professional astronomers. The superb work of Mr. Evered Kreimer of Prescott, Arizona, is a good example; his fine photographs of deep-sky objects are familiar to most of us and are of a far higher quality than most would expect from an f/7, 12" Newtonian; his home-constructed cold camera is an outstanding example of what can be done by a dedicated amateur with relatively limited resources.

Most of the good-deep-sky photography done by amateurs falls roughly into two categories: that done at moderately long focal lengths, and that done at relatively short focal lengths. Photographs in the first classification usually demonstrate the high resolution obtainable with long focus instruments and their associated large plate scale. The useful field coverage is limited by aberrations, though, and generally amounts to less than 1°. Many pictures in the second category are recorded either by relatively fast Schmidt cameras or by moderately fast aerial camera lenses. The field of good definition in these cases may approach 15° x 15°, but much interesting detail is lost in the diminished plate scale. Resolution is limited by the grain size of the emulsion, rather than by optical aberrations.

A gap exists which may be bridged only by a long focus instrument with extended field coverage.

To bridge the gap economically, I decided to design and construct a photographic Maksutov. At the outset, I decided to limit the use of the instrument to the prime or Newtonian focus, thereby eliminating the compromises which are necessary if the telescope is to be convertible into a Cassegrain type instrument. A 10" instrument was selected as being the most consistent with portability, economy, adequate optical potential and available resources. A focal ratio yielding a plate scale of about 1° per inch was deemed desirable. This should, following expectations, permit detail on the order of 5" of arc to be resolved on the most common emulsions. The 1° plate scale was found to require a focal ratio of about 6.5, which in turn might require a slightly clumsy, but not intolerably long, tube. Experience told me that it would be reasonable to expect performance optically better than 5" of arc over a 3° field.

With proper attention to optical fabrication, mounting details, guiding, etc., I expected such an instrument, when used in conjunction with a cold camera, to be capable of outperforming most instruments (the very large Schmidts excepted) on extended objects such as M31, the Rosette, the North American nebula, etc.

My design finally evolved into that at the beginning of this account. Note that an unvignetted image requires the diameter of the primary to be 13.35" and the minor axis of the Newtonian secondary to be 4.8". This means that the primary mirror, mirror cell, etc., may represent more of an undertaking than one might have originally intended. I suggest, therefore, that a smaller primary mirror be used, such as one of 11½" to 12½" diameter. Reducing the primary image to 11½" will reduce the brightness of the images by about .32 stellar magnitude at the edge of a 3° field, but this is not a terribly high price to pay for a lighter, less cumbrous instrument.

The 4.8" given as the minor axis of the secondary is rather arbitrary. This dimension allows for a reasonable tube diameter, sufficient clearance (from the meniscus) for mounting, and no vignetting. If an undersized primary mirror is used, the secondary may also be made slightly smaller at no additional expense in terms of vignetting. This compromise, in turn, actually increases the light gathering area slightly, and will foster improved contrast when the telescope is used visually.

A possible stumbling block to others wishing to construct this design is obtaining the specified glass for the corrector plate. The glass used is Bausch & Lomb 611588, a dense barium crown. One is normally inclined to be content with what is available and when my friend, Norman Cole, offered me a blank of 611588 at a very reasonable price, it suddenly looked far more attractive than the customary BSC-2. The 611588 corresponds very closely to Schott SK-8 and Ohara 611588, and either could probably be substituted with no ill effects.

Performance curves for this design are plotted in Fig. 2. The curves represent the image curve displacements (from the principal ray) of a meridional and sagittal fan of rays traced from the field points 0°, .75°, 1.13° and 1.5° (see Fig. 2b for optical geometry).

A meridional fan is one whose rays have pupil intercept coordinates $(\eta, 0)$, sagittal rays having coordinates (o, ξ). By recording the y image and the x image displacements of the sagittal fan, much may be learned about image size and

FIGURE 2 10-INCH PHOTOGRAPHIC MAKSUTOV

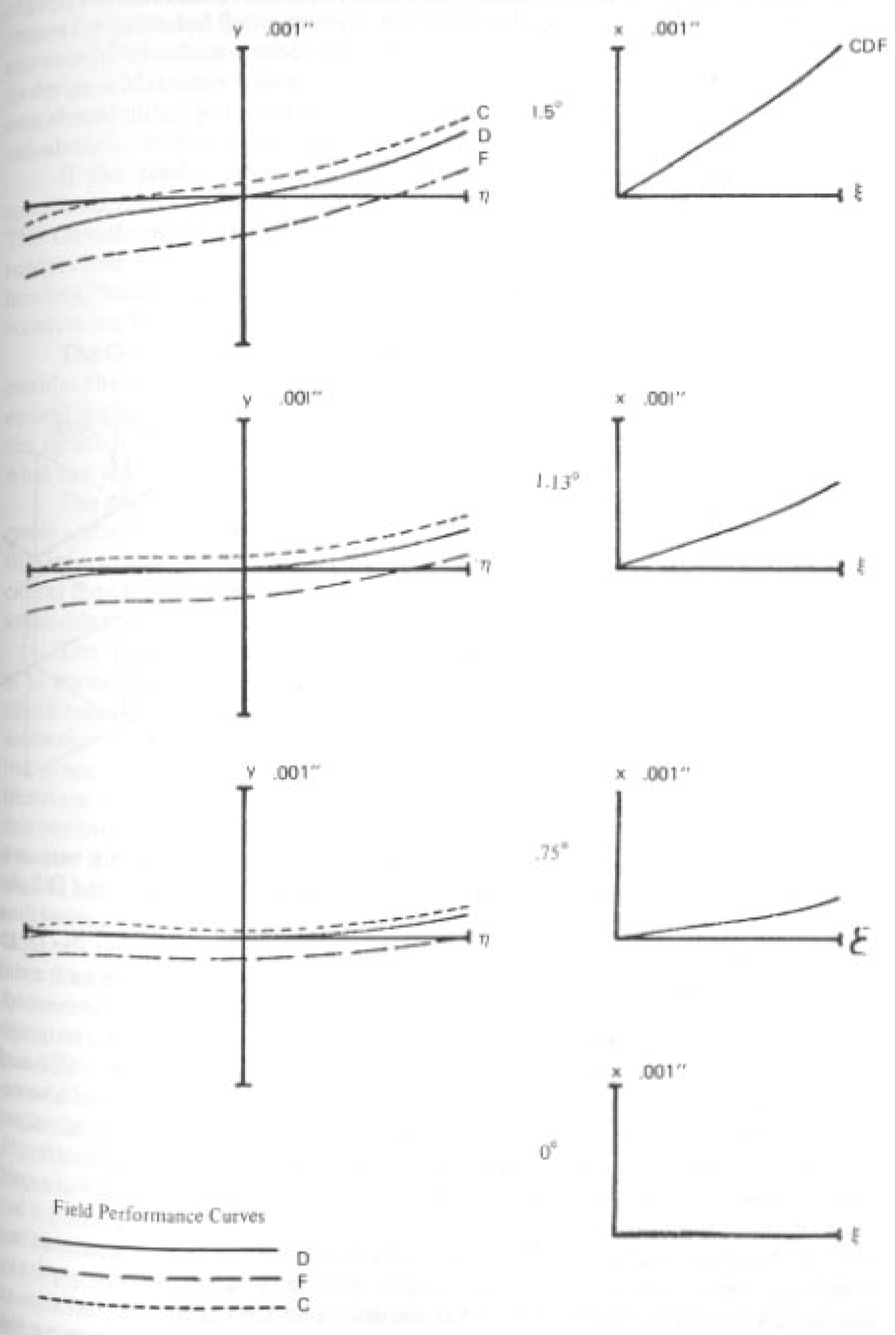
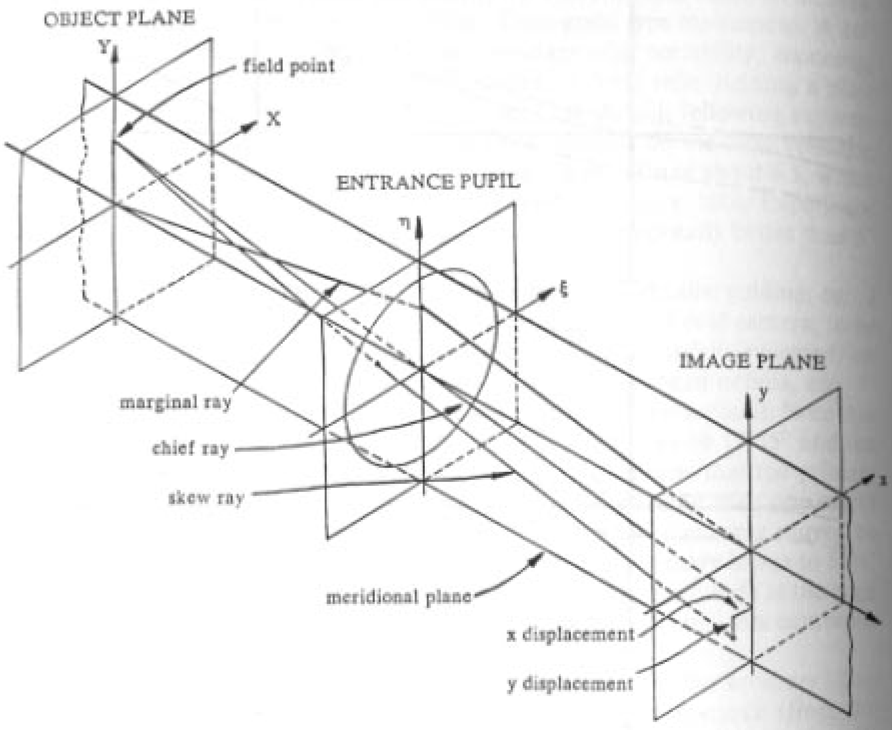


Figure 2b

OPTICAL SYSTEM GEOMETRY FOR RAY FAN EVALUATION



character. There is little additional information in y versus ξ plots or in x versus η plots, and these are omitted. Note that each fan has been traced in C, F and D light in order to show the magnitude of the transverse chromatic aberration, as well as the chromatic variation of the various aberrations. In the x vs. ξ curves, the C, D and F lines are indistinguishable and are plotted as a single curve. Since total axial symmetry is preserved for the axial field point, only the sagittal fan is presented. As will be observed by those familiar with this method of evaluation, the only significant residuals are a small amount of lateral color (about .0003" at 1.5°), and some third order astigmatism and field curvature. This specific balance of aberrations was intentional; astigmatism and field curvature were left with the intention of using a Rosin-type corrector (Rosin S., "Ritchey-Chretien Corrector System", *Applied Optics*, Vol. 5, No. 4, pp.675-676, 1966) as an entrance window for a cold camera, to be added later.

It should be emphasized that, while many Maksutovs are aspherized as a final touch-up, the aspheric on the primary mirror is an integral and necessary part of the design illustrated in Fig. 2. Most amateurs aspherize the primary mirrors of their Maks *after* completing the corrector, monitoring the result by testing the

entire system by autocollimation. This strategy is sound, however, only when the instrument is to be used solely to view objects of limited angular subtense, such as planets, double stars, and lunar features. If this technique is applied to instruments meant for extended field coverage, the spherical aberration will be corrected at the expense of introducing other aberrations off-axis, and may nullify all one's efforts to design a Maksutov which will perform well off-axis. I believe that in such cases one should either put forth the effort required to incorporate the aspheric into his calculations, or else be satisfied with a spherical primary.

If the reader does decide to construct an instrument from the above specifications, the problem of aspherizing the primary will not be insurmountable. The Gaviola modification of the Foucault knife-edge test should be familiar to readers and need not be elaborated upon here (maybe more familiar under the heading "caustic test" — Ed.). This testing procedure is the key to producing an accurate aspheric on the primary mirror.

The Gaviola (caustic) test, properly carried out, performs a single function: it enables the optician accurately to map the loci of the local radii of curvature of an optical surface. Deviations of the experimental caustic from its desired shape tell the optician a great deal about the actual contour of his aspheric surface. This is what the test accomplishes, nothing more.

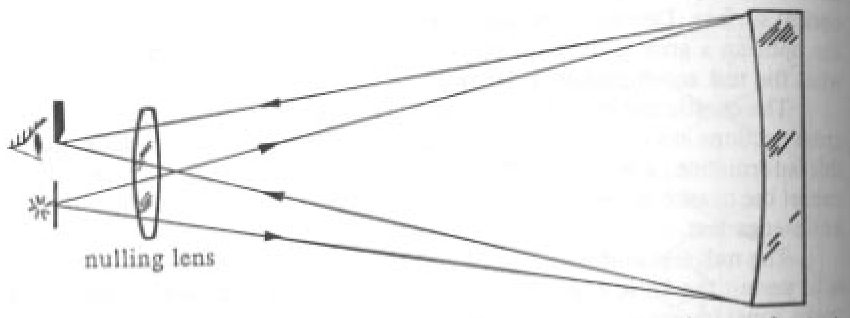
The caustic test provides little information about surface irregularities whose cross-sections are of the same magnitude as the openings in the mask. To obtain this information, a more quantitative null test must be devised which will closely cancel the caustic of the surface and make it appear like a sphere under the normal knife-edge test.

The null test in this instance should perform one and only one function: this is to permit the knife-edge to darken the entire optical surface evenly enough to make zonal irregularities prominent. Admittedly, all the fourth power conics (the aspherics most commonly employed by ATMs) may be tested at conjugate foci, but proper location and alignment of the test apparatus may be a tedious and tricky business. In the case of the Newtonian Maksutov outlined above, the aspheric on the primary is a weak oblate ellipsoid (eccentricity imaginary), especially difficult because the two conjugate foci do not lie along the optical axis, but on a perpendicular to the axis. In this case, astigmatism prevents us from nulling more than a small strip through a major diameter of the optic (Everhart, E., "Null Test for Wright Telescope Mirrors," *Applied Optics*, Vol. 5, No. 5, pp.717-718, May 1966).

Contradicting myself immediately, let it be stated that a null test *may* indeed be used to control the contour of an optical surface, but only under selected conditions. Most of us realize, for example, that the most efficient way to produce a good sphere is to work towards a good cutoff at its center of curvature. The same procedure applies to a paraboloid, *if* you have a good flat handy. To test any aspheric at its center of curvature by autocollimation, accessory optics are necessary. Usually a flat may be borrowed to test the paraboloid. But in order to test a hyperboloid, ellipsoid, etc., one must insert a special "null" lens between the optical surface and the tester. The null lens is designed specifically to cancel the spherical aberration of the desired surface. The null lens may consist of one or more simple lenses (depending on the severity of the aspheric), and must be used in monochromatic light. The null, however, will be only as accurate as the auxiliary lens system, as will be the final optical surface. The design of such a lens will usually require the services of a high-speed computer (except for the simplest cases), and the lens elements must be fabricated, centered and spaced to *very* close tolerances if it is to perform properly. Moral—amateurs had better scrap this one!

Fortunately, we have an out. A seemingly trivial gimmick familiar mostly to opticians faced with the problem of nulling large aspheric mirrors. The procedure is this: employ the caustic test exhaustively to establish the proper contour of the optical surface. Then, from an assortment of small (but fairly high quality) singlet lenses, select one, mount it vertically on a ring stand or other support, and place it between the tester and the mirror so that the entire test beam passes through the lens on both the outgoing and return trip (see Fig. 3).

FIGURE 3
NULL TESTING SET-UP

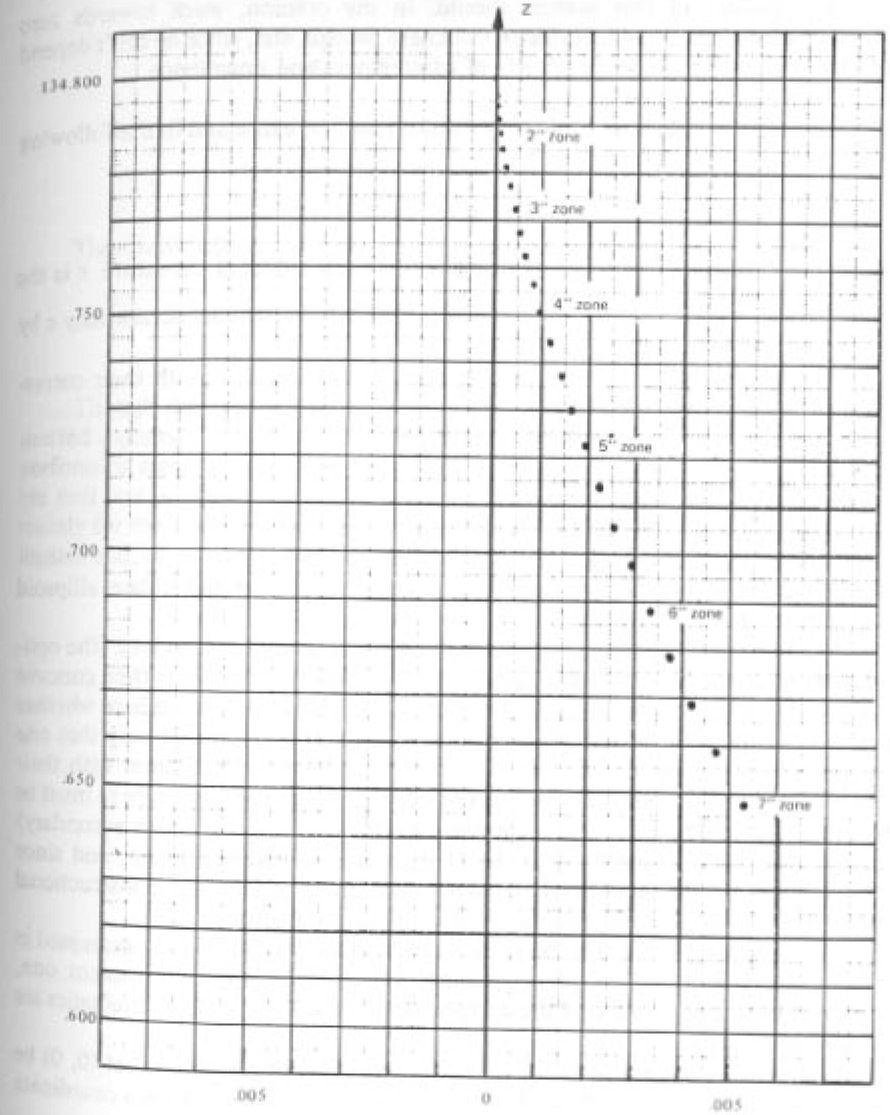


If one adjusts the axial location of the lens over a short distance, a change in the character of the knife-edge "shadows" will be observed. The resulting "null" may or may not be superior to that seen without the nulling lens. But if other lenses of different power, thickness and shape are tried, one will probably discover one which yields an excellent null, allowing minute zonal structure to be observed easily. If the experimental caustic closely approximates the theoretical one, and if the optician has a good feel for the final figuring process, the null test will probably only confirm the existance of an excellent optical surface. The test should be conducted in monochromatic light, of course.

Fig. 4 is the plotted caustic for the primary mirror of the instrument described above. This caustic characteristically decreases in local radii as the zonal height increases, the optical surface having a gently turned-up edge. The dimensions given are in inches. Local radii are plotted for zonal increments of ¼-inch, the outermost zone plotted corresponding to 7" off axis. Though the graph is probably accurate enough to be used directly, one may calculate the coordinates of this caustic, or any conic desired, by means of the formulae supplied below.

It may be observed that the caustic is quite small, and the aspheric deformation therefore very weak. Actually, the departure of the surface from the paraxial sphere amounts to only about two wavelengths at the edge of a 14" primary, which

FIGURE 4 CAUSTIC FOR OBLATE ELLIPSOID



represents only a few educated strokes with a slightly doctored lap. This aspheric is only 25% as severe as a paraboloid on the same paraxial sphere, and the caustic looks much like that for a paraboloid 25% corrected, only it is directed in the opposite fashion.

Before the reader assumes that the aspheric is too slight to be bothered with, it should be mentioned that the writer traced a few rays in order to evaluate the design in the absence of the aspheric. The unavoidable conclusion: aspherize. The system was designed with the aspheric as an integral part, not an afterthought. Performance at all points in the field will be noticeably inferior, even extended to a factor of five if the aspheric is omitted.

The builder of this system should, in my opinion, work towards zero tolerance on corrector radii, corrector thickness, wedge, etc., since he can't depend on asphering to remedy the effects of carelessness and impatience.

The Caustics of Conics.

The sag z of a general conic of revolution may be expressed in the following form:

$$z = \frac{CVr^2}{1 + [1 - (CC+1)CV^2r^2]^{1/2}}$$

where the curvature $CV = \frac{1}{R}$ R being the paraxial radius of curvature. r is the zonal height, and CC is the conic constant, related to the familiar eccentricity e by

$$CC = -(e^2)$$

Using this notation, the various conics are listed below, with their corresponding conic constants:

$CC = 0$	sphere
$CC \angle -1$	hyperboloid
$CC = -1$	paraboloid
$-1 \angle CC \angle 0$	prolate ellipsoid
$CC > 0$	oblate ellipsoid

The reader need not be disturbed that the eccentricity of the oblate ellipsoid becomes imaginary.

A simple and consistent sign convention is important here, so let z (the optical axis) be positive towards the right. A surface with positive sag is then concave towards the right, and has positive curvature. It is of no consequence here whether glass lies to the right or left of the optical surface. It is important only that one keeps track of the signs of CV and CC, and that these are consistent with their meaning during the optical design process. The formulary to be given here must be modified if one desires to test a convex glass surface (Cassegrainian secondary) through the back. The glass must be of high optical quality, though, and since modification of the equations demands that many additional constructional parameters be considered, this digression will be omitted here.

The equation (1) for the sag of the conic surface of revolution is expressed in a form convenient for use in ray tracing. The form is not a convenient one, however, for the calculation of the corresponding caustic, and the mathematics are somewhat messy.

To calculate the shape of the caustic of any conic of revolution, let (0, 0) be the vertex of the optical surface. Then if z is the optical axis, and y is a coordinate perpendicular to the z axis, we may calculate the following:

$$\frac{dz}{dy} = \frac{CV.r}{[1 - (CC+1)CV^2r^2]^{1/2}}$$

$$\frac{d^2z}{dy^2} = \frac{CV^3.r^2(CC+1)}{[1-(CC+1)CV^2r^2]^{3/2}} + \frac{CV}{[1-(CC+1)CV^2r^2]^{1/2}}$$

The coordinates (z, y) of the center of curvature for any zone r in terms of equations (1), (2) and (3) are given by:

$$z_{c\ of\ c} = (1) + \frac{[1+(2)^2]}{(3)}$$

$$y_{c\ of\ c} = r - \frac{[(2)+(2)^3]}{(3)}$$

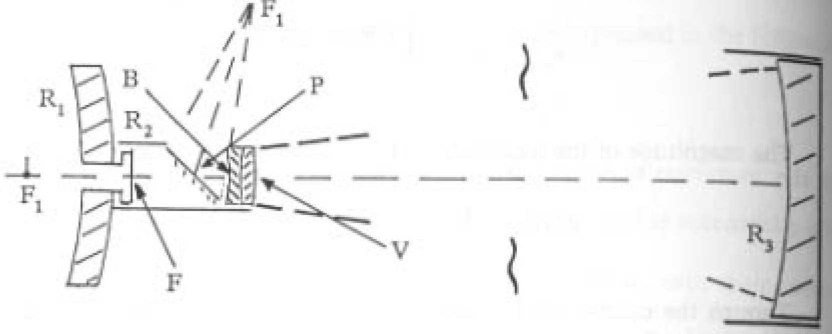
The magnitude of the local radius of curvature is expressed:

$$RCDV = \frac{[1+(2)^2]^{3/2}}{|(3)|}$$

Though the caustic test provides a very accurate means for producing any desired aspheric, the procedure is tedious and time-consuming. If the means for performing a *good* null test are available, take advantage of the opportunity; a reliable null test is straightforward, and a real time-saver. The caustic test is useful mainly for the oblate ellipsoid, or the prolate ellipsoid with widely separated conjugates and, of course, as a means of performing the final evaluation of any conic.

MAKSUTOV-BARLOW-NEWTONIAN PHOTO-VISUAL TELESCOPE

by Tore Sjogren



Corrector	Diameter	11.2"
	R_1	−16.929
	Thickness	1.102
	R_2	−17.559
	Hole dia.	0.9
Distance	Corrector to mirror	48.032
Mirror	Diameter	12.6
	R_3	−93.150
Distances	Mirror to focus	47.481
	Mirror to Barlow	43.701
	Barlow to focus	3.780
Barlow	Diameter 1.5	
	Flint Schott F2,	620364, r_1 5.472
		thickness 0.158
		r_2 −9.843
	Crown Schott BK-7,	517642, r_3 −9.843
		thickness 0.079
		r_4 1.874
Distances	Vertex V to plane P	1.260
	Vertex B to plane P	1.023
	Vertex B to focus F_1	7.354
	Plane P to focus F_1	6.331
Diagonal angle	100°	

Focal plane concentric with main mirror r −46.575
Photographic diameter of focal plane 2.4
Equivalent focal length 94.062
Vignetting Visual 2.1% Photographic 5.2%
Visual magnitude 14.2

Dimensions in inches.

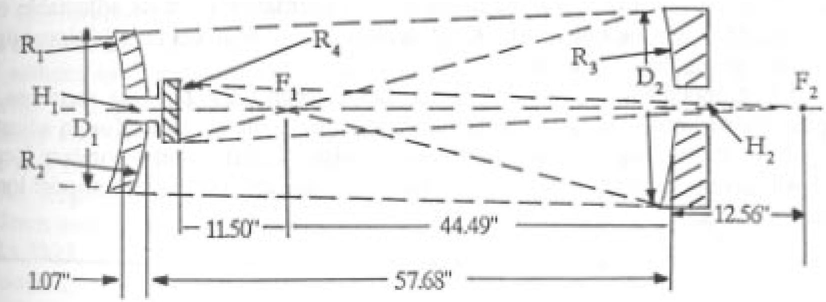
Comments. This design has been checked by Mr. John Gregory on the computer and he remarks as follows:

"It is a fine design and I recommend it heartily. Through the Barlow, residual and zonal aberrations are only a quarter of the Rayleigh tolerance, but coma gives an image of about .003" at the edge of a 2" diameter field. This is O.K. visually because the only way you can see a 2" dia. field is through an eyepiece of at least 2" e.f.l., and that is low power. Photographically it would be noticeable, but wide field photography should be done at prime focus and *not* through the Barlow. I get a vertex B to paraxial focus of 7.490" in 555 light, an e.f.l. of 94.847" and f/8.47 for 11.2" aperture. At prime focus residual and zonal color are within ¼ Rayleigh also. Coma will give a .0006" dia. glob 1" off axis (and about .0012" at the edge of a 4" dia. field).

"I must say that I am impressed at the smallness of the errors introduced by the Barlow and I think that the amateur will stand a better chance at perfection with this design than with a Cass. secondary."

MAKSUTOV-GREGORIAN PHOTO-VISUAL TELESCOPE

by Norman Cole



Specifications.

Clear aperture	10.70"	
R_1	16.35"	concave
R_2	16.97"	convex
R_3	88.08"	concave
R_4	19.72"	concave
Thickness of corrector	1.07"	
Corrector to primary	57.68"	
Radius of prime focal surface	42.7"	(convex toward primary)
Equivalent prime focal length	42.81"	(f/4)
Equivalent Gregorian focal length	256.86"	(f/24)

Diameters.

Front aperture of the corrector may be stretched a little larger than the specified 10.70", but provision should be made for adequate mounting.

Back aperture of corrector, considering 2.5 degrees off-axis rays and 10.70" front aperture, is 11.0" (10.95" for axial rays). Primary mirror aperture for axial rays is D_2 − 11.28" (12.5" with standard Corning blank).

Secondary aperture is 2.89" for axial rays.

Hole in corrector is optional, depending on the secondary mount (H_1). Hole in primary is 2.5" for half degree field (H_2).

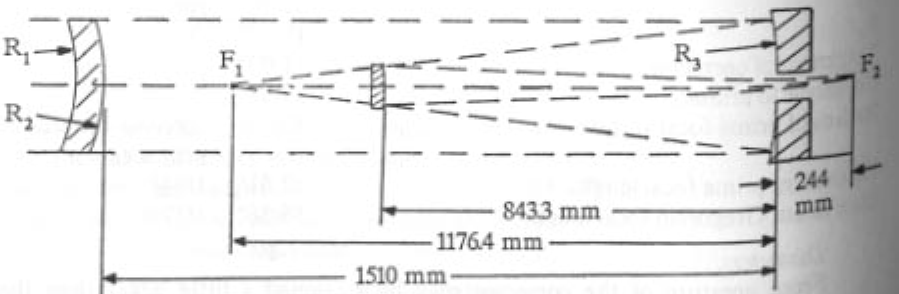
Comments. The aim was to give the best prime focus images over a 5° field. A 4" circle of film cut from a 4 x 5 cut film will cover close to 5° at prime focus with 19.9% vignetting at the edge of the 5° field. This should hardly be apparent on film since 19.9% loss represents only about 0.08 stellar magnitude.

The film-holder assembly can be supported from one side of the tube by means of a single, stiff vane, connected at its outer end to a flat metal plate. This plate, which carries the support vane and film-holder must fit a socket of kinematic design so that it may be replaced exactly in the same position after each use of the Greg. focus. The assembly should be equipped with a combination focus and temperature screw, or else invar steel rods must be used as separators between mirror and film.

The secondary is a simple ellipsoid with foci 11.5 and 69.0 inches from its vertex, giving an amplifying ratio of 6. It can be ground on a standard 4¼" pyrex blank and easily figured by the null method with slit at one focus and knife-edge at the other. It should be edged, before figuring, to a maximum of 2.89 inches for full axial illumination, and can accordingly be left permanently in its adjustable cell (fastened through the hole in the lens) because it will obstruct no additional light when the prime focus is used.

I had hoped for a Gregorian focus shorter than f/24, but this seems to be impossible without putting the secondary too close to the corrector for an adjustable cell, or shortening the space between the primary mirror and secondary focus. f/24 will give good high power views, but lower powers will require special long-focus eyepieces.

MAKSUTOV-CASSEGRAIN VISUAL TELESCOPE
by A. M. Crooker, PhD



The Corrector.	R_1	−428mm	Aperture 279mm
	Thickness	27mm	
	R_2	−444mm	
	Glass	BSC-2	
The Primary.	R	−2305mm	Aperture 318mm
	Focal length of corrector and mirror	1120mm	
	f/4 at prime focus		
	e.f.l.	3823mm	(150.5")

General.

Field of view 33'	1.5" eyepiece	88.4x	EP'	3.17mm
" 22'	1.0" "	132.5x	"	2.11mm
" 16'	.75" "	176.8x	"	1.58mm
" 11'	.50" "	265 x	"	1.06mm
" 5'	6mm "	560 x	"	0.50mm

Radius of Petzval surface at prime focus 1116mm (convex to incident light).
Radius of Petzval surface at secondary focus −842mm (concave to incident light).

Comments. Since the ray parallel to the axis through the margin of the corrector strikes the primary at a height of about 140 x 1.04935, or 147mm, and the primary has a nominal radius of 6¼", or 159mm, that leaves an angle of 12/1510, or 45° before any vignetting whatever occurs (.008 radians).

Concerning the secondary, it requires a radius of 140 x .2857883, or 40mm to look after the axial fan, and an extra .008 x (1120 − 320), or 6.4mm, to look after .45° without any vignetting. However, I believe that most amateurs would prefer to settle for a little vignetting in the intensity near the field edges for better axial intensity and have therefore suggested a secondary of 3¼" diameter (82.5mm) held in a mirror cell of 3¼" dia. This reduces the axial light loss to a minimum (10%). Regarding the hole in the mirror, since the e.f.l. of the total telescope is 3823mm and the primary can look after a field angle of .45°, the image height is .008 x 3823, or 30.6mm. This would require a hole of approximately 2½" diameter, although 2¼" would probably fill the bill nicely.

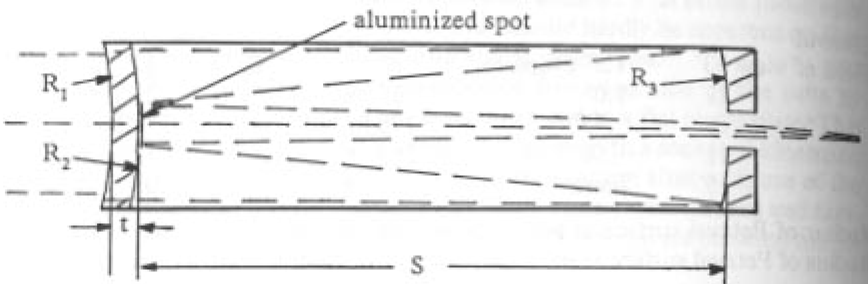
On my sketch of the optical assembly I have added some slide-rule calculations of the real field of view with modern good eyepieces, and have also calculated the diameters of the exit pupils.

Possibly I should say a word to justify my use of a telephoto ratio of 3.25. My own feeling is that this is already higher than is good for amateurs to shoot for. You will notice that the light still has a long way to go after striking the secondary, and unless you are prepared to settle for a spherical surface (even then higher telephoto ratios are bad), the lower you hold this ratio the easier it is to make and the better the results.

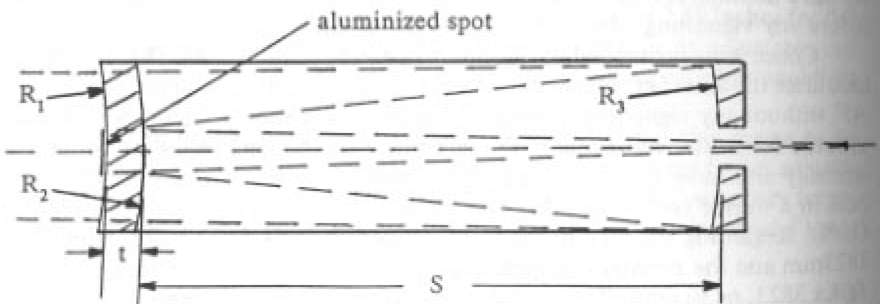
I had thought of modifying the design to cut down on the 333mm of dead-space between the corrector and the prime focus. One should keep the prime focus available for photography at f/4, so at best you could shorten the 'scope by only 20cm, or 8".

TWO 6" MAKSUTOV-CASSEGRAINIAN VISUAL TELESCOPES
by R. G. Hires

Single-Pass Design.



Double-Pass Design.



Specifications.

Single-pass	Clear aperture	6.00"
Corrector glass	BSC-2	
R_1		−7.553"
R_2		−7.830"
Thickness, t		0.475"
R_3		−37.110"
Separation, S		15.574"
Cass. focus		f/20
Double-pass	Clear aperture	6.00"
Corrector glass	BSC-2	
R_1		−7.553"
R_2		−7.830"
Thickness, t		0.475"
R_3		−37.110"
Separation, S		15.242"
Cass. focus		f/20

Comments. This design originally started as an attempt to satisfy my curiosity about an area of ray-tracing which I hadn't previously tried. What started off as idle curiosity ended up after months of evening work with something I can say with satisfaction is my own. I also ended up with reams of used paper, a book of trig. functions to 10 places, and a new calculator.

Using Maksutov's thickness and radii formula for minimum chromatic aberration, a negative lens of very long focal length (about f/150) is evolved which gives the object distance to the main telescope mirror. A certain amount of trial and error procedure allows a choice of R_2 which must also serve as the Cassegrainian amplifying mirror, and once R_2 is chosen, R_1 and thickness more or less fall into line. As John Gregory has pointed out, page 63 of *ATM I* gives approximation formulae for the Cassegrainian system including component separation, main mirror radius and back focal distance. From this point on, the process consists of tracing a marginal ray as well as one coming close to the secondary spot. When these two rays, after many trial and error procedures, can be made to intercept at a common point which would also be an acceptable back focal distance, then more rays are traced (I used 9) to give a good picture of the longitudinal spherical aberration. When the zonal aberration has been found to be of reasonably small value, several appropriately chosen rays are again traced through the system but this time using a different index of refraction for the corrector. This affords a look at the remaining longitudinal color aberration. This is called the color check.

A slight readjustment by moving the components closer together allows the secondary spot to be placed on the first surface R_1, instead of R_2. The resulting aberration curve is left essentially unchanged from the original; to me this was somewhat of a surprise. The shift in separation was changed to maintain the same overall f/ratio as in the original version.

One might question the advantage of having the light make a total of three passes through the lens with the attendant loss from absorption. But this loss is small and the advantage is that of having a truly spherical reflecting surface, no matter how thick or uneven the aluminum coating is applied. I have had too much trouble already from poor aluminizing jobs! I might mention that the result of any high or low area in the aluminum spot on R_2 is magnified by between 40 and 50 times back at the focus. Another advantage would be of having the aluminum spot on R_1 painted over and thereby indefinitely protected.

So far as these ray-traces are concerned, they show a system which is corrected to a very small fraction of the Rayleigh quarter-wave tolerance. Aspherizing the mirror would, of course, further improve the performance, probably more so in an aesthetic sense than in a practical one.

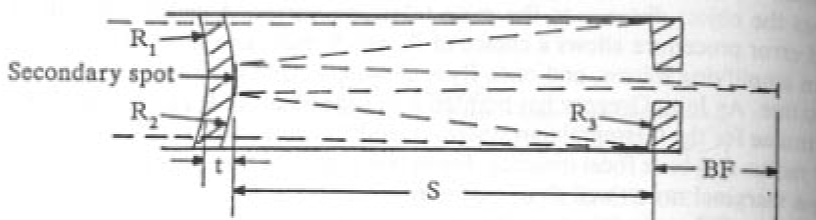
The telescope, like others of its kind, has a very small field (½ degree, or so) and consequently suffers very little from coma or astigmatism. With such small fields, it does not seem worthwhile to ray trace off axis—at any rate, I didn't do it.

The design of the corrector stemmed from the standard formula for thickness:

$$t = \frac{(R_2 - R_1)\, n^2}{n^2 - 1}$$

After all the work, I consider it a relaxing way of getting away from other problems.

A "MAVERICK" MAKSUTOV
by John McQuaid



Specifications.

R_1	13.305"
R_2	13.590"
Thickness	0.5"
Separation	19.188"
R_3	49.250"
Distance BF	8"
Dia. secondary spot	1.32"
Dia. primary perforation	1.250"
E.F.L.	133.125"
Clear aperture	5 7/8"
Dia. of primary	6"

N.B. This design must be aspherized under autocollimation for good results.

Comments. I have called this a "maverick" Maksutov because I designed it without any ray trace—I simply combined Wright's formulae for color correction in Book III, *A.T.M.* (and I hope this also includes coma!), with the usual old Cass. formula; anybody can do it and, in fact, I wonder why some TN has not done it long ago. I paid no attention to aperture and diameter and used a slab of BSC-2 which I happened to have on hand.

The first telescope was made mostly as an experiment but after aspherizing, it worked so well that I made another just like it. The aperture and primary diameter may well be off, but both these Maks beat a really good (1/20th wave) Newtonian hands down so far as seeing lunar and planetary detail is concerned, and the moon's edge is just as hard and crisp as in the Newt.

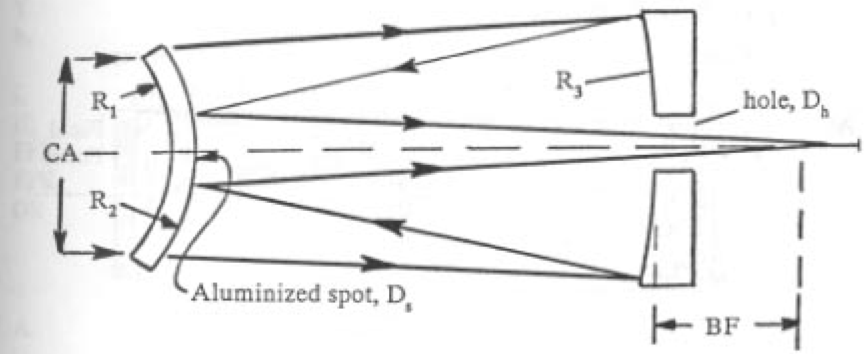
Whatever a trace may show, the design is pretty good *after* it has been aspherized. The lens blanks were of the usual BSC-2, same indices of refraction and dispersion as in all Maks. Before aspherizing, both showed the same under-correction, rather more noticeable at the zone from the edge in to about 1", then rather gently into the center.

The easy doubles such as ϵ Lyrae are a cinch—you could drive a load of hay between the 2 and 3 second pairs. The companion of Polaris was very easy—this was seen several times when a Newt. of known high quality failed to resolve it.

These two "bastard" Maks showed themselves to be superior to the Newt. and *especially* on planetary detail; it is in this phase of celestial observing that the absence of the metal spider becomes most valuable.

Incidentally, when I am trepanning the lenses, (always after roughing out), I use a wooden nest for holding the glass (concave side downward) and a carbid tipped boring cutter for taking out the slight taper left by the biscuit cutter and carbo.

8" MAKSUTOV-CASSEGRAINIAN WITH QUARTZ OPTICS
by Philip H. Morgen



Specifications.

Clear aperture	8"
Corrector	material fused silica (458675)
	N_c=1.4564, N_d=1.45843, N_f=1.4632
	R_1= 12.1652"
	R_2= 12.5847"
	Thickness = .775"
Secondary (aluminized spot) D_s=1.750" dia.	
Axial separation of mirror and corrector S = 27.240"	
Primary	R_3=64.000"
	central hole D_h=1.750" dia.
	mirror dia. = 8.750"
Back focus (to best focal point) = 5.918"	
Effective focal length	197.103"
Optical speed (f/ratio)	24.638

Note: This design is for amateur use only, all commercial rights are reserved.

Aberrations.

1. Angular spherical aberration = .208 secs of arc (max.)
2. Angular chromatic aberration = .260 secs. of arc (max.)
3. Angular sphero-chromatic aberration = .216 secs of arc (max.)

4. Chromatic difference of magnification = .079" (.040% of F)
5. Deviation from coma-free principal surface radius
   Coma = .250" (.127 of R) max.
6. Deviation from coma-free principal surface radius for 60% versus 100% zones, coma = .040" (.020% of F)

MAKSUTOV-CASS.-PRIME FOCUS TELESCOPE

by Jacques Labrecque

The Mak-Cass-Prime Configuration

a) The Cassegrain version

b) The Prime-Focus version

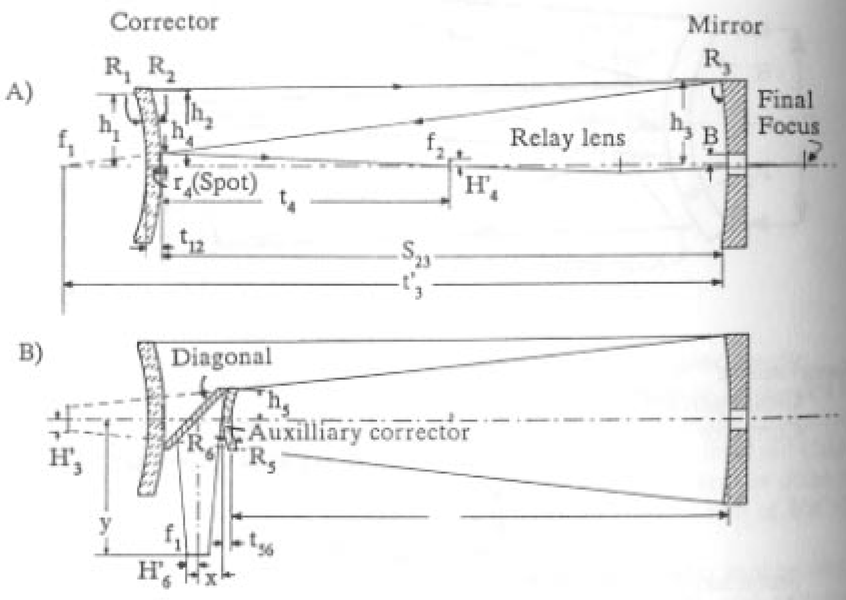


Table 1. Physical Dimensions (inches.)

A.	Cassegrain version.	C.A. = 8.34
h_1	semi-aperture of corrector (C.A./2)	4.17
R_1	radius of curvature of 1st lens surface	13.460
t_{12}	central thickness of corrector	0.665
R_2	radius of curvature of 2nd lens surface	13.844
S_{23}	corrector-mirror separation	33.20
R_3	radius of curvature of mirror	75.00
h_3	semi-aperture of mirror	4.33
R_4	same as R_2	13.844
h_4	semi-aperture of spot (R_4)	0.66
l'_4	separation of focal plane and R_4 (back focus)	−16.832
H'_4	semi-diameter of usable focal surface	0.50 (0°.4 total field)
B	semi-diameter of mirror perforation	0.72
OR	obscuration ratio (h_4/h_1)	17%
EFL	equivalent focal length	126.80
EFR	equivalent focal ratio	f/15.2
B.	Prime Focus Version.	
S_{35}	separation, mirror to auxiliary corrector	29.00
R_5	radius of curvature, auxiliary corrector (conc.)	−7.88
t_{56}	central thickness, auxiliary corrector	0.500
R_{56}	radius of curvature, auxiliary corrector (conv.)	−7.85
X	separation from vertex of R_6 to center of diagonal	1.80
Y	separation from optical axis to prime focus (f_1)	7.23
h_5	semi-diameter of auxiliary corrector	1.60 (for 1° semi-field)
l'_6	back focus of corrector (X + Y)	9.0305
H'_6	semi-diameter of flat focal surface for 1° off axis	0.65
EFL	equivalent focal length	37.20
EFR	equivalent focal ratio	f/4.46
OR	obscuration ratio (h_5/h_1)	37%

Table 2. Aberrations and their Tolerances (inches.)

A.	Cassegrain version.	C.A. = 8.34
LA'_{4m}	marginal spherical aberration	−0.0088
LA'_{4Z}	zonal spherical aberration	0.0063
Tol. (LA'_4)	tolerance spherical aberration	0.1000
OSC'	offence against sine condition	0.00027
$l'_F - l'_C$	marginal chromatic aberration	−0.0019
$l'_F - l'_C$	paraxial chromatic aberration	0.0040
Tol. ($l'_F - l'_C$)	tolerance chromatic aberration	0.0250
$Coma'_s$	sagittal coma	very small
Ast.	astigmatism	very small
B.	Prime Focus Version.	
	(1) Without auxiliary corrector.	
LA'_{3m}		0.0085
LA'_{3z}		0.0052
Tol. (LA'_3)		0.0070
$Coma'_s$	1.5 degree off axis	−0.0009
x'_{s3}	(sag of sagittal astigmatism) field conc.	0.0138
X'_{t3}	(sag of tangential astigmatism) towards eyepiece	0.0077
$Ast._3$	astigmatism	0.0061
DCL_3		0.0007

(2) With Auxiliary Corrector

LA'_{6m}	marginal spherical aberration	−0.0002
LA'_{6z}	zonal spherical aberration	0.0008
Tol. (LA'_6)	tolerance spherical aberration	0.0104
OSC'	offence against sine condition	−0.00079
$l_{F6}-l_{C6}$	marginal chromatic aberration	−0.0020
$l_{F6}-l_{C6}$	paraxial chromatic aberration	−0.0028
Tol. $(l'_{F6}-l'_{C6})$	tolerance chromatic aberration	0.0025
$X'_{s6}=l'_{s6}-l'_6$	sag of astigmatic focal line (sagittal)	(on axis)
$X_{t6}=l'_{t6}-l'_6$	sag of astigmatic focal line (tangential)	(on axis)
$X'_{s6}-X'_{t6}$	astigmatism (astigmatic difference)	
Upr_1	off axis angle of incoming ray	
DCL	disc of least confusion due to astigmatism	

Upr_1 (degrees)	X'_{s6}	X'_{t6}	Astig.	$Coma'_s$	DCL
0.5	0.0008	−0.0006	0.0014	−0.00024	0.00016
1.0	0.0030	−0.0026	0.0056	−0.00047	0.00063
1.5	0.0066	−0.0061	0.0128	−0.00067	0.00140
2.0	0.0116	−0.0116	0.0232	−0.00082	0.0026
2.5	0.0178	−0.0197	0.0375	−0.00087	0.0042

Comments. While studying some of the many mirror-corrector combinations possible with a Maksutov telescope, one is struck by the fact that all solutions for the possible different systems are continuous but have varying degrees of aplanatism (freedom from spherical aberration and coma). This means that an f/15 Mak.-Cass. may be made with a mirror of fixed radius but correctors of various curvatures, provided that the separation is changed to preserve the desired focal ratio while admitting that the secondary focal plane may be located anywhere outside or inside the system.

It is a fact of common knowledge that if the secondary focus comes closer to the secondary mirror, the focal plane will be better corrected for all aberrations except field curvature. This, in turn, implies that the secondary focus should be re-imaged by a relaying system to the final focus outside the primary (Dall, Bulletin C, *Sky & Telescope*, p. 31). Barring the difficulty of transporting the secondary focus to a final focus with the help of ordinary small achromats, the final focus should be highly corrected with a system made only of true spherical surfaces. This is a net gain that overweighs the slightly longer tube-length that is necessary. While examining the different solutions possible, I was naturally tempted to see what was happening to the latent prime focus of the instrument.

In the system designed by John Gregory (published in *Sky & Telescope*), when scaled up to a C.A. = 8.34 inches at f/15, the spherical aberration (LA'_4) at the secondary Cass. focus lies just outside the Rayleigh tolerance, therefore one of the elements needs to be re-figured. In the same version, the spherical aberration at prime focus (LA'_3) is some twelve times outside the tolerance and no use can be made of the prime focus! It has been stated that a Mak-Cass could become a convertible by changing the primary mirror to another one of slightly different radius and adding a diagonal to bring the prime focus out of the main tube. Although this

is very true, it entails making another primary of fairly large dimension and finding a means to effect the change-over without disrupting the sensitive alignment of the Mak-Cass.

In the final range considered, from f/4 to f/5, and by adjusting the parameters, it is possible to get a prime focus having spherical aberration lying close to the Rayleigh limit while the secondary focus is three to four times inside the tolerance at f/15 for a system with a C.A. = 8 inches. This gave me the idea to develop a Mak-Cass telescope usable at prime focus by the introduction of a diagonal situated close to R_2, between corrector and mirror. At f/4.5 such a system would work well as a rich-field telescope while the removal of the diagonal would restore the Cassegrain function: the prime focus turns out to be quite aplanatic and, in that respect, quite superior to a Newtonian.

One may go further and add, in the beam converging towards the prime focus, a small auxiliary meniscus whose purpose is to correct the residual spherical aberration. This small auxiliary corrector may seem to add great complication but it is, in fact, an easy one to fabricate as its radii and distance from the primary are not too critical. It is of weak positive power with the concave (R_5) surface directed towards the primary; moreover it can be made at any time after the regular Mak-Cass combination has been in operation. It does bring spherical aberration and coma to insignificant values and the instrument at prime focus can properly be called an aplanat over a reasonable field. Its only drawback lies in the fact that it alters the excellent achromatism of the regular Maksutov: it does introduce longitudinal chromatic aberration of the ordinary kind whose largest amount is in the paraxial region and lies barely outside the tolerance for color.

Astigmatism is the only aberration that limits the field; its disc of least confusion (DLC) at 2.5 degrees off axis, for C.A. = 8.3″, at f/4.4, reaches 0.0040 inch, a value noted by Conrady as giving good definition. The interesting part of it turns out to be that the curves of tangential and sagittal astigmatism are such as to fall on opposite sides of the flat surface passing through the best on-axis focal position. This implies the introduction of a small meniscus results in the instrument becoming a flat-field telescope or camera possessing the same qualities as the Wright (short) telescope to such an extent that its astigmatism fits rigorously an astigmatism curve. The rationale is that a large negative meniscus plus a small positive one become equivalent to a deep Schmidt plate but without the figuring complexities of the latter. The introduction of the auxiliary corrector has permitted, to a certain extent, the use of "bending," reducing spherical aberration at the Cassegrain focus so that now the two foci yield excellent images, as can be seen in table 2.

From table 1, one can see that the obstruction ratio at the Cassegrain function is about 17%; that, coupled with the feeble aberrations, should give excellent definition and contrast. For the corrected prime focus, one has a choice of auxiliary corrector and diagonal size; for visual use they can be small, but if the instrument is to be used as a camera they should be 37% of the clear aperture for full illumination over a 2° field, and 43% for 3°. An obstruction ratio of 40% would be a good average for a total field of 5°.

In table 2 aberrations are also listed for the uncorrected prime focus. One can see that for an aperture ≤ 6.3 inches the spherical aberration lies on the tolerance, hence a good visual instrument is possible.

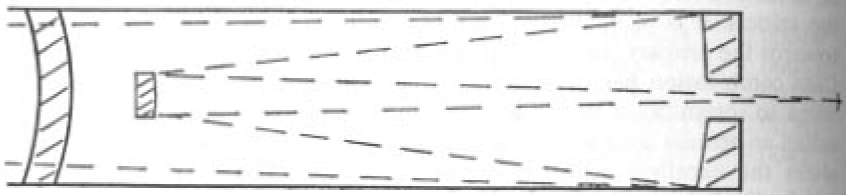
Details on how to mount the auxiliary corrector are left to the builder; it would seem preferable to mount the small meniscus and diagonal as a solid assembly held by spiders on a large ring that could be quickly inserted in the main tube.

The advantages of this telescope are:

1. Its two functions.
2. Lack of aspherical surfaces.
3. Excellent imagery at either function.
4. Its flat field at prime focus.

MAKSUTOV-CASSEGRAIN DESIGN AT f/15

by Harrison Sarrafian



Specifications.

CA	clear aperture of correcting lens			11.0
BA	back aperture of correcting lens			11.23
R_1	radius of curvature of 1st corrector surface			−16.630
R_2	radius of curvature of 2nd corrector surface			−17.175
d_1	center thickness of corrector			0.946
	Corrector lens material BSC−2	n_d=1.517	V=64.5	
d_2	separation of corrector and primary			33.486
R_3	radius of curvature of primary mirror			−83.0
$(DM)_o$	diameter of portion of primary mirror illuminated by on-axis light			11.388
d_3	separation of primary and secondary			31.645
R_4	radius of curvature of secondary mirror			−28.0
D_S	diameter of secondary mirror			2.840
BFL	back focal length			42.6
EFL	effective focal length			165.
EFR	effective focal ratio			15.0
ϕ	field of view			1.0 degree

(Unless specified, all dimensions are in inches.)

Comments. The Maksutov-Cassegrain telescope has enjoyed a substantial amount of popularity among both commercial telescope manufacturers and advanced amateurs who desire a telescope of high performance in a compact size.

In addition to compactness, the reasons for this popularity include the advantage of a closed tube, freedom from visual chromatic aberration, and comparative ease in fabricating the corrector which can use spherical surfaces.

However, astronomical telescopes of this kind generally have used a secondary mirror consisting of a spot aluminized on the rear surface (or occasionally on the front surface) of the correcting lens. Such an approach provides a simple solution to the problem of fabricating a secondary mirror by eliminating the need for grinding and polishing another optical surface. Unfortunately the telescope builder must pay a very substantial price in performance in exchange for this convenience. As we shall see, this sacrifice in performance results from lack of flexibility in varying telescope parameters (i.e., radii, separations, etc.) which is forced on the designer when the secondary is made coincident with one of the corrector surfaces. As a consequence of such a compromise, the designer must accept the following limitations in a Mak-Cass with the secondary spot on one of the corrector surfaces:

1. Comparatively large amounts of residual coma which will typically be several times as great as that obtained with an ordinary Cassegrain or Newtonian of the same effective focal ratio.

2. Substantial residual spherical aberration which may necessitate aspherizing one of the optical surfaces in the telescope unless the effective focal ratio is quite large.

3. An extremely fast primary mirror in conjunction with a high secondary amplification ratio. Both of these factors impose severe collimation tolerances which are difficult to achieve and maintain, especially in a portable instrument. In addition, the high amplification ratio will result in increased amplification of zones and small scale roughness on the primary mirror. The result will be a decreased intensity of the Airy disc in the diffraction pattern produced by the telescope and increased brightness in the surrounding diffraction rings. Consequently, the contrast on fine lunar and planetary detail will be reduced. It is likely that this effect will more than offset any contrast improvement afforded by the somewhat smaller obstruction ratios made possible by the higher secondary amplification ratios, with the result that substantially lower contrast on planetary detail would be obtained with the conventional Mak-Cass using a spot secondary, even when it has been carefully figured and collimated.

In order to understand more fully the severe design constraints imposed by a spot secondary, let us examine a typical procedure which a designer might follow in developing a Mak-Cass design. First, the effective f/ratio is selected and a simple Cassegrain is roughed out, based upon such considerations as maximum allowable obscuration ratio, distance of focal plane behind the primary mirror. This establishes approximate values for R_3, R_4 and the separation between the primary and secondary. However, if a spot secondary is used, this *also* establishes R_2 (or R_1 if it is a double-pass system) *and* the position of the corrector, making it impossible to vary these parameters in order to reduce residual aberrations.

Next, the designer uses the paraxial achromatization formula:

$$\frac{\Delta R}{d_1} = \frac{n^2 - 1}{n^2} \qquad (\text{where } \Delta R = R_2 - R_1)$$

to establish the approximate value of the ratio $\Delta R/d_1$. (This value may be refined later during the ray-tracing process to achieve a common focus in C and F light close to the 70.7% zone.) Finally, the design is ray-traced with different trial values of ΔR and d_1, until the combination yielding minimal residual spherical aberration is found.

We see therefore that in reality only one parameter ΔR (or d_1, depending on which is chosen as the independent variable) is variable. This is due to the fact that the other parameters have already been established by practical constraints, i.e., focal plane position, obscuration ratio, primary f/ratio, etc. Such a situation enables the designer to minimize residual spherical aberration, but does not give him any means for correcting coma. In addition, the residual zonal spherical aberration will be quite large and may exceed the Rayleigh tolerance. Residual coma, which cannot be reduced owing to the aforementioned restraints will be very substantial and will be several times as great as the coma obtained with an ordinary Cassegrain or Newtonian of the same f/ratio. This problem has been rather dramatically portrayed by Ronald Willey (*Sky & Telescope*, April 1962, pp. 191-193), which compares off-axis spot diagrams of several compound telescopes, including the Gregory f/15 design. The disappointing spot diagrams have probably disillusioned many amateurs concerning Maksutov telescopes in general, which had been reputed to be highly corrected optical systems.

Unfortunately the design compromises associated with the use of a spot secondary, generally have resulted in Mak-Cass designs which fall far short of achieving the performance of which the Maksutov concept is capable. The only exception known to the writer is the excellent design by Jacques Labrecque (described earlier), which is also the only convertible Maksutov which has good aplanatism at both foci. The compromises in using a spot secondary were largely circumvented by allowing the Cassegrainian focus to fall between the primary and secondary. This permits the designer to "bend" the corrector as well as varying ΔR and d_1, and thus allows more latitude with which to reduce aberrations further. However, a focal plane situated inside the optical system requires the use of a relay lens to transfer the image outside where it will be accessible to the observer. While there are some who favor the use of a relay lens as advocated by Horace E. Dall, and indeed it does provide a very effective method of stray light suppression, the relay lens will introduce aberrations of its own which are substantial. This is due to the fact that the relay lens must be of very short focus and large in diameter and operate at large angles off-axis. The high dioptric power of such a lens will generally result in a highly curved Petzval surface which in turn results in a large amount of field curvature, astigmatism, or both.

All-Spherical Maksutov-Cassegrains Employing Separate Secondaries.

An obvious solution to the difficulties encountered in using a spot secondary is the use of a separate spherical secondary. Such an alternative provides the designer with the following advantages:

1. It is now possible to "bend" the corrector as well as varying ΔR and d_1 in developing the design for minimum aberrations. This is due to the fact that it is no longer necessary that one of the corrector surfaces has the same radius of curvature as the secondary.

2. It is possible to vary the position of the corrector while leaving the secondary fixed.

3. It is possible to use a comparatively slow primary mirror and a conservative amplification ratio, resulting in much less critical collimation tolerances and a reduction in the amplification of primary mirror defects which is aggravated by a large secondary amplification. Such a conservative design cannot be corrected for spherical aberration if a spot secondary is used, since the large value of R_4 required results in a corrector which is much too weak. It could be corrected, of course, by using an ellipsoidal primary.

Design.

The design is an f/15 Maksutov-Cassegrain utilizing a separate secondary. It was developed by means of a computer ray-trace program. The design was carefully optimized by iterative ray-tracing in order to achieve the best possible correction for spherical aberration, coma and color within the scope of practical dimensional constraints. The degree of improvement afforded by the separate secondary exceeded expectations and indicated that coma and spherical aberration can be reduced to less than one-tenth of the residuals obtained with a spot secondary design whose Cassegrainian focus lies behind the primary. The residual spherical aberration is less than one-fifth of the Rayleigh tolerance in the 11" size, with all surfaces spherical. Residual coma, OSC', is 0.00012, which is less than half as much as obtained in a straight f/15 Cassegrain, and less than one-tenth as much as in the Gregory f/15 Maksutov. Coma is within the Rayleigh tolerance over a field of nearly six inches in diameter (if such a large field were available for observation). For optimum color correction, the C and F lines have been brought to a common focus near the 70.7% zone, although the chromatic residual would be completely negligible without this refinement.

It should be noted that the corrector radii are close to those of many of the prime focus designs and thus may be fabricated easily from a standard 11¼" molded corrector blank. A standard 12½" pyrex blank may be used for the primary. The diameter of the hole in the primary may be made any size up to the diameter of the secondary without increasing the central obscuration. It will be possible, therefore, to cover a field almost exactly one degree in diameter if a suitably large ocular can be obtained or fabricated. Acquiring such an ocular would be very worth while and the low power views obtained would be really spectacular, since the image fidelity would be decidedly better than that provided by the more usual short focus instrument, and star images will be needlesharp clear to the field stop with a good ocular. The diameter of the secondary given here is equal to the diameter illuminated by on-axis rays only and therefore does not allow for off-axis movement of the light beam. This was done in order to keep the obscuration ratio to an absolute minimum (25.8%) for best performance on lunar and planetary objects. The vignetting introduced is utterly negligible, even for variable star work. The separate secondary also facilitates the mounting of a light baffle cone over the secondary as is done in a straight Cassegrain, although this involves a slight increase in obscuration. A suggested method for making the fabrication of the secondary easy with regard to achieving a good spherical figure on the convex surface is as follows: grind a larger blank, say 6 inches, to the desired radius of curvature and trepan a central portion equal in diameter to the desired secondary, almost through to the convex surface, and then fine grind and polish. Even if the figure is poor over the whole disc, the inner part should be excellent. I have not tried this, but it seems certain to work and in such a case would eliminate the need for testing the convex surface. It might be wise to make the secondary very slightly oversized in order to avoid any possible problem with a very thin turned edge, which might occur due to heating and expansion of the thin glass in the trepanned area during polishing. The secondary can be mounted in a machined, adjustable cell, mounted through a hole in the corrector which should be made somewhat smaller than the secondary.

It should be pointed out that this particular design can be scaled up to 12 inches clear aperture when a 12½" mirror blank is used, provided that a suitable corrector blank is available. Although (DM_o) will be almost as large as the primary, vignetting at the margin of even a 1° field will be of the order of a hundredth of a stellar magnitude, and thus quite negligible.

TWO LENS. ALL SPHERICAL CASSEGRAIN CATADIOPTRIC TELESCOPE DESIGN
by Robert D. Sigler

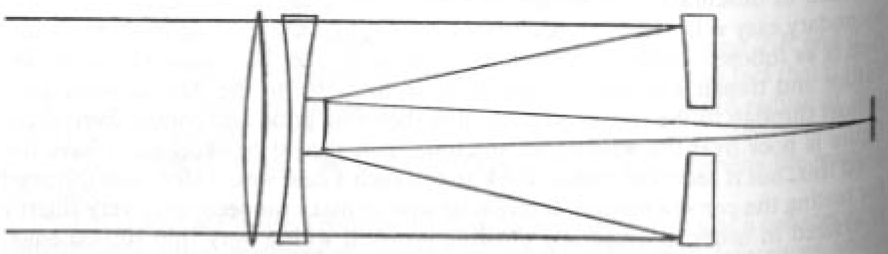
About the only real problem with large Maksutov-Cassegrain telescopes is that the cost of the corrector blank has become astronomical (pun intended!). Not only must one mortgage his soul to buy the blank, but the steep radii and tight tolerances are enough to keep you awake at night.

One solution to this dilemma is to split the Mak shell into two lenses which are both thinner and have much longer radii and looser tolerances. The three designs in this article are examples of this technique and came out of a recent session on the computer. All are anastigmats and a little faster than the usual Mak-Cass. A Schmidt-Cass. aplanat is also given.

Configuration A.

This is a nice compact design with a small secondary and excellent performance. Neither the third nor the fifth order spherical aberration is zero, but are balanced against each other such that the marginal longitudinal aberration is zero and only residual zonal aberration remains. However, this residual is about half the Rayleigh limit for this type of error and only a purist would try figuring one of the surfaces (if you *must* do it, do it on one of the concave surfaces of the corrector). The coma and astigmatism over a 2° field are trivial, resulting in essentially diffraction limited images on the Petzval image surface, which has a radius of curvature

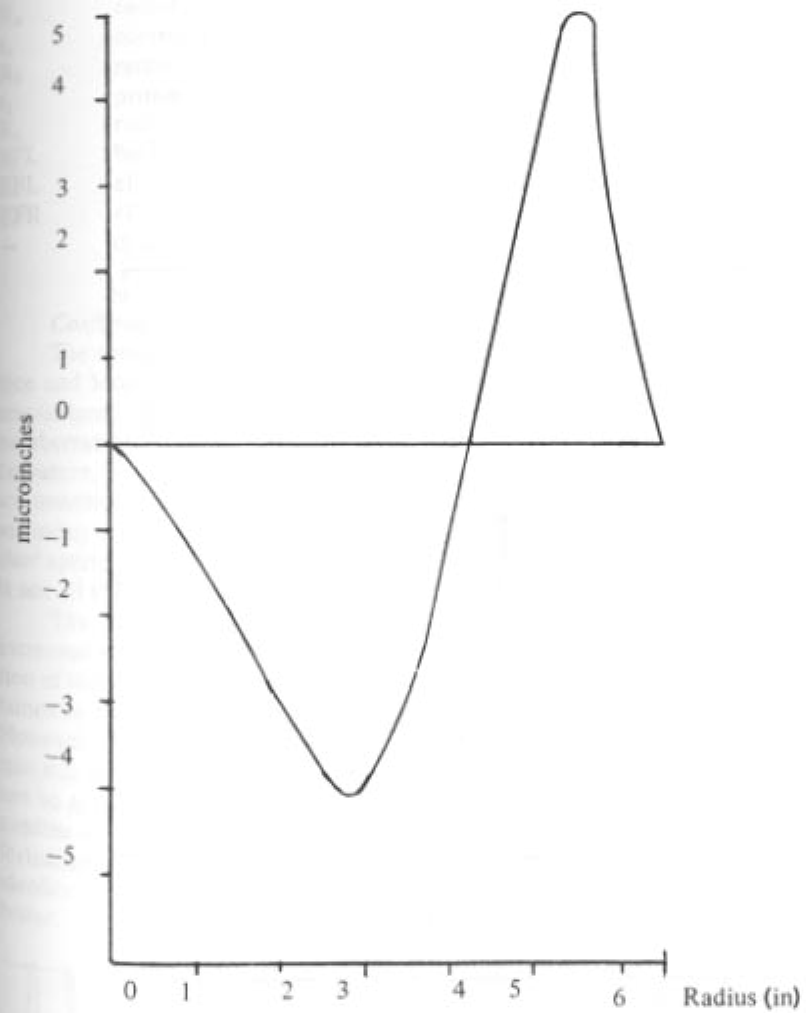
Configuration A



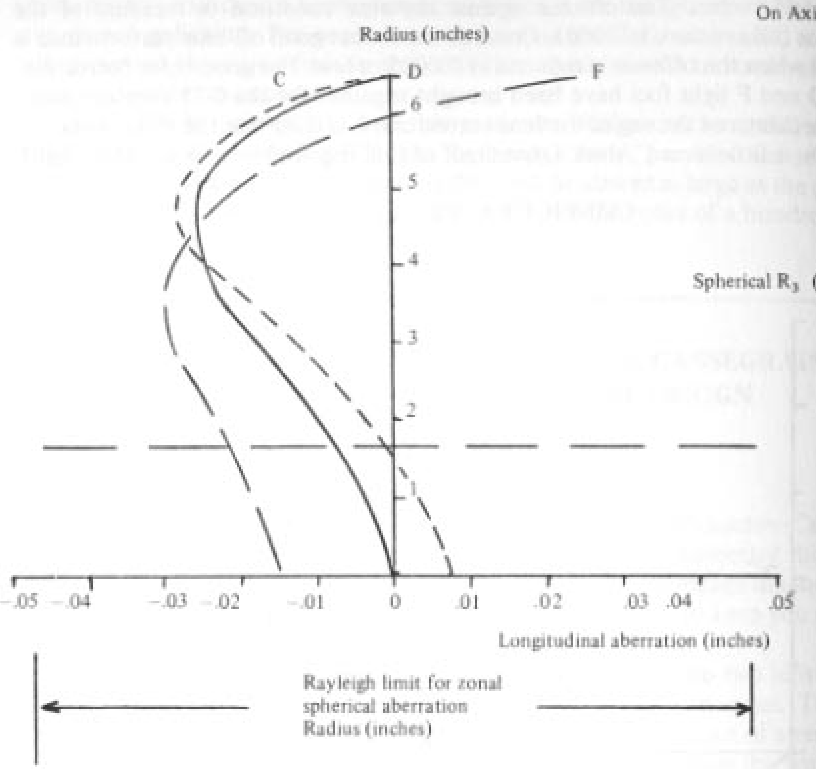
of −16.645 inches. The offence against the sine condition (a measure of the coma) for full aperture is 0.0003. Conrady states that good off-axis performance is obtained when the offence is reduced to 0.0025 or less. For good color correction, the C, D and F light foci have been brought together for the 0.71 aperture zone.

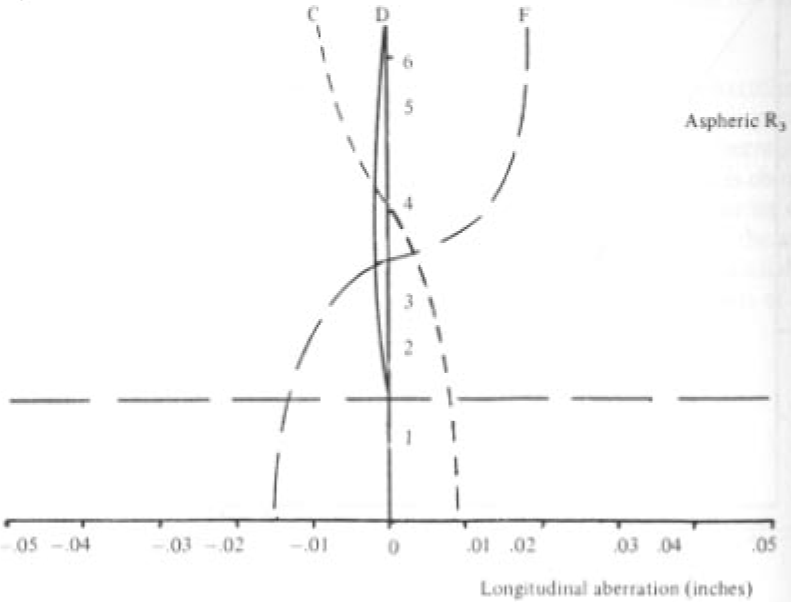
Checking out the sag of the lens correctors, it is clear that the glass blank will have to be a little over 1" thick (about half of that required by a single Mak shell).

CONFIGURATION A



Departure of surface R_3 from best fit sphere (R_3=−46.694")
for complete absence of spherical aberration (3rd & 5th order)



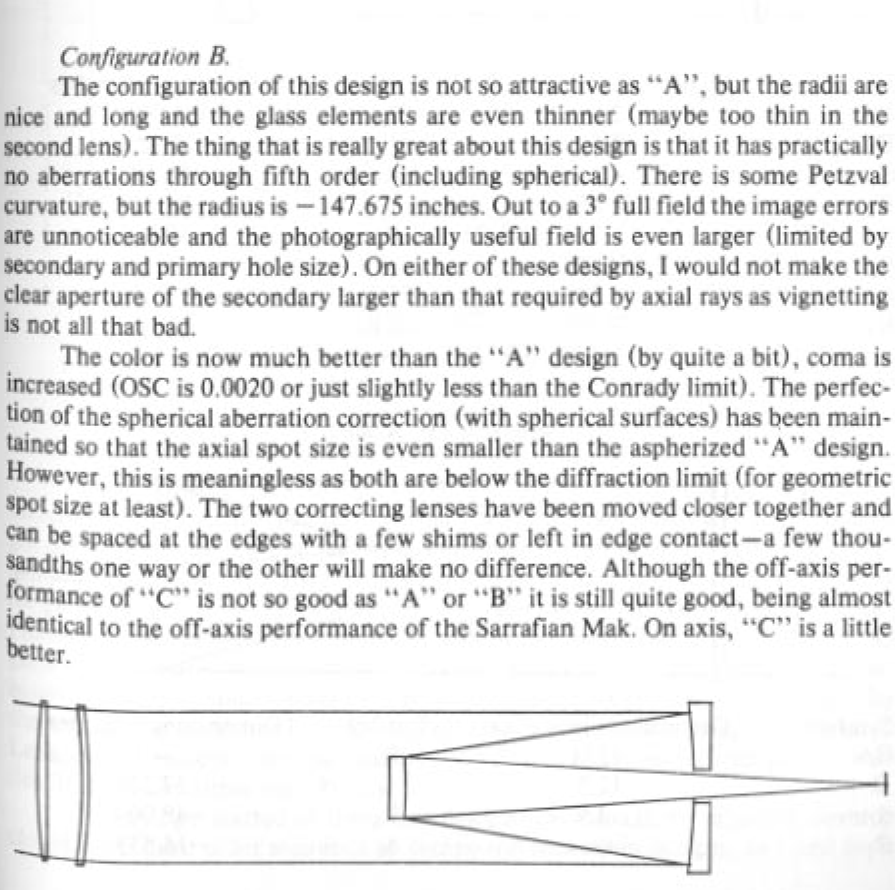


Symbol	*Description*	*Dimensions in inches*	
CA	clear aperture of correctors	12.5	
D	diameter of primary mirror	12.5	
d	diameter of secondary (axial rays)	3.3	
R_1	radius of lens No. 1	40.483	
t_1	axial thickness of lens No. 1	1.000	(BK-7)
R_2	radius of lens No. 1	−61.116	
t_2	axial corrector spacing	1.001	
R_3	radius of lens No. 2	−46.669	
t_3	axial thickness of lens No. 2	.250	(BK-7)
R_4	radius of lens No. 2	46.072	
t_4	corrector to primary spacing	22.737	
R_5	radius of primary	−58.335	
t_5	primary to secondary spacing	−21.600	
R_6	radius of secondary	−21.037	
BFL	back focal length	32.831	
EFL	effective focal length	124.504	
EFR	effective focal ratio	9.96	
—	diameter of 2° field	4.36	

Configuration B.

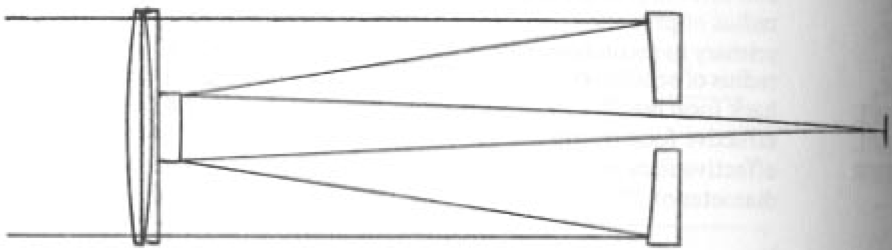
The configuration of this design is not so attractive as "A", but the radii are nice and long and the glass elements are even thinner (maybe too thin in the second lens). The thing that is really great about this design is that it has practically no aberrations through fifth order (including spherical). There is some Petzval curvature, but the radius is −147.675 inches. Out to a 3° full field the image errors are unnoticeable and the photographically useful field is even larger (limited by secondary and primary hole size). On either of these designs, I would not make the clear aperture of the secondary larger than that required by axial rays as vignetting is not all that bad.

The color is now much better than the "A" design (by quite a bit), coma is increased (OSC is 0.0020 or just slightly less than the Conrady limit). The perfection of the spherical aberration correction (with spherical surfaces) has been maintained so that the axial spot size is even smaller than the asphered "A" design. However, this is meaningless as both are below the diffraction limit (for geometric spot size at least). The two correcting lenses have been moved closer together and can be spaced at the edges with a few shims or left in edge contact—a few thousandths one way or the other will make no difference. Although the off-axis performance of "C" is not so good as "A" or "B" it is still quite good, being almost identical to the off-axis performance of the Sarrafian Mak. On axis, "C" is a little better.



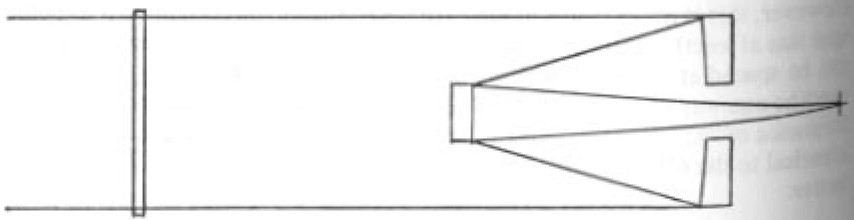
Symbol	Dimensions in inches		Symbol	Dimensions in inches
CA	12.5		R_4	−70.013
D	12.5		t_4	53.512
d	5.2		R_5	−92.871
R_1	281.965		t_5	−27.086
t_1	.650	(BK-7)	R_6	−69.710
R_2	infinite		BFL	43.533
t_2	2.389		EFL	104.828
R_3	−56.014		EFR	8.39
t_3	.280	(BK-7)	–	3.67

Configuration C.



Symbol	Dimensions in inches		Symbol	Dimensions in inches
CA	12.5		R_4	131.006
D	12.5		t_4	27.921
d	4.2		R_5	−81.192
R_1	74.855		t_5	−27.017
t_1	.750	(BK-7)	R_6	−40.019
R_2	−131.006			
t_2	.125		BFL	41.582
R_3	−74.855		EFR	10.06
t_3	.400	(BK-7)	—	4.38

Schmidt-Cass. Aplanat

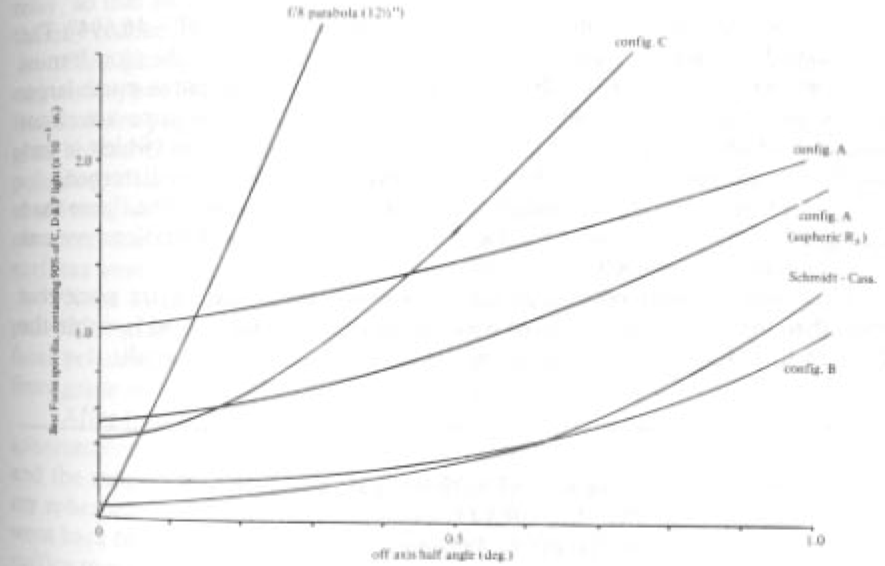


Symbol	Dimensions in inches	Symbol	Dimensions in inches
CA	12.0	R_4	—
D	12.5	t_4	37.332
d	3.9	R_5	−48.000
R_1	plano	t_5	−16.533
t_1	not critical (BK-7)	R_6	−20.914
R_2	−3324.0*	BFL	25.193
t_2	—	EFR	6.8
R_3	—	—	2.87
t_3	—		

* This is the central radius of curvature of the aspheric Schmidt plate. The total sag of the plate measured from the vertex is:

$$Z = -1.505 \times 10^{-4}y^2 + 0.2767 \times 10^{-5}y^4 + 0.9065 \times 10^{-9}y^6.$$

Half of the aspheric can be put on each side of the corrector if desired. Since the plate is nearly plane parallel, the thickness is not critical unless the vacuum deformation process is used to make the corrector, in which case the thickness will be fixed by that required for the proper deformation (less than .750 for a full atmosphere).



A few words about corrector glass cost. While I have not priced glass for these designs, I recently bought a similar blank for a Schmidt-Cassegrain. What I got quotes on was a piece of BK-7 or equivalent, 13" in diameter and 0.75" thick. Schott and Hoya wanted $180 for grade A, O'Hara (through Bourns) wanted $95 for grade A, Coulter quoted $75 for "Ophthalmic Crown" (quality?), and Chance-Pilkington (through Alpha-American) quoted $29.50 for SW-3 extra white strip glass with no striae when inspected through the face. I bought the O'Hara, but believe that the Chance would have been fine (it is available up to 1.4" thick). By the way, never try to use Deutsch Spiegel drawn sheet crown glass (from United Lens, etc.), I made this mistake and must admit that I have seen better glass in bottles. It has more striae than Pyrex.

The way I got started on these lens designs was through my efforts to develop closed form third order solutions to compound Maksutov designs, as I had done for the compound Schmidts. The problem with the Mak equations is that the thickness of the corrector is very important to its correction, and thin lens third order approximations are useless. Usually the third order residual spherical is balanced out by fifth order of the opposite sign. However, for the two-lens configurations, the lenses are in many cases thin enough for the third order thin lens approximations to be useful. This is true of configuration B and, to a lesser extent, configurations A and C. In any case, the equations I have developed are useful in finding a good starting point for optimization and can also be useful in investigating the tolerances of a system.

Some additional information on configuration A may be in order. If we decide to aspherize R_3 to eliminate the residual spherical aberration in the primary wavelength (D light), the equation for the sag of the required surface is:

$$z = -1.0707 \times 10^{-2}y^2 - 9.8752 \times 10^{-8}y^4 + 1.8772 \times 10^{-9}y^6 + 2.783 \times 10^{-12}y^8 - 6.7564 \times 10^{-14}y^{10}$$

The best fit sphere to this surface has a radius of curvature of −46.694". The departure of the required surface from the best fit sphere is as in the plot. It must be remembered that this is a refractive surface and as such requires much larger surface deformation than would a reflecting surface to effect the same wavefront change. Putting the figuring on a surface near the aperture stop (which is surface R_1) insures that the off-axis correction of the system will not be disturbed.

The plots of the longitudinal aberration are self-explanatory. The figure for a spherical R_3 (that is, all surfaces spherical), shows the axial aberrations present with a nominal R_3(−46.669").

You will probably notice that the color errors for config. A are somewhat larger than those of a well-corrected Mak. However, the color spread is within the Rayleigh limit for this error. Config. B has almost no color error at all.

A NEW CATADIOPTRIC TELESCOPE CONFIGURATION
by Donald C. Dilworth

Several years ago, while rummaging through a mountainous collection of rejected parts in the attic of a very small optics company, I discovered a wooden crate with carefully wrapped contents. These proved to be a dozen or so negative meniscus lenses, each with an inconspicuous chop or scratch.

The shop foreman recognized them, informed me that they were corrector lenses for a night vision system, and dug out a blueprint giving the exact dimensions.

I managed to abscond with several choice pieces, and the print. As is customary with scrounged parts, I then began to ponder whether they could be used, somehow, to make a telescope.

The question was put to a computer, and a configuration was found that was practically ideal for amateur use. The lens could be used as a second surface mirror: it would function simultaneously as a negative lens, thus producing positive power but negative (overcorrected) aberrations. The remarkable thing was that all the aberrations could then be cancelled out (even chromatic) by two simple lenses used as a relay system. The resulting package was mechanically convenient, shorter than a comparable Newtonian and gave, as a fringe benefit, an erect image!

The idea was forced to take a four year recess, and re-emerged with the acquisition of adequate shop facilities. Lens blanks were ordered and with the spending of actual money, the die was irrevocably cast. The ensuing month saw the manufacture of various equipment peripheral to telescope building—including a lens grinding and edging machine and a three-ball spherometer—and work began with a mechanical layout of the telescope.

The chosen configuration, which is shown in the figure, called for a hub-mounted primary, and centrally mounted secondary spiders. One advantage of using a relay system is that complete baffling can be accomplished internally to the relay, so that an exterior tube was unnecessary. Weight and wind resistance were thereby reduced.

Plate glass grinding tools were cut and edged round (the tedious edging process was skipped on the second set of lens tools with no ill effects). Grinding of the lens surfaces proved a snap—a great surprise considering that I had never ground glass before. Each surface was roughed out in but half an hour, and was ready for polishing after two more hours of the usual grinding with successively finer abrasives. A frequent check of radius was made with the spherometer, and I observed that it was easy to shorten a radius but very hard to lengthen it. So the surfaces were left very slightly long (about .001 inch on the sag) prior to polishing.

None of the celebrated contrariness was apparent in the pitch laps, which proved invariably successful (of course, I've never made a *large* one), and the surfaces polished out in about four hours. I suspect that if I had bought that one last finer grade of abrasive, it wouldn't have taken so long. Live and learn!

After finishing the second lens, the two were measured accurately on a good spherometer elsewhere; there was only a vague correlation between my readings and the supposedly good ones, with no systematic deviation. Since the design of my spherometer was faultless, I chalked it up to loose threads or something, and went back to the computer. It turned out that a slight change of one surface would suffice to give as good a design as the nominal one, and this was done. The lenses were edged and the hole bored in the primary, and the metal parts of the telescope proper were made—the conical metal pieces were hogged out of solid aluminum stock, next time I'll buy tubing! The secondary mirror was made by cutting out a circle from a large sheet of aluminized plate glass from Edmund's; of course, it isn't flat, but when tested it proved to be almost perfectly spherical, by about six fringes. Since it is used at normal incidence, this figure error is of no consequence, and it was already aluminized.

At this point, with a bad case of telescope fever to contend with, work was proceeding around the clock. I decided to silver the primary instead of getting it aluminized, since it would have a higher reflectivity and the coating would be chemically protected on the second surface. I studied *A.T.M. I* thoroughly, bought the chemicals and gave it a sporting try. Third time the coating was pretty good, and I painted the back black. The silver eventually darkened—probably due to something in the paint—and I tried a fourth time. Worst results of all. I believe that silver nitrate is haunted, and the mirror now has a shiny aluminum coating!

For testing the telescope I rigged up an earlier, Springfield mounted 'scope, as a collimator, and examined the pinhole image. Upon first assembling, I was confronted with the unhappy sight of an image degraded by something like 30 or 40 waves of undercorrected spherical aberration. The cause was eventually traced to the primary which, upon interferometric testing, turned out to have enormous asphericity—I think it was a case of gift horses! After a very gallant attempt to compensate by polishing a weak hyperbolic figure in one of the relay lenses (believe it or not, I came within half a wave!), a second meniscus lens was selected (and tested) and substituted for the first. Fine adjustment of the rearmost relay lens surface radius, by polishing for a few minutes at a time, was used to tweak up the image. The resulting wavefront is corrected to better than a quarter of a wave using all spherical surfaces. Alignment of the telescope was accomplished by performing a tilt adjustment of the secondary mirror. When out of alignment, the telescope produces a prismatic effect on an on-axis star.

The only significant defect in the present telescope is that the primary is really too thin for use as a mirror—it warped to about one wave of a cylinder. Slight pressure on the sides at two places is sufficient to restore it to a good sphere and this function is performed by two small spring clips inside the mirror cover. It requires only occasional adjustment.

A really novel feature is embodied in the lens coatings. Because of the extremely high index of refraction of the SF-6 glass used in the relay lenses, the reflection losses for four uncoated surfaces would be excessive (8.25% per surface, or total transmission of 70.86%), but when polishing, I noticed that water droplets that were left standing would make stains on the glass. It seems that a weak acid will leach out some of the elements that give the glass its high index, leaving a region of lower index at the surface. With a little experimentation I devised a procedure for giving a fairly uniform high-efficiency anti-reflection coating to the lenses: mix about 1cc of HNO_3 in water and dip the *freshly* polished surface. Agitate slightly, and in half a minute or so (don't go too long) an intense magenta color is observed in reflected light. Presto—an expensive coating! I'm still experimenting, but for certain concentrations and temperatures the reflected light is quite faint.

Most of the features of the telescope mount are obvious from the photos; both axes utilize conical spring-loaded bearings for slewing, and ball bearings (4 in. diameter on the polar axis) for fine adjustments and tracking. Home made worm gears mesh with ordinary spur gears—with satisfactory results. The yoke is made of fiberglass and epoxy, plastered over a perforated aluminum-sheet form.

The secondary supports are made of brass, which was chemically blackened. This procedure, which was devised mostly by trial and error, is this: dissolve some copper in nitric acid, dilute about 4:1 with water and add a little KOH solution. The weak blue liquid will form a whitish precipitate, with a deep blue liquid here and there. Stop adding KOH before all the deep blue liquid disappears. Then slowly add NH_4OH until most of the mixture turns deep blue. Pour this part into a shallow glass pan and heat slightly. Dip the freshly shined (steel wool is O.K.) brass parts and agitate. They should turn black in a minute or so and should then be rinsed and dried. The black so applied will withstand gentle handling. Perhaps some day a chemist will read these humble instructions and figure out what happens—I would like to know!

In the event that anyone else wants to give this type of telescope a try, design specifications are given below for a slightly modified version. The thickness of the primary is one-half inch and the image quality is about 1/10 wave.

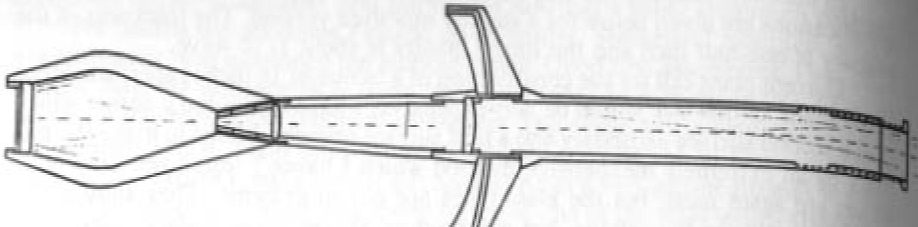
Current plans call for the construction of a 'scope of 16 inches aperture. Since a lens blank of that size would be *very* expensive, I have computed a design which uses a second surface secondary and a first surface primary. I hope to make the primary by an extremely inexpensive method which I haven't tested yet. Two relay lenses are again used, but the glass types are not so extreme. They should still stain, according to the catalog, but will produce almost no secondary color.

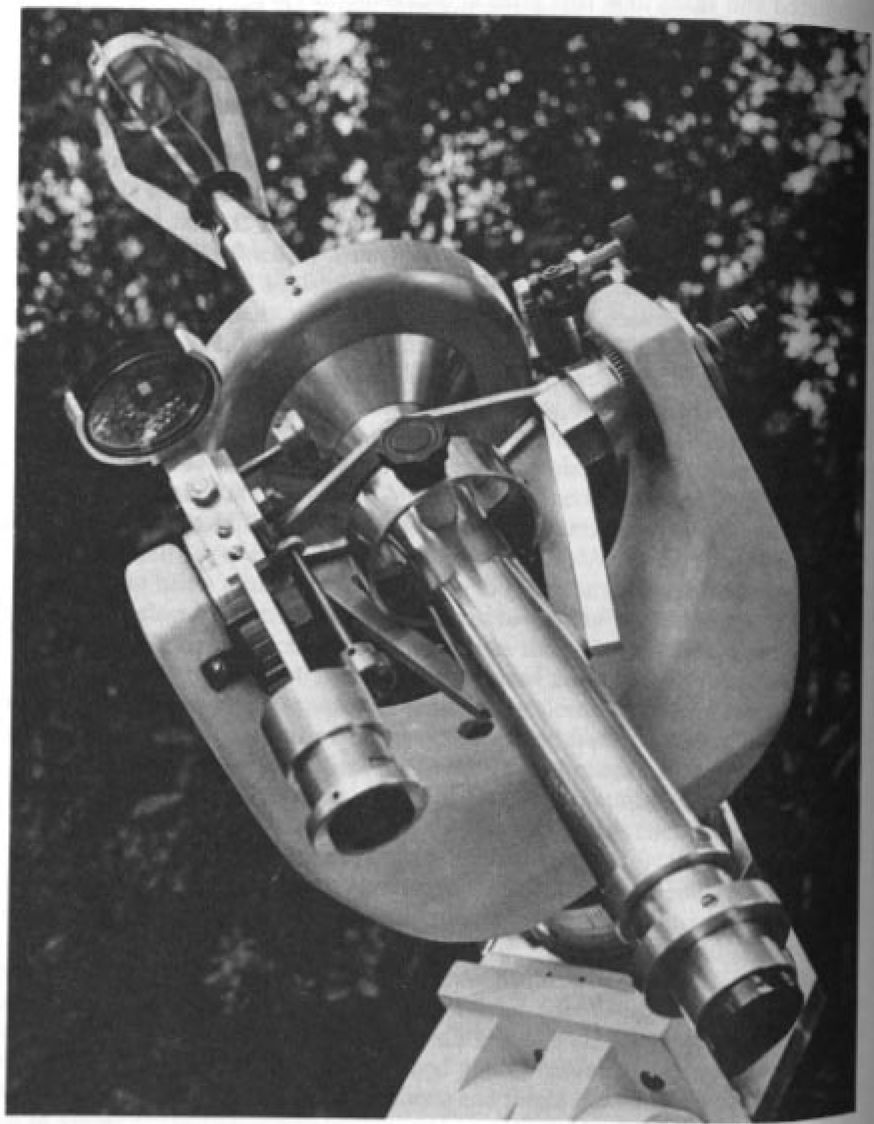
(Note by Ed.) This telescope took first prize at Stellafane. The 16" has been completed and again took first prize at Stellafane in 1976.

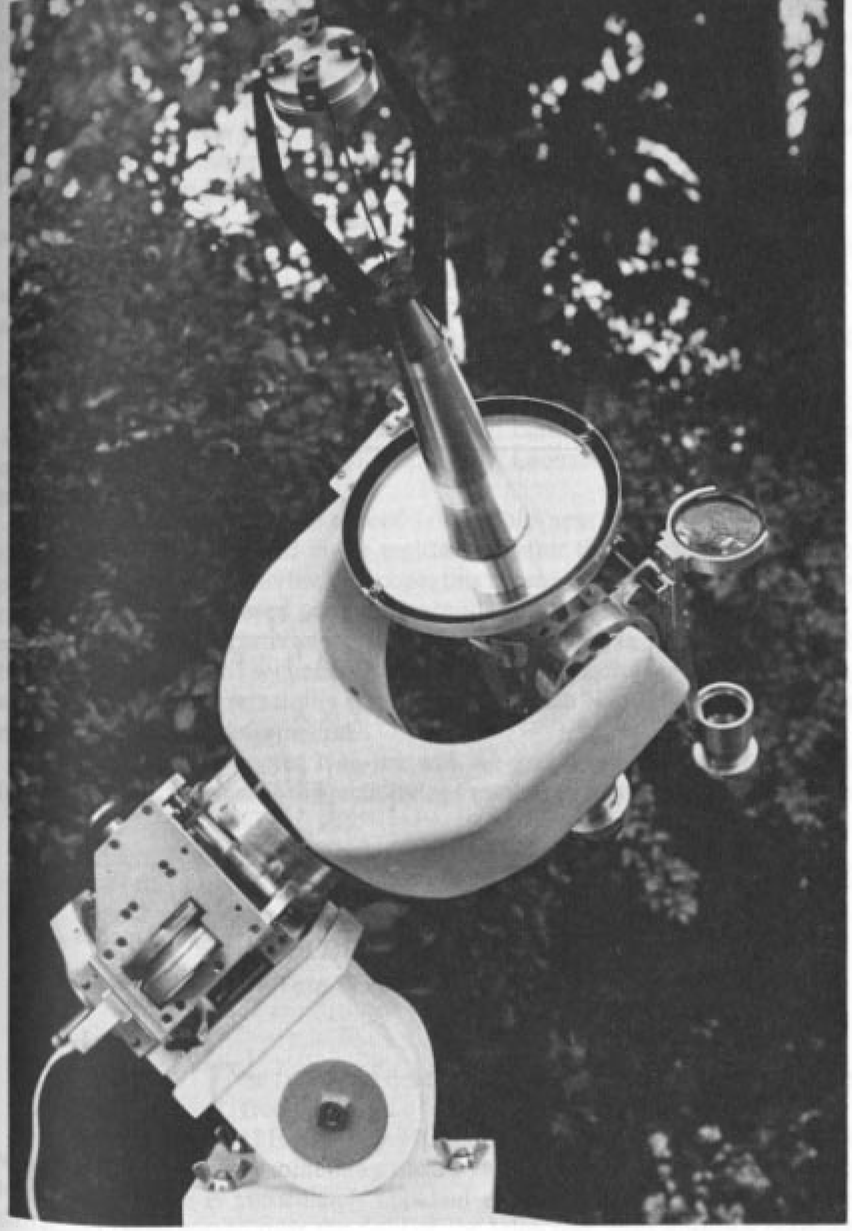
Specifications.

focal length 43.1623 aperture dia. 5.75
field of view 0.5°

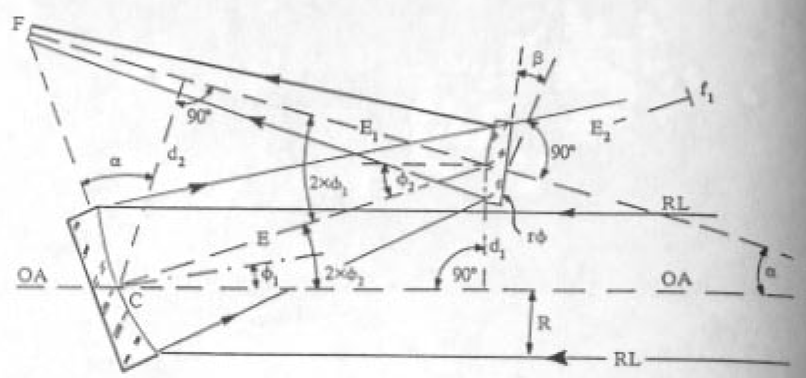
Surface	radius	spacing	material	CA radius	comments
1	−12.393	0.500	BK-7	2.881	
2	−22.009	−0.500	BK-7	2.292	reflect.
3	−12.393	−12.202	air	2.810	
4	infinite	4.984	air	0.948	flat mirror
5	infinite	1.429	air	0.166	intermed. focus
6	12.988	0.250	SF-6	0.389	
7	−2.910	3.498	air	0.407	
8	infinite	1.593	air	0.535	intermed. pupil
9	39.359	0.25	SF-6	0.744	
10	−4.061	10.006	air	0.755	
11	infinite				focal plane







A 6" NEO-BRACHYT TELESCOPE
by Robert Venor



$d_1 = R + \frac{r\phi}{2}$ $\quad \alpha = 2\phi_2 - \phi_1$ $\quad F = \frac{f_1 \times f_2}{f_1 \times f_2 - E}$, or also $A = \frac{E_1}{f_1 - E}$

$d_2 = E \times \sin 2\phi_2$ $\quad \beta = \phi_2$ $\quad F = f_1 \times A$ $\quad A = \frac{E_1}{E_2}$

$\phi_1 = \frac{2\phi_1}{2}$ $\quad \gamma = 2\phi_2 - 2\phi_1$ $\quad E_1 = \frac{f_2(f_1 - E)}{f_1 + f_2 - E}$ $\quad E_2 = f_1 - E$

$\sin 2\phi_1 = \frac{d_1}{E}$

Specifications.	inches
Primary diameter	6 1/3
Primary focal length	76 3/4
Primary R.C.	153 1/2
E	46
Secondary diameter	3 1/4
Secondary focal length	76 3/4
Secondary R.C.	153 1/2
E_1	51 1/4
d_1	5 1/4
ϕ_1	3° 16′
ϕ_2	12° 54′
d_2	20
α	22° 30′
β	12° 54′
δ	19° 14′

Comments. The incoming light rays RL — RL hit the primary mirror at an angle ϕ_1. Thus the primary's axis E is inclined by 2 x ϕ_1 to the axis OA of the incident rays. The primary's focus would be at f_1. But, as in a Cassegrain, the convex secondary intercepts the primary's light cone at a distance E_2 (or E) from the focus f_1 or primary's center C respectively. The secondary is tilted by the angle ϕ_2, thus reflecting the new elongated cone of light at 2 x ϕ_2 angle to the final focus at F just slightly behind the primary and at a distance E_1 from the secondary.

Maximum image aberration or diffusion at the edge of a 30′ field of view amounts to .004".

You will note that the focal lengths of both primary and secondary mirrors are the same, therefore the secondary can be made directly and easily from the glass tool used to make the primary.

Coma has been practically corrected by mathematical calculation of just the right amount of inclination of the primary and secondary mirrors.

It is not possible to correct astigmatism by mirror tilting alone because 40 to 45 minutes of arc in astigmatism remain. To eliminate astigmatism, the same method (arrived at independently) used by Mr. Leonard to correct astigmatism in his Yolo is used.

The secondary should not exceed 1/4" in thickness. This convex secondary is thus mechanically deformed in the sagittal axis after the optical system has been properly collimated, within the telescope; this means that in the sagittal direction a cylindrical figure is pressed upon the secondary, thus correcting astigmatism. In actual practice the mirror is supported at two points in its cell, a vertical metal bar being forced against the secondary's back by a screw. Therefore the elimination of astigmatism, the only remaining aberration in a 6-inch Neo-Bra, becomes a simple matter of cylindrical deformation.

A carefully constructed Neo-Bra will, on nights of good seeing, show perfectly round and concentric diffraction rings around a star when using 400x power.

A FOLDED REFLECTOR
by Tore Sjogren

The following describes an obstruction-free and aberration-free telescope.

Why unobstructed? Everhart and Kantorski have proved what happens in the way of diffraction when something obstructs the correct path of light rays in a telescope. Trouble is immediately apparent either in diffraction "spikes" or in diffraction being spread over the field of the telescope, thus lowering contrast.

Let us consider what happens in an ordinary Newtonian. We have a fine mirror, as good as the Foucault test can tell us, and we fix this in a cell:

1) we use three hooks to prevent the mirror from falling out,

2) the diagonal must be in the center, about 20% of the diameter of the primary and often more than this,

3) the diagonal cannot float on air, so we must have some supports, com-

monly called the "spider"; some TNs prefer three legs, some four,

4) and then, in some models, the holder for the ocular protrudes into the light path,

5) last, but not least, the diagonal must be fixed with some hooks of its own.

No wonder that some TNs get much better seeing from the 'scope with a *round and clear* diaphragm of 1/4 the diameter of the primary.

Very early in the history of optics, Herschel tried to get rid of the central obstruction in his reflectors. His intention was, naturally, to get more light by avoiding the second reflection in a bad metal mirror. It has been recorded that he was not willing to let other people have a look—coma and astigmatism must have spoilt his picture. In such an optical system, he should have used upwards of f/100!

Next, around 1900, came the Brachyt telescope (the elbow telescope) with one concave and one convex mirror, and no obstruction. This system worked well with small mirrors and narrow f/numbers. The spherical aberration was tolerable but the coma and/or astigmatism were not. The system never became popular.

In the 1940s, Anton Kutter in Germany developed the same idea further into his "schiefspiegler"—the oblique reflector and a telescope of high definition as he describes it. He investigated the optical possibilities thoroughly and gave the formulas for the construction—more, in order to correct the inevitable remaining astigmatism, he put in a cylindrical lens—the same kind that some of us use in our spectacles.

Arthur S. Leonard in this book analyzes the possibilities of all kinds of mirror combinations—on and off axis, with concave and/or convex mirrors. In the Yolo he corrects astigmatism with a harness, which can force the secondary to give negative astigmatism.

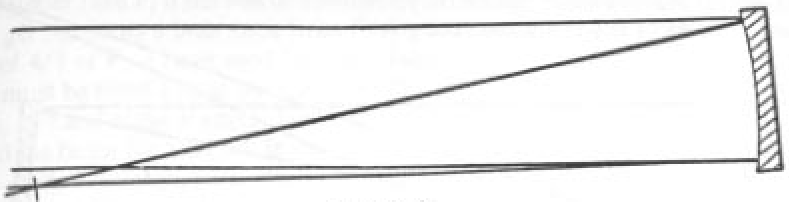
This same problem, with two unobstructed mirrors, has haunted me for more than 20 years. When I read Leonard's proposal, I heartily agreed—with the exception of the harness. I do not believe in a harness, the pressure on the glass is against all optical instinct—as Conrady says—and it cannot be stable. Further, the harness must have a vignetting effect, or it will require an increased tilt angle.

During a sleepless night, the idea flashed through my head, Why not take the best from both of these, from the schiefspiegler and the Yolo, and make them into a new combination?

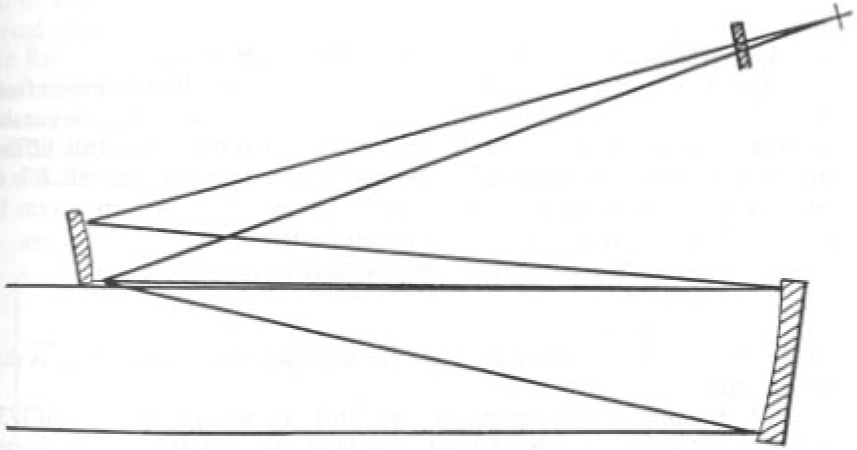
For some long evenings I figured out the conditions for this new instrument, with plenty of trig., logs. and graphs. I had a sub-conscious feeling that it was "too good to be true." Just to be sure, I made a small half-scale instrument and had a first look through it—the picture was horribly blurred! However, it was possible, slowly, to get the angles and position of the cylinder lens correct. On top of this, I had to invent a method of collimation of the lens, and after that it was easy. The result has fulfilled my highest expectations; I do not yet know how good this telescope is because the seeing in Sweden is not good enough.

I propose that this new 'scope, a new combination of elements known before, be called the Folded Reflector. It is, in fact, an obstruction-free and aberration-free telescope.

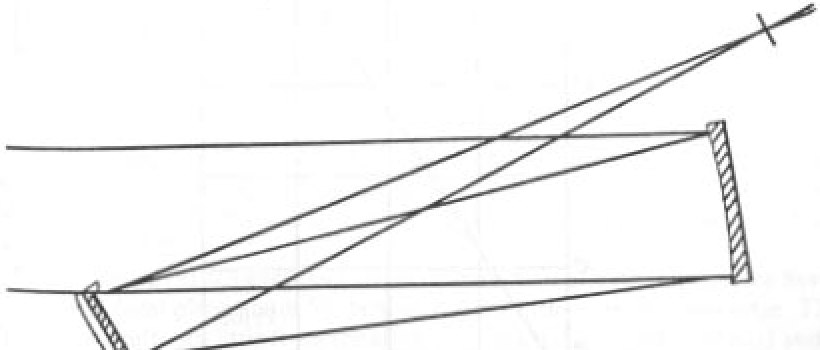
The plans of the telescopes described so far are as follows:



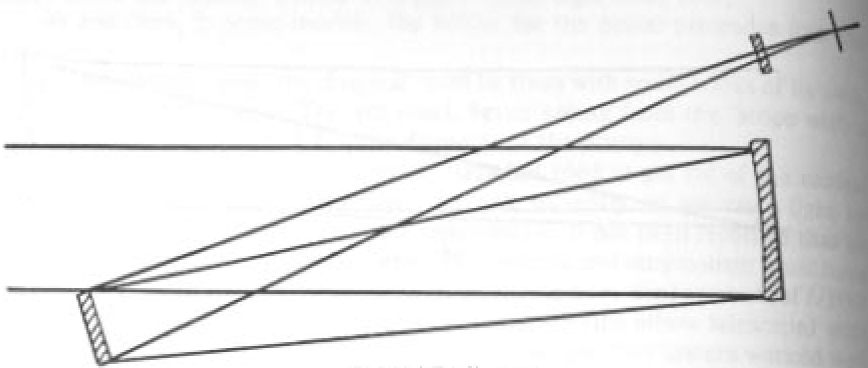
Herschel



Kutter



Leonard



Folded Reflector

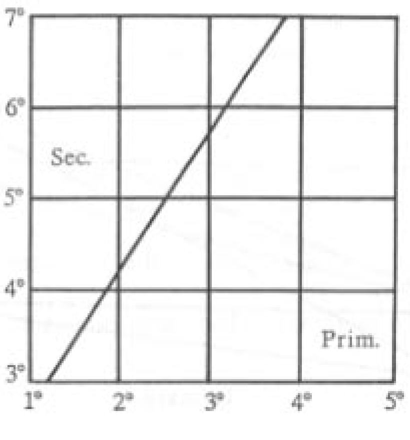
Let us have a look at the optical parts for the folded reflector.

The Primary (P for short) is concave and nearly flat, with f/numbers from 12 and upwards. P can be made spherical but should, strictly speaking, be paraboloidal. The glass disc should be 1/4″ larger than usual in order to avoid all diffraction effects from hooks which prevent the mirror from falling out of the cell. It is tilted downwards at a small angle (from 2.5 to 4 degrees) to get the convergent beam clear of the incoming rays. It introduces some aberrations:

A very small amount of spherical aberration.
Coma, and
Astigmatism.

Please observe that the angle between the incoming and outgoing rays is double the tilt angle.

The Distance, d, between the mirrors. This can be anything between 1/3 and 1/2 of the P focal length. By trial and error (and a lot of both!), I have found out that about 40% is favorable. In the prescriptions to be given later on, I have used 39%. This measure, d, is rather critical in order to get the focal plane in the correct position.



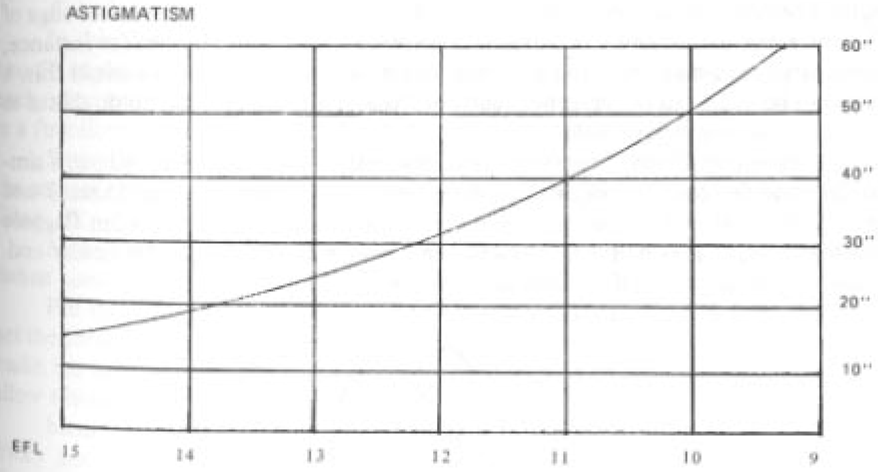
The Secondary, S. If S has the same or more curvature than P, its compensating effect is strong, but the final focus comes inside or too near to P. If S, instead, is made flatter than P, it has less compensating effect and requires more tilting, but we can get the focus a little back from P. A good compromise is to give S a focal length of 4/3 of P—I have used 1.31 as a factor.

S must be tilted a little more than P. The tilt angle is a function of both curvatures, of d and of the P angle. The following graph shows the relation, when d is 39% and the factor for S is 1.31. If you don't like to figure out such things, trust the graph—a small difference can always be collimated and cancelled out.

With d at 39%, the diameter of S will, obviously, be 61% of the P diameter. To get full field illumination it can be recommended that S should be made about 1/10 larger, but to avoid vignetting, its upper edge must be ground off to the net diameter.

S introduces some more aberrations: spherical aberration, less than P but added to what we have from P. If you make S an hyperboloid you can get rid of spherical aberration, but for smaller instruments a sphere will give tolerances within Rayleigh's limit. Coma of the same amount, but with a reverse sign from P—the coma is cancelled out! And a little more astigmatism, unfortunately with the same sign as P—they are added.

The astigmatism increases, of course, with broader f/numbers, see next graph. This is the reason why the telescope is inadvisable with broad f/numbers.



The Equivalent Focal Length (EFL). As S continues to make the convergent beam from P more convergent, we get an EFL that is shorter—it will be somewhere around 2/3 of the P focal length—but the total length of the 'scope will be only about 40% of P.

The Cylinder Lens (Cylast). As a result of the action of both mirrors, we have: A central focal plane about 5% behind P and a little over its upper edge. The end focal plane suffers a little from spherical ab. (which can be polished out) and a heavy amount of astigmatism—but no coma.

The central ray is directed upwards with an angle of twice the sum of the tilts of P and S; that is, nearly 20° for comfort in observing.

The inevitable amount of astigmatism can be cancelled out by a cylindrical lens of low power—let us name this the Cylast, which means CYLinder lens to correct ASTigmatism. The name "lens" is not quite adequate; there is no power, only some negative astigmatism.

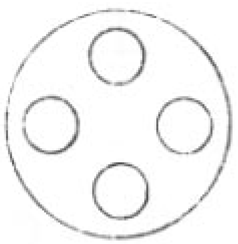
The position of the cylast is the only part of the instrument which is critical; its axis must be vertical, if a positive cylinder, and its distance from the focal point correct. Hence the cylast must be mounted to permit of small adjustments.

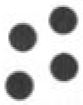
You may think that a simple lens must add some chromatic error to the system—a pity, since a reflector is free from this. You are right; there is a little color aberration, but the cylast is weak and it should be placed as near to the focal plane as is possible—about 2 inches is suitable for a cylast with 2 cyl. diopters. The net result of this is that the color aberration is well within the Rayleigh tolerance. For bigger instruments, it is not too difficult to make the cylast from crown and flint glass, and thus perfectly achromatic.

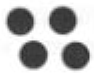
By the way, this cylast opens up some interesting possibilities. The lens can be bent (see Conrady) and made to compensate small amounts of spherical aberration, both plus and minus. A negative cylast can, furthermore, act like a Barlow lens and increase the EFL.

The Tube. As the light rays have to go through the telescope three times in different directions, the tube must be rather thick (or high). This is no disadvantage at all since the tube, with 5 or 6 stops inside, provides a lot of traps for stray light. The construction has its weak point, however, and that is at the lower edge of the entrance. If the 'scope is aimed at a point a little over the moon, for instance, some stray rays may enter the eyepiece and disturb the contrast. To avoid this, a stop can be put 1/10 of the tube length in front. The simplest way to do this is to use a lid opening downwards.

Collimation. Using ideas from Hartmann and Vaisala, I have developed a simple method for collimation. Make a mask with four holes in it (see Sketch) and place it in front of the tube. Aim the tube at an artificial star—a golden flagpole knob will do, if it is half a mile away—and have a look through the ocular end. Draw the ocular out half an inch and see the extra-focal picture.

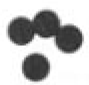


Probably you will see something like this: 

Put in the cylast and look again: 

By trial and error it is possible to get the four point figure exactly symmetrical:

By going nearer and nearer to the focal plane, you can collimate the instrument exactly:

Perhaps your picture will show this figure: 

This means that coma is not cancelled out. In such a case, the S tilt angle must be changed, and this is the reason why the ocular end of the telescope must be designed to allow of small adjustments.

With a high power ocular just outside of focus, this collimation procedure is extremely sensitive. After removing the mask, the picture will certainly be to your satisfaction.

Tolerances.

In this system there are *five* main elements to vary: the two curvatures, the two tilt angles and the distance d between the mirrors. In a way, they all depend on each other and the most sensitive factor is d, because the position of the final focus is a function of this factor.

Since both curvatures are rather flat, it is not so easy to grind the mirrors to the correct radius. A spherometer is a necessity—I use the Mackintosh model, (see Chap. 5).

Make the secondary first, this is the fastest one. Try then to make a P with radius about 3/4 of S.

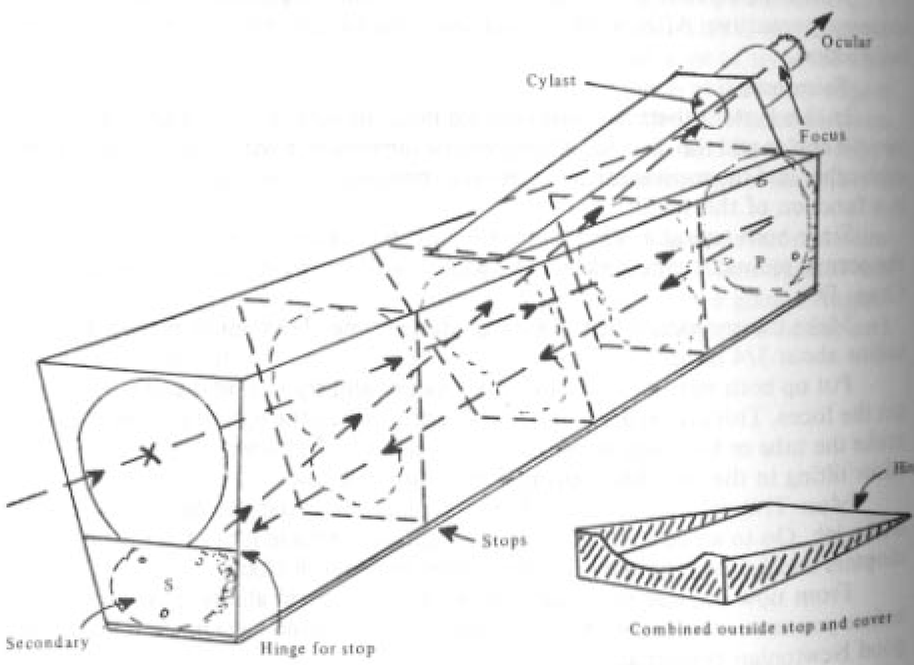
Put up both mirrors in a provisional mount and try to find d and where you get the focus. This can be done without silvering. When the optical parts are ready, make the tube or box, whichever you like to call it, and arrange the mirror cells to allow tilting in the meridional plane—that is up and down.

Most TNs will not be interested in making the cylast themselves as it is a tricky job. Go to an optician and buy an ordinary spectacle lens of zero spherical diopters and 1.5 or 2 cylinder diopters—they are kept in stock.

From now on, use your common sense and optical ability. Just one word before you start—this is not a job for a beginner, you should have made at least one good Newtonian beforehand.

For those not interested in computing, here are two examples of folded reflectors. The first one (I) is made with both mirrors spherical; the aberrations will, with the narrow f/number, be well inside the limit. The second (II) is a broader one; here the spherical aberration will be visible and cannot be tolerated, therefore at least one mirror (preferably both) must be corrected to a paraboloid. The advanced TN understands that the P must be a paraboloid and the S an hyperboloid—the corrections are, with these flat curvatures, extremely slight and can easily be overdone.

	I	II
Primary focal length	106	82.5 inches
Factor M	1.31	1.31
Secondary focal length	139	108
Diameter of P	5.5	5.5
Diameter of S	3.35	3.35
Distance between the mirrors	41.6	32.2
Distance from S to final focus	44.0	34.3
Focus behind P	2.40	2.00
P angle of tilt	3° 02′	3° 55′
S angle of tilt	4° 15′	5° 26′
Equivalent focal length	72	56.5
f/number	13.1	10.3
Remaining astigmatism to correct	23″	49″
Cylast, cyl. diopters	1.5	2



OPTICAL SYSTEMS FOR SOLAR AND LUNAR TELESCOPES

by Jim Daley, Jr.

I hope that these new systems will encourage the serious solar, lunar and planetary observers. A brief history of our efforts is in order to clarify the origin of the systems.

About a year ago Ken Leathers and I discovered, as so many other amateurs have done, that unobstructed off-axis sections of a paraboloid give remarkable lunar and planetary detail. From this starting point, we determined to try to improve the performance of reflector type clear aperture systems.

A plano-parallel window placed over the aperture improved definition to some degree, and the next step was to try to eliminate the need for an aspheric primary mirror. To this end I made a 3″ spherical mirror of f/21 and used it in the conventional Herschelian layout. At the same time, in order to reduce the excess light given by an aluminized mirror in lunar viewing, I had my mirror coated with Titanium Dioxide, 20% reflectivity. This system gives perfect imagery on lunar detail and also does very well on Jupiter and Venus.

The main disadvantage of this system was found to be the excessively long tube needed for larger apertures and the location of one's head near to the aperture, thus causing convection currents and spoiling fine detail.

About this time (June 1962) Mr. Hector Durocher invented a lunar telescope, the details of which are shown in Fig. 1:

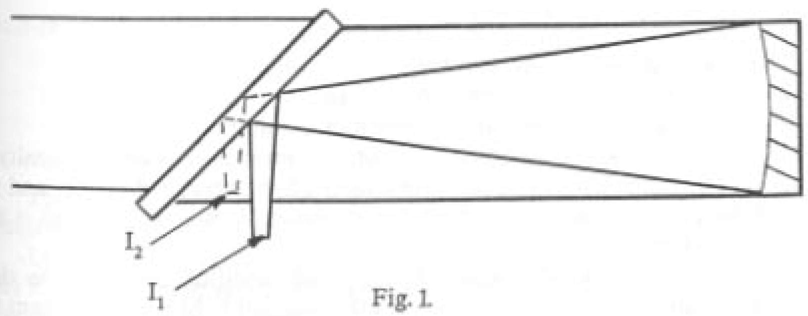


Fig. 1.

This instrument is very successful. It allows the use of long radius spherical mirrors, it has a sealed tube and, with the unaluminized primary, it makes an excellent solar telescope and, of course, *it has no central obstruction.* In the original system, the second image produced by the second surface of the diagonal is displaced along the tube and does not enter the eyepiece.

For the planets, Mr. Durocher introduced the idea of coating the surface of the diagonal with aluminum of 20% transmission and this, used in conjuction with a fully aluminized primary, gives sufficient light for the brighter planets.

Some basic problems still remained:

1) The observer's head is still near the aperture of the telescope and this is

not desirable because of the convection currents mentioned above, and also difficulty in reaching the eyepiece in telescopes of larger sizes, necessitating a step-ladder.

2) The thick window, which is necessary to displace the image, causes the tube to be front-heavy and makes for a balance and vibration problem.

3) Since the window is at a 45° angle in the tube, a slab of glass must be bought 1.5 times the aperture, and this puts up the price.

4) Any small deviations from optical flatness in the diagonal, such as slight convexity, will cause astigmatism in the final image.

We then decided to tip the front window nearly normal to the tube and place it half-way down the converging beam. The new folded system is half the focal length of the mirror and brings the focus to the side of the tube near to the primary mirror—Fig. 2:

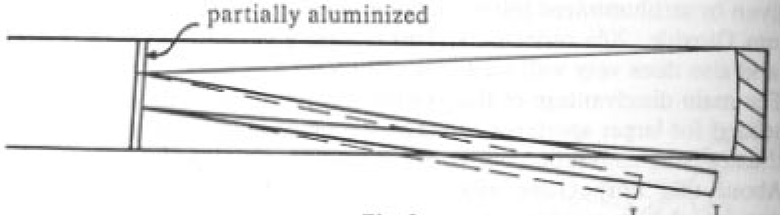


Fig. 2.

The advantages of this system are:

1) A long f/ratio mirror is easy to manage.

2) The window is lighter, smaller and much thinner.

3) For solar work, the second image from the primary is down in intensity by a factor of one million times from the intensity of the observed image, and the observed image from the primary (½% transmission aluminized surface) is at a comfortable brightness.

For planetary work, the system needs some modification. With the right choice of transmission, an image of nearly 20% incident light is formed from the diagonal. The image intensity from the second surface of the diagonal is very low and slightly out of focus, but it is very little displaced. A choice of transmission could be made which would nearly, if not quite, extinguish it; by applying a magnesium fluoride coat to the second surface of the diagonal, the bothersome residual second image is reduced three times.

With regard to the moon some trouble may be experienced, especially if no magnesium fluoride is used on the second surface of the diagonal; the background light will be of sufficient intensity to be objectionable. In order to overcome this I have made my front window very slightly double-convex (10 waves), Fig. 3:

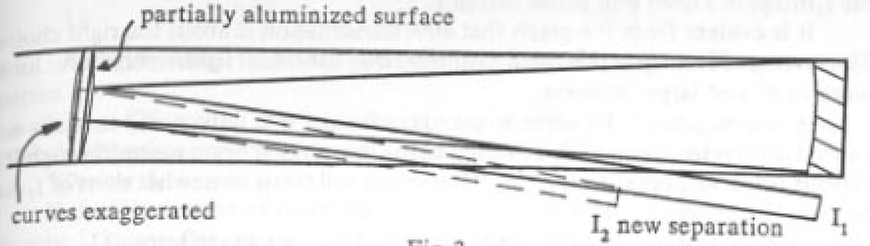


Fig. 3.

A great difference in the position of the focus of the two images is obtained, thus expanding and greatly dropping the intensity of the ghost image. No astigmatism is introduced provided that a small tip angle and shallow curves are used, and color will be impossible to detect visually.

Now, for actual construction:

We will start by setting up a typical optical layout (Fig. 4):

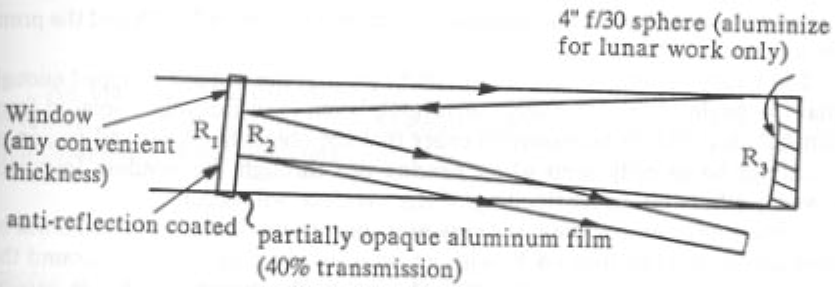


Fig. 4. Lunar type telescope

The rays forming the image are easily traced and the image is of a quality inherent in a good f/30 sphere on axis.

Let us now examine the various ghost images produced from the interfaces R_1 and R_2. These ghosts add light to the region of the focal plane and must be reduced to an unobjectionable level. To ascertain the ghost intensities, a graph of the beam-splitter characteristics was made using the available reflection, transmission and absorption (RTA) curves available for silver films. We were unable to get data on aluminum films., but the RTA curves for aluminum should look about the same (see graphs at end of this article).

The first ghost image is parfocal with I_1. I_2 is formed by internal reflection of the parallel incident light. The image will simply add to the I_1 image if a perfect plane-parallel window is used.

Since some amateurs do not have the measuring facilities to make a plane-parallel to ½ second of arc, we will have to reduce the brightness of the I_2 image below the threshold of the eye with I_1 present. The graph shows that a nice choice of film transmission, glass type, and anti-reflection coating can be made to reduce the I_2 image to a level well below that of I_1.

It is evident from the graph that 40% transmission is about the right choice. The system efficiency at this relationship is 12% of incident light—perfect for lunar work in 4" and larger systems.

A second ghost I_3 (in order to avoid confusion, it is to be noted that this was called I_2 earlier in this article) is formed as the convergent beam passes through R_2, reflects off R_1 and back through R_2. This image will focus somewhat short of I_1 due to glass thickness.

The graph shows I_3 at about 40% transmission—about the same as I_2, and will be reduced along with I_2 (see I_2A, I_2B, I_3A and I_3B on graph). The ghost intensity of both I_2 and I_3 will be greatly reduced by employing glass of a refractive index of 1.7 and triple layer anti-reflection coating.

If the amateur has the ability to make the window perfectly plane-parallel, the I_2 ghost image will be completely eliminated. In such a case, the graph shows that the I_3 intensity is well down, with no anti-reflection coatings necessary. System efficiency will be 11% at 20% transmission. This, coupled with the anti-reflection coating would, of course, make the most ideal lunar instrument.

It can be clearly seen from the graph that in the case of a solar instrument, the ghost intensity is very low at ½% transmission. The solar type differs very little from the drawing in Fig. 4. The window transmission is ½% to 1/10% and the primary is left unaluminized.

The builder of this system should take care that the window is tipped enough so that the angle of the returning converging beam is sufficiently displaced from the optical axis. This is necessary in order that the object being viewed (moon or sun) cannot be directly seen when peering out through the window (eyepiece removed), otherwise direct flooding of the eyepiece will occur.

The system could be built as a very nice solar double-pass monochromator by coating the aluminum film on R_2 with an interference film centered around the hydrogen alpha line. With the long f/ratio used, the convergent beam passing through the interference film would not detune the band-pass enough to cause any problem.

Element Spacing.

It should be obvious to all that since the window has no power—for the most compact instrument the window should be placed at half the focal length of the primary mirror, but one foot either way would not hurt—it would just shift the focus x2.

Primary Mirror Accuracy.

The primary mirror must be 1/20 wave accuracy and no worse—this means that the following chart must be strictly adhered to if 1/20 wavefront error at the focus is to be preserved:

Mirror Dia. (inches)	Focal length (inches)	f/D	Spacing between R_2 & R_3 for most compact instrument	
3	43	14.33	21.5	
4	63	15.75	31.5	
5	85	17.00	42.5	Plane
6	108	18.00	54.0	parallel
7	133	19.00	66.5	window
8	159	19.875	79.5	only
10	214	21.4	107.	
12	273	22.75	136.5	

Note. A slight change in focus position occurs when using the double-convex system.

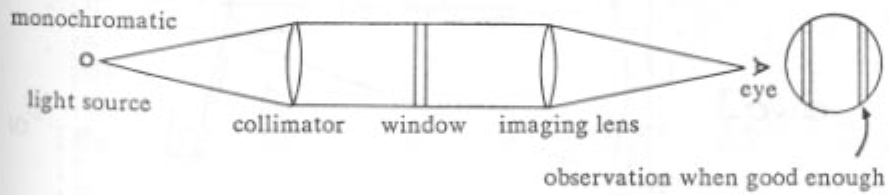
If the TN would like to make a very stubby 'scope, he could make a paraboloidal primary mirror—just think, a six inch f/6 system only 18" long!

Window Accuracy.

If the TN decides to make the window perfectly plane-parallel, the surfaces must be 1/8 wave flat and the total wedge must not be greater than the total resolving power of the instrument in seconds of arc. Resolving power in seconds = 4.5 Angstroms, or a 4.5" system must be wedge-free to better than 1 second of arc. If I_1 and I_2 are to combine, the wedge should be as follows:

Dia. (inches)	Wedge in seconds of arc	Wedge in wavelength of .555μ (green)
3	1.5	1 wave
4	1.12	1 "
5	.9	1 "
6	.75	1 "
7	.642	1 "
12	.375	1 "

All plane-parallel windows should be allowed no more wedge than one wavelength at .555μ or two fringes when the window is viewed in monochromatic light collimated by the following test:

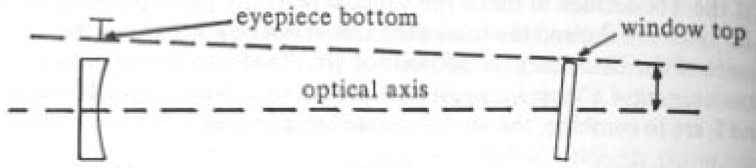


A simpler alternative is the double-convex system where the ghosts are spread out and brought below the threshold of vision. Tests have shown that 10 waves convex on each surface is sufficient for a 4" system. The surface accuracy must again be 1/8 wave spherical; this, of course, means making a test plate concave 10 waves and spherical 1/8 wave.

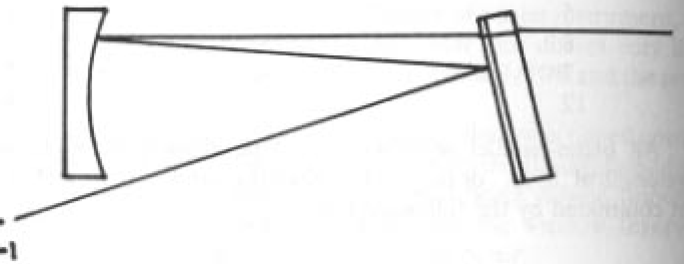
An alternative is to make the window 10 waves convex using a good spherometer and correcting the system as a whole by means of autocollimation; 10 waves is about .0005" sagittal "hump" and could be measured with a good straightedge and .0005" shim stock. Wedge tolerance for the double-convex is no greater than .0005" per 4" of aperture.

Tip Angle.

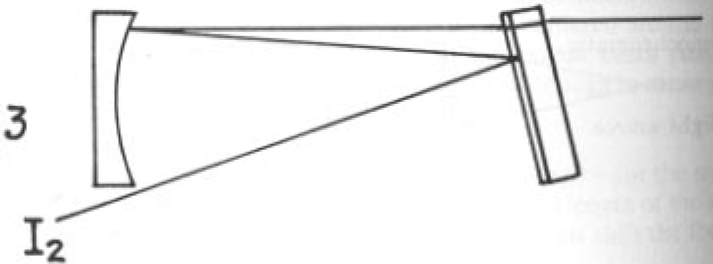
The window tip angle will vary depending upon the aperture chosen, but this information is not what is needed as you simply tip the window the amount necessary to bring the image to the eyepiece position. The information needed is the angle between the prime optical axis and the possible path for direct light to enter the eyepiece. The largest object viewed is the moon or the sun, ½°. When viewing the top of the moon, we don't want light from the bottom entering the eyepiece directly through the window. The following sketch will clear things a little:



dwg 2



dwg 3



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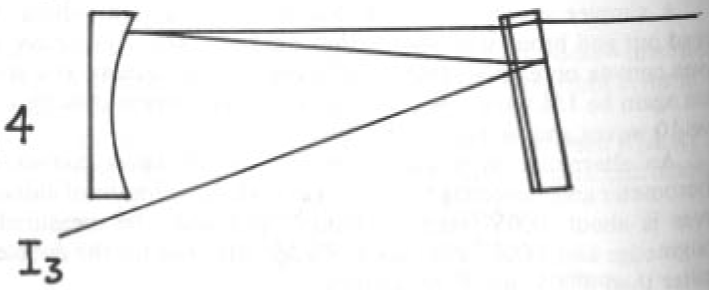
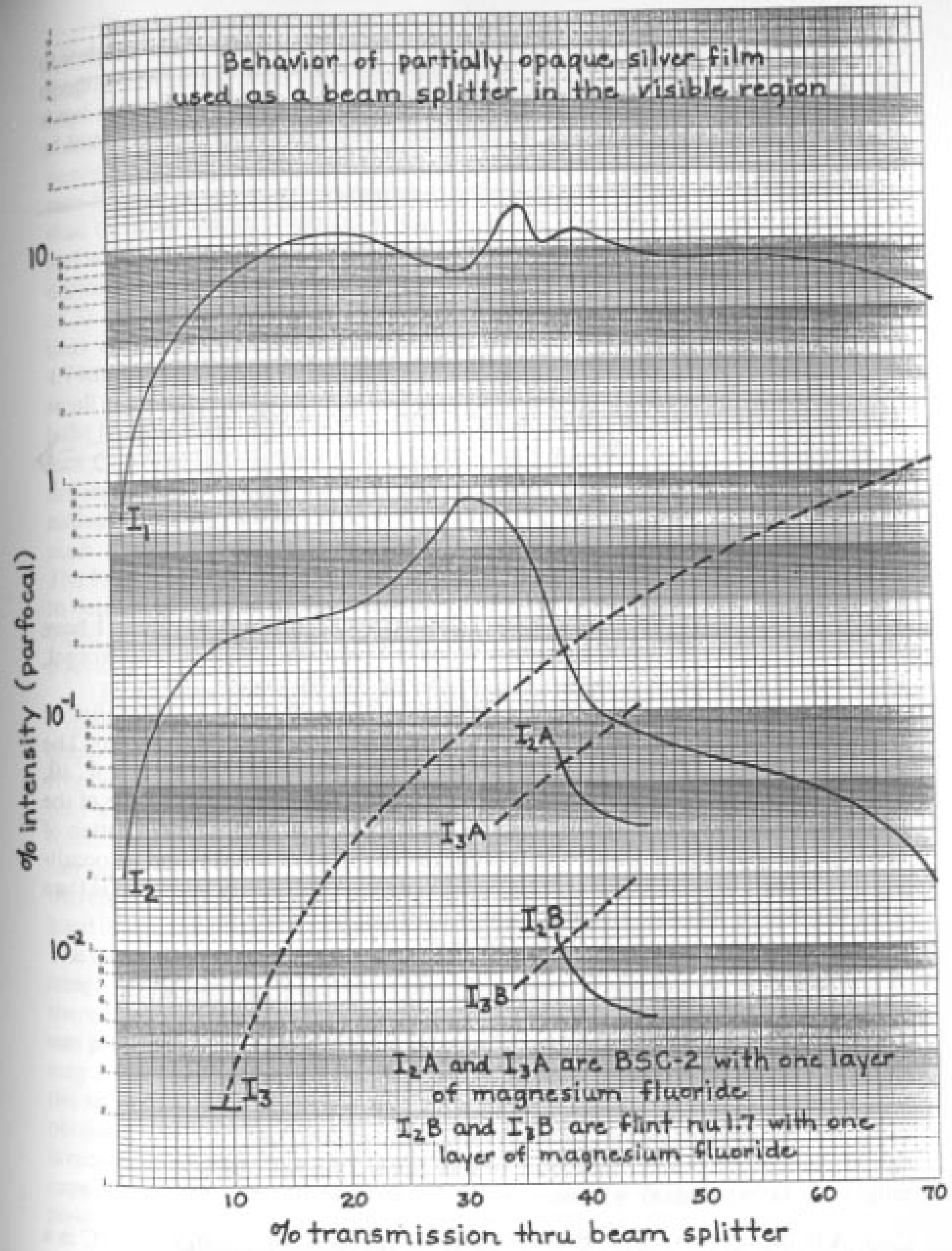
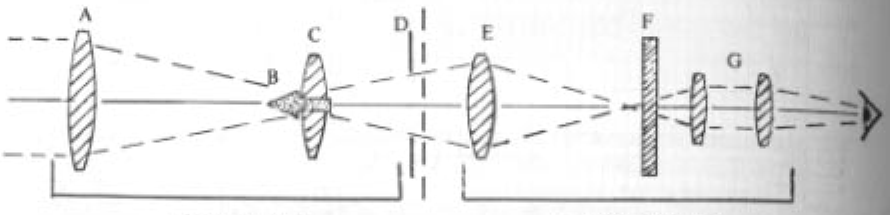




To keep all stray light out, make the angle between the top of the window to the bottom of the eyepiece at least 1°—this gives ½° safety margin for the moon and the sun. The tip of the window comes naturally with an adjustable cell, but it can be figured out ahead of time, if desired. In any case, the tip angle should be kept as small as possible.

A SUN TELESCOPE

by John A. Snell, F.R.C.S., F.R.A.C.S.



The following is a description of the sun telescope I have made and which is really a German design by Otto Noegel, published in a variety of German sources during the last decade.

Mine was constructed from the translation of an article by Rudolph Brandt who is apparently on the staff of the Sonneberg Observatory in East Germany. The article appeared originally in the German bi-monthly "Die Sterne", Vol. 40, 3/4/64, publishers Johann Ambrosius Barth, Leipzig, and translated by one of the members of our society here (Melbourne, Australia). It is really a modification of the Lyot coronagraph in which a lens produces an image of the sun and an occulting disc is used to produce an artificial solar eclipse. A subsidiary telescope is then used to observe this disc and any prominences can be clearly seen.

In the above schematic of the telescope:

A = biconvex lens, 50mm diameter, 500mm focal length.
B = brass cone, 4.8mm diameter.
C = biconvex lens, 30mm diameter, 160mm focal length.
D = diaphragm, 22mm diameter, 236mm from C.
E = lens (achromatic), 30mm diameter, 125mm focal length.
F = double interference filter—lambda maximum
6560 Angstroms (red H alpha C line of hydrogen).
G = standard eyepiece.

A is the objective lens, B is the cone which acts as an occulting disc, C is a small lens which is used to mount the cone and also to produce an image of the main objective A at D where there is a diaphragm which is slightly smaller than the image of the objective so that any scattered and extraneous light is completely removed. E, F and G constitute the secondary telescope for viewing the prominences at B, E being the objective lens, G the eyepiece and F the special interference filter which produces monochromatic light.

Clearly this instrument can be made in any convenient size and the original article advocated the use of a Zeiss objective of 50mm aperture and 540mm focal length. The one I have used is of 50mm aperture and 500mm focal length. It is important that this glass be free from small air bubbles and from any mechanical surface flaws. A good objective is essential for a proper performance of a prominence telescope. At the focus of the objective is placed the occulting disc, in this case a metal cone cleanly machined, the diameter of the base being slightly larger than the solar image produced by the objective. This cone must have a very clean and accurate edge. The solar image produced by the objective will, of course, alter during the year with the apparent diameter of the sun. This varies from a diameter of 32 minutes 36 seconds in January to 31 minutes 31 seconds, roughly, in July; thus with a lens of 500mm focal length the solar image produced will vary from 4.74mm at maximum to 4.59mm in diameter at minimum. Since a stop that is too small is useless, I made mine with a diameter of 4.8mm. Mine was turned up in the lathe from brass, integral with a small pin to go through a hole in the middle of the lens C; it was fitted with a small shoulder and threaded 10 B.A. so that it can be drawn up firmly against the shoulder when inserted in the hole in the lens. Alternatively, this peg can be made with a slight taper so that it fits easily with a gentle push. The lens C conveniently has a focal length of 160mm (plus 6.25 diopters). The focal length of this lens is not critical, but we must know it accurately in order to determine the size of the image of A and the distance away that this will be provided, so that the diaphragm D can be made to the right size and placed in correct position.

In my telescope, it worked out that using a focal length of 160mm, the objective image would be produced at 236mm from the lens C and the hole in the diaphragm would have to be 22mm across in order to mask out the unwanted light from the objective. The effective aperture of the objective lens is then reduced by only a very minimal quantity. The dimensions and lenses used in the auxiliary telescope are similarly not critical, but it must be designed so that this telescope can be focused on the cone C in order to view the prominences. The lens E, therefore, need not necessarily be an achromat, but it is desirable for the sake of a good image. The one on my telescope is an objective lens from a pair of binoculars. The lens is 30mm in diameter and 125mm focal length. This is mounted so that the image of the sun on the cone is reproduced with a ratio of 1:1 and the lens E, therefore, is located at a distance of 250mm from the cone B and the image of the sun produced by E will be located 250mm behind it. It will be seen that the lens is only a few mm behind the diaphragm D. Standard eyepieces are used to examine the secondary solar image and with a 25mm focal length eyepiece, a power of 20 is obtained—with a 16mm eyepiece a power of a little over 30 is produced. The latter is recommended by the author of the original article, but I have not yet had enough experience with mine to be firmly in favor of one or the other, but the higher power eyepiece does seem to be better.

The business part of the whole telescope is, of course, the interference filter which is located one or two centimeters in front of the eyepiece. With a very transparent sky, a heavy red filter is sufficient at times for the observation of bright prominences. Best results occur, however, with filters which are more monochromatic and with a much narrower passband. I have obtained one of these from Carl Zeiss, Jena, centered on the hydrogen alpha line at lambda maximum 6560

Angstroms. The deviation from maximum wavelength is only plus or minus 7 Angstroms and the half width value 5 to 9 Angstroms. The maximum transmission of this filter is about 15% and the minimum about 8%. It is important that this filter should be mounted as squarely to the light path as possible. Displacement of the transmitting maximum towards shorter wavelength will be caused by an inclination exceeding 5 degrees relative to polarity at right angles to each other. Five degrees, however, is a relatively gross tilt and it should be fairly simple to remain below this tolerance.

All optical components must be well centered to obtain results and this, of course, goes without saying, but the average TN should have little difficulty with this. Mine is mounted in a thin-walled piece of aluminum tubing, normally used for water piping.

The complete instrument works as a terrestrial telescope, the solar image appearing upright and true with respect to right and left. All internal surfaces should be matt black to avoid light scatter; the cone, however, should be metallic bright.

Photographs can be taken without difficulty with red sensitive emulsions, the author of the original paper advocating Agfa-Spectral-Red, Agfa H alpha film, or plates. An excellent picture of prominences is displayed in the original article, said to have been taken through one of these telescopes. I have used mine visually so far, but have not yet been able to take any photographs.

The only snag is the procuring of the filter consisting of thin dielectric layers as free from absorption as possible, which are deposited by evaporation under a high vacuum and of the thickness of the order of the wavelength of visible light. In order to increase reflection at the boundary surfaces, they are coated with semi-transparent metal layers. The color of the filters in the region of maximum transmission depends on the thickness of the dielectric layer which can be produced by any method. The filters are, therefore, dependent on angle as are all interference phenomena.

Metal interference filters are used for filtering out very narrow bands of wavelength from a continuous spectrum, or for separating spectral lines from a line spectrum.

In addition to transmitted light, they are also used as selective mirrors. The wavelengths of the incident beam which the filter transmits will be missing in the reflected light. By repeated reflection it is possible to remove a certain range of wavelengths almost completely from the incident beam.

Compared with monochromators and spectral lamps, they have the advantage of a high intensity of the transmitted beam, which can be varied by the choice of suitable powerful light sources and corresponding filters. Obviously the spectral purity of the beam cannot be compared to that of a good monochromator.

These are quotes from the Zeiss manual, but I thought that they might be of value in obtaining the correct type of filter in the U.S. if the German one is unobtainable.

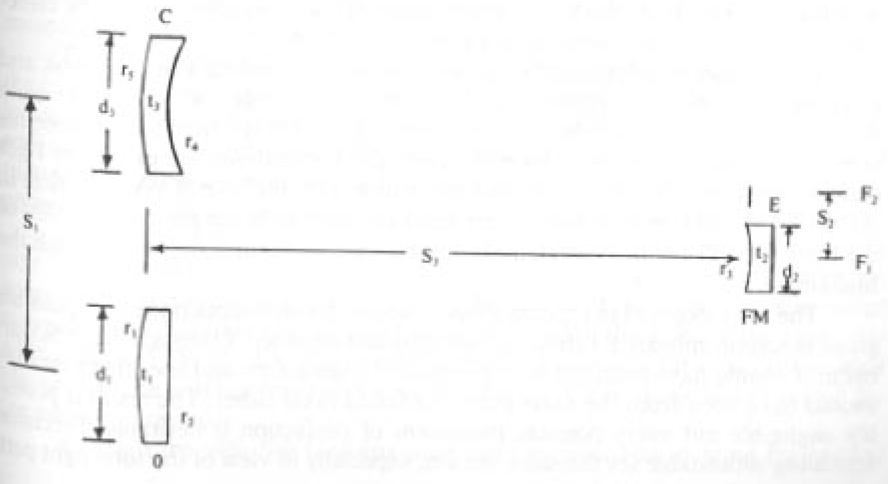
A SCHUPMANN FOR AMATEURS

by Edwin A. Olsen

My telescope is of the type known as the Schupmann from the name of the German professor who first proposed this basic system in 1899. It may be described as a catadioptric refractor, as deriving its optical power by refraction and as requiring supplementary reflection. The principle of this design proposes that it is possible to achieve a refractive system fully corrected for color by neutralizing the chromatic aberration of the primary objective with an equal but opposite chromatic aberration of a secondary objective. How this may be achieved in the particular form that I have chosen is the substance of this paper.

Very few Schupmann telescopes have ever been made in spite of the apparently promising possibilities of the design. What serious attention has been given to it has been largely professional in purpose. My intent has been to explore the possibilities of this design with strictly amateur considerations in mind. I have become convinced that the design can be reduced to a very reasonable simplicity and I trust that my own telescope demonstrates this possibility. Accordingly, my only argument is the process of my own experience in working towards an actual Schupmann telescope.

My interest in the Schupmann design began with the reading of a discussion of the subject by Dr. James Baker, which I recommend strongly as an authoritative study of the basic principles of the design. This article suggested to me an answer to my search for a maximum telescope within my own means of acquisition. It seemed to me that a 6″ aperture and a 90″ focal length were about as much as I could expect to manage. At the same time, I felt that such dimensions were quite adequate for rather serious amateur use. Also, it seemed desirable to limit the length of the instrument to about 90 inches for reasonable facility of operation. Finally, it seemed best to avoid any unnecessary optical complexities and thus to ensure as far as possible a successful result. These considerations led me to choose the specific design outlined in the schematic.



Specifications.

0	BK7 (1.56786/64.38)	FM	fused quartz	C	BK7 (1.51718/64.00
d_1	6.00"	d_2	2.0"	d_3	6.00"
r_1	50.670"	r_3	90.00"	r_4	36.269"
r_2	564.8"	t_2	.5"	r_5	60.200"
t_1	.717"			t_3	.565"

S_1 10" S_2 2.5" S_3 90"

Focal apertures variable with field of oculars.
Image orientation:

F_1 + F_2 +
Optical Elements.

In this design, parallel incident light is refracted by a primary objective to a first focus, where a field mirror reflects the rays to a secondary objective, which refracts the rays at its front surface and reflects them at its back surface with the net result that the rays are brought to a second and final focus, where an eyepiece or other device presents the rays as an image to the observer. The primary objective is of crown glass with its surfaces shaped convex to refract parallel rays to a focus at a distance of 90 inches. Most of the curvature is given to the front surface and only enough is given to the back surface to correct the lens precisely for coma. The field mirror is of fused quartz with its front surface shaped concave and aluminized to reflect the cone of rays to the secondary objective and to control the path of oblique rays within the cone. The secondary objective is of crown glass of the same type and preferably of the same melt as the primary objective. The first surface is concave and refractive, and the second concave and reflective by aluminizing, together constituting a lens-mirror, or Mangin. This element can also be called a corrector because its function is to correct the chromatic aberration of the primary objective. It does this by refracting rays divergently precisely by the same degree as the primary objective refracts the rays convergently. This is done at the first surface of the corrector as the rays pass through this surface twice, entering and leaving the corrector. The back surface of the corrector simply returns rays to the first surface along their original path and so acts in effect as an optical flat, with the corrector in its thickness acting essentially as a plane-parrallel. The effective focal length of the corrector is equal to that of the primary objective.

For a basis of calculation of specifications, I consulted Chester Cook and received from him the figures for his Schupmann design which, while quite different from mine, involved the same basic idea. At first I tried to transpose his terms to my conditions by a transition formula, but without success. Then I got down to fundamentals and ray-tracing my system with the help of Wyld's article in *ATM III.* I found I could ignore the reflections except as to the general direction of the light path. The critical problem was in the analysis of the light path through the Mangin.

The next step was to procure glass. It seemed well to obtain the best possible glass, precision annealed. I chose Schott glass and obtained it through Fisch-Schurmann. I should have obtained both pieces at the same time and specified that they should have been from the same melt, but failed to do either. The result is probably negligible but every possible increment of perfection is desirable. Precision annealing is desirable for the same reason, especially in view of the total light path

(270"). Such annealing is expensive but there probably is no choice if one desires superior performance. The difference between superiority and mediocrity may be numerically small but it is all-important. Precision glass for this system (two discs, BK-7, coronagraph quality, 158mm x 20mm, precision annealed) cost close to $150 in 1964. Glass with standard grade A annealing would cost about one-third as much, but would it be adequate? Of course, one could reduce the cost by one-half with a fractional (one-third) corrector but at the risk of reducing the probabilities of success. Incidentally, one should be sure to ask for a proof-sheet for each disc.

The working of the glass was largely routine. I used pyrex tools which were also used as test plates. I used slow, soft aluminum oxide for grinding to avoid deep pits (Nos. 80, 180, 320, 600). The No. 600 was elutriated and graded according to Hanna in *ATM III,* with finer grades used for pre-polishing. Polishing was with washed Barnesite followed by washed rouge on plain, rather soft pitch. Discs were held at the upper edge with the side of the hands for only a minute or two at a time. A black polish, with no grayness, no sleeks, no scratches was sought and just about achieved.

Radii were taken seriously and held, I think, to at least one part in two thousand. A well tested spherometer was used for first approximations. Final curves were established by polishing, using radius rods and re-imaging a fine wire beside itself with both wire and image in sharp focus as viewed in a positive eyepiece. For the radius of the test-plate for the back surface of the primary, an engineer's steel tape was used. Actually, a test-plate for radius may be necessary only for the first surface of the primary, the radius of the second surface of the primary may be established by autocollimation with monochromatic light at the focus. The radius of the concave surface of the field mirror should be no problem.

Each element was figured to a null test. I did not dare to use the test-plates to check figure and did not feel that I needed to. For the primary an approximate sphere was probable for the first surface with its relatively deep curve, and final figuring, including zonal figuring, was applied to the second surface. For the corrector, the first surface being concave was easily figured and the second surface was then given the final correction. The system as a whole was then checked. Testing for figure was in each case by monochromatic light at the focus. For monochromatic light I used a Corning three-element filter for the green line of mercury.

The optical elements of the system were then mounted in simple cells. I had the cells for the large elements machined from thick-walled aluminum tubing. The lenses were well separated from the cells by 1/16" cork insulation. The field mirror was mounted in an Edmunds cell with exterior threading. The cells were then mounted on plywood bases which in turn were mounted at the ends of a shaped plywood tube with ample provision for adjustment by means of push-pull screws.

A system of baffles was constructed within the tube to conduct each cone of rays and to prevent flooding of the eyepiece by rays proceeding directly from the aperture of the primary objective. The baffles are of sheet brass with sharpened aperture edges, mounted on plywood bases attached to the sides of the tube; this adds greatly to the rigidity of the tube. The interior of the tube was thoroughly blackened. The exterior was given a varnish finish. A dew shield was provided for the objective aperture.

A draw tube with full focusing range was so placed as to bring the second focal plane as close beside the first focal plane as possible in order to minimize the necessary tilt of the Mangin. The separation of the centers of the two focal planes amounts to 2.5 inches, corresponding to a tilt angle of the Mangin well within a permissible 3°. The angle of rays approaching and leaving the field mirror is not critical because the field mirror is at focus.

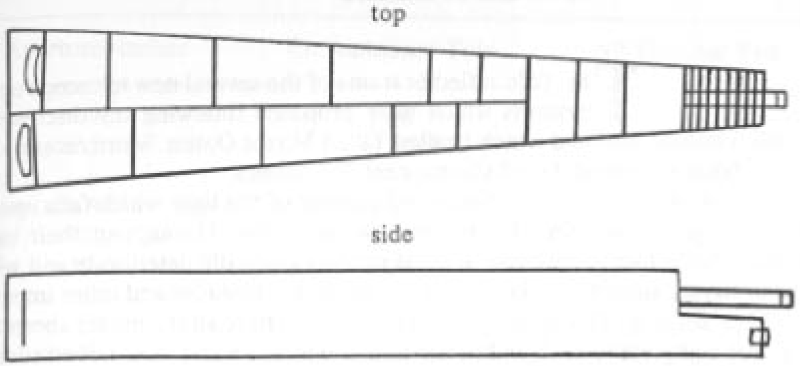
The tilt of the Mangin introduces some astigmatism into the system which may be corrected by toroidal figuring of the back surface of the Mangin or by tilting the primary an equal but opposite amount. The second device was adopted as being far more practical, and quite adequate.

Collimation of the system is simple because the elements are accessible, fully adjustable and rigidly supported. With field mirror and eyepiece removed, the Mangin is collimated by reflecting light from a pen-type flash bulb from the center of the field mirror aperture to the center of the eyepiece aperture by adjustment of the Mangin. The objective is then collimated by directing light from the field mirror aperture and reflecting images at the same time from the two surfaces of the objective and the two surfaces of the Mangin and adjusting the objective until its images are equal in separation but opposite in direction to the Mangin. The field mirror is then adjusted by directing light from the eyepiece aperture and reflecting images from the surfaces of the primary objective and the Mangin in one field until the pairs of images are directly centered relative to each other but in precisely opposite directions. The eyepiece is then adjusted by directing light from the center of the field mirror aperture by way of the Mangin and adjusting the orientation of the draw tube until the light is centered in the field of view and until it remains centered as the eyepiece is racked out all the way and all the way in.

The system as a whole may be collimated at any time by autocollimation by having a flat mounted in a special dew cap readily slipped into place and by having a special solar diagonal with eyepiece at the viewing position. A very small pinhole would transmit light through a very small perforation in the center of the Herschel wedge of the diagonal, through the entire system of the telescope and then back upon itself to the point of origin. Then, by racking the diagonal in, the returning ray can be expanded beyond the dimensions of the perforation until the diffraction ring appears in the eyepiece. If the front surface of the diagonal is aluminized, a very small light could give a bright image in the otherwise completely darkened interior of the telescope. This could serve to check both optical figure and optical collimation of the system. For an f/15 system such slight longitudinal displacement of the image would not be serious. This arrangement has not yet been tried, but is planned.

A final step in collimation is longitudinal positioning of the field mirror until the primary objective is precisely superimposed optically on the Mangin. This can be judged at the eyepiece as a final adjustment of the chromatic correction of the system. The final position of the field mirror should be such as to re-image the objective precisely upon the Mangin and at the same time to be displaced slightly from the primary focus to avoid any dust particles on the field mirror from being unduly conspicuous in the field of view of the eyepiece. This can be achieved by mounting the Mangin somewhat nearer to the primary focus than the objective. The final arrangement of the optics as mounted in the tube is shown in the diagram below.

Arrangement



A rather rugged equatorial is necessary for this telescope because of its length and weight. I was fortunate in acquiring a very substantial mounting which is wholly adequate. I have been advised that I could have used quarter-inch rather than half-inch plywood for the telescope tube without loss of rigidity and so have reduced the weight of the tube by half. The weight of the telescope itself, as is, is about 80 lbs.

Possible uses for a telescope such as this are interesting. It should, of course, serve all purposes of any 6" f/15 refractor. However, this instrument is completely photo-visual in all colors and so is far more adequate for photography than a conventional refractor. Moreover, the field of this Schupmann is flat and uniform. The telescope is essentially coronagraphic in design—this by no means is meant to imply that it could perform as a coronagraph but it does mean to suggest that it might be effective in prominence work. An experiment is underway to make a perforated field mirror which will pass all light and heat out of the instrument and reflect prominences to the Mangin and thence to a 10-Angstrom interference filter at the eyepiece. Another experiment proposes a field mirror which will serve also as a Herschel wedge which, with another Herschel wedge at the second focus, may provide a highly scatter-free image of the solar disc for sunspot and granulation study with full aperture definition and with a moderate transmission filter. A precision rotatable field mirror with several apertures for different purposes is possible.

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THE YOLO REFLECTOR
by Arthur S. Leonard

The Yolo reflector is one of the several new telescope optical systems which were proposed following my discovery in the early 1950s of the field which I called Tilted Mirror Optics. More recently that field has been re-named Tilted Component Telescopes.

Since no mirror surface reflects 100 percent of the light which falls upon it, each mirror in the system adds to the total light loss. Throughout their useful lifetimes, the reflective coatings of most mirrors gradually deteriorate and will be found to have a surprisingly large number of sleeks, pinholes and other imperfections. Also, since no TCT system can be designed to have all the mirror aberrations cancel out completely, each additional mirror will add some minor aberrations to the total. For these reasons the ideal TCT system will utilize toroidal surface curves and other modifications in order to reduce to a minimum the number of mirrors required to achieve the desired degree of perfection of the system as a whole.

A toroidal surface curve is one in which the radii of curvature in two mutually perpendicular planes through the axis of the mirror are different. The ocean surface at the earth's equator is toroidal. In the east-west plane of the equator, the radius of curvature is 6378.16Km. In a north-south plane it is 6335.46Km. This amount of toroidalness (ratio of the two radii of curvature) is just about the same as that encountered in a typical TCT.

By using one or more toroidal surface curves, very good performance can be realized in TCT systems employing only two tilted mirrors; the Neo-Brachyt and Yolo are two such systems. In designing a Yolo reflector we adjust the tilt angles and radii of curvature of the two mirrors and other parameters of the design to make the ordinary coma of the secondary just equal and opposite to the ordinary coma of the primary mirror. The ordinary astigmatism of the secondary is of the same sign as that of the primary, so the two are additive. In this optical system, the surface curve of either the primary or secondary (or both) is made toroidal by the correct amount to cancel the ordinary astigmatism of the system. By designing a fairly long focal length, the sum total of all the minor aberrations can be made small enough not to be bothersome.

In a 12-inch f/17 Yolo which has been in operation for the past eight years, the ordinary coma of the primary (which is cancelled exactly by the coma of the secondary) amounts to $\pm 2.62\lambda$. The net line coma of both mirrors together amounts to only $\pm 0.0055\lambda$. However, if we were to cut the focal length in half, the line coma would be increased by a factor of 32! In this case it would go through a complete range of 0.35λ (from -0.175λ to $+0.175\lambda$) and its presence in star images would be noticeable.

The following table gives limiting back focal length to aperture ratios for Yolo reflectors for a range of different apertures. Two slightly different designs—"Conventional" and "All Toroidal"—are listed. The Conventional Yolo has all the necessary aspherization applied to the primary mirror while the secondary has a spherical but toroidal surface curve. The All-Toroidal Yolo employs a paraboloidal curve on its primary and an hyperboloidal curve on its secondary. Both mirrors are made toroidal by the optimum amount. A limiting total residual aberration of $\pm 1/20$ wavelength was employed in making the calculations.

Aperture, inches	Conventional Yolo	All-Toroidal Yolo
4	5.06	3.06
5	5.30	3.15
6	5.49	3.30
8	5.83	3.49
10	6.10	3.64
12.5	6.38	3.81
16	6.71	3.99
24	7.29	4.31
30	7.63	4.50

Table 1. Limiting back-focal-length-to-aperture ratios for Yolo reflectors for a total residual aberration of $\pm 1/20$ wavelength.

A comparison of the performance of the Yolo with other well-known optical systems shows its residual aberrations to be about equal to those of the achromatic doublet. The Yolo can be designed as fast as f/5 with a 5-inch aperture and still give diffraction-limited performance on axis. This is about equal to the performance of a good 5-inch, f/5 doublet lens with monochromatic light. The All-Toroidal Yolo can provide a satisfactory design for an aperture as large as 120 inches. This design requires aspherization of its primary mirror, but not nearly so much as that of a Newtonian. The primary of the Yolo must be tilted out of proper collimation by about three times the angle of the Newtonian to produce the same optical error.

Experience with the already mentioned 12" Yolo has shown that it is easy to keep in proper adjustment. If any reader thinks he would like to make a Yolo, I shall be pleased to give him the necessary information. My address is: 740 Elmwood Drive, David, Calif. 95616.

DESIGN FOR A YOLO REFLECTOR
by Arthur S. Leonard

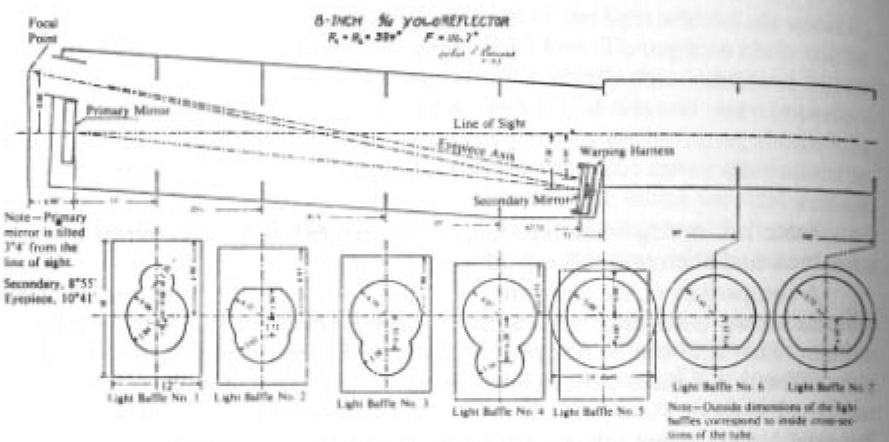
Glass.	Standard Corning 8" and 6" mirror blanks. Recommended fine annealed.	
Primary.	Front surface radius of curvature	32′ 0″
	parabolization	392%
	Back surface may be left as cast, but recommend grinding reasonably flat and deep enough to remove most of the depressions left by the casting process. The thickness should be uniform to within .001" to .002".	
Secondary	Front surface radius of curvature	32′ 0″
	parabolization	none

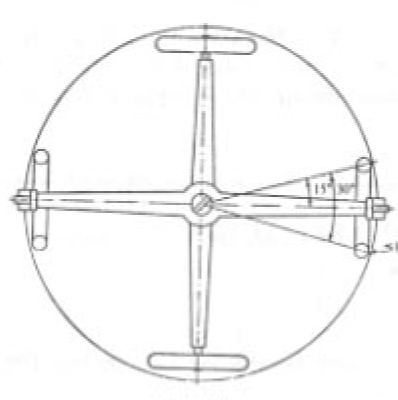
Back surface must be ground reasonably flat and deep enough to remove *all* depressions left by the casting process. Edge thickness uniform to about .001"

Thickness Reduce by grinding to about 0.75".

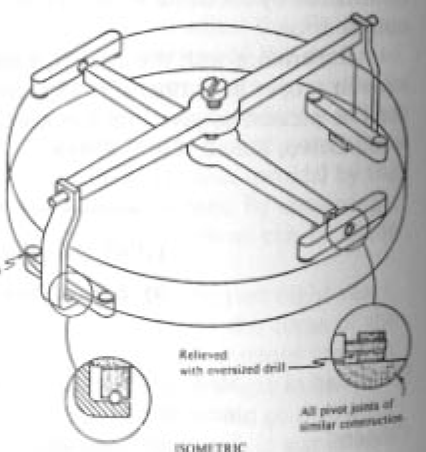
Effective focal length 116.7".

Note. All grinding should be completed on both sides of the blank before starting to polish it.



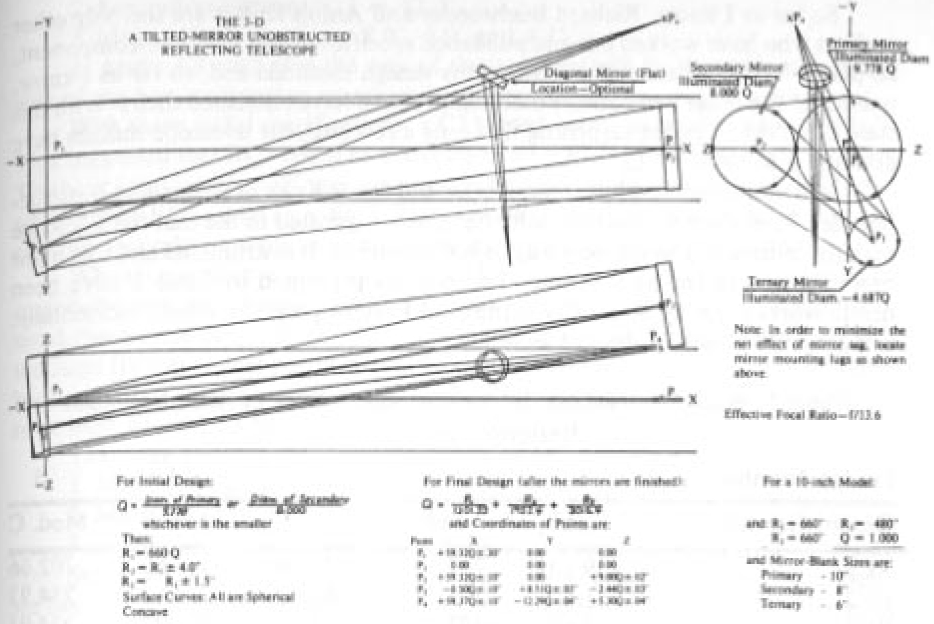


PLAN VIEW



ISOMETRIC

WARPING HARNESS DETAIL
YOLO REFLECTOR



THE SOLANO REFLECTOR
by Arthur S. Leonard

The Solano reflector can be described as a three-mirror, coplanar (all mirrors tilted in the same plane), tilted-component telescope which employs a concave primary, a concave secondary and a convex tertiary mirror. The basic configuration of this optical system is shown in Fig. 1. The Solano optical system was first described in 1969, the first specific (workable design) was published in 1971.

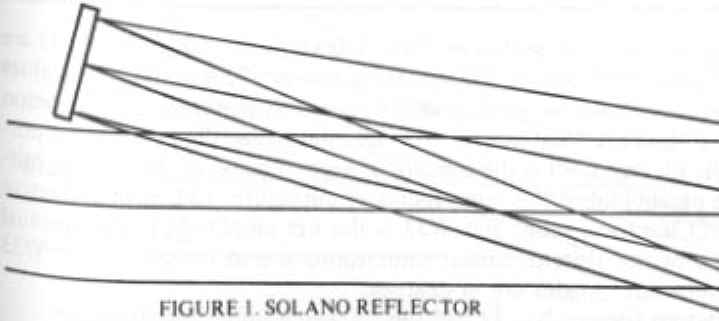


FIGURE 1. SOLANO REFLECTOR

BASIC CONFIGURATION

So far as I know, Richard Buchroeder and Anton Kutter are the only other authors who have worked out and published specific designs for three-component, co-planar TCTs. I have not published my design methods and, so far as I know, neither of the other two authors mentioned above have published theirs. With this state of affairs, it is not surprising that only a few amateur telescope makers have attempted to build TCTs.

Recent publication by Anton Kutter and Oscar Knab of design and construction details of their 4.3-inch tri-schiefspieglers suggested to me that the telescope making community might be ready to build more such instruments and that a few more designs might be welcome. The designs presented in Table 1 have been delete worked out by a recently completed Fortran program which, incidentally, will generate tri-schief designs as well.

Table 1. Numerical values for various parameters of sample Solano Reflector designs.

Design Number	1	2	3	4	5
Design Geometry	Basic	Basic	Mod. A	Mod. B	Mod. C
RC1	239.20	287.20	231.76	565.68	702.66
RC2	381.60	393.77	480.65	224.82	234.93
RC3	−381.60	−393.77	−93.81	−224.82	−234.93
S12	42.00	52.00	42.00	42.00	42.00
S23	41.00	50.50	42.50	44.00	43.50
S3F	15.35	12.83	20.00	46.00	64.50
A1	10.40	8.40	10.40	11.70	11.70
A2	8.00	6.46	8.50	8.40	8.40
A3	80.60	82.44	44.00	28.2204	23.2282
D1	8.00	8.00	8.00	8.00	8.00
D2	5.19	5.10	5.10	6.81	7.04
D3	1.33	0.98	1.26	2.90	3.44
−K1	2.24	2.60	1.65	21.46	29.08
EFL	92.5	104.6	126.6	126.9	149.8
F/D	11.52	13.08	15.82	15.86	18.72
W33	±5.95	±3.00	±2.71	±1.99	±1.42

The numerical values presented in Table 1 (except the values for W33) are sample outputs from this program. RC stands for radius of curvature. Plus values mean that the mirror is concave—minus values convex. S stands for the separation distance, and S3F the back focal length. D is the illuminated diameter of the mirror. A is twice the tilt angle. K1 is the amount of aspherization of the primary mirror relative to a paraboloid of the same radius of curvature. EFL is the effective focal length, F/D the focal ratio, and W33 is the net amplitude of the residual three-cycle coma of the system. Linear dimensions are in inches, except W33 which is in microinches. Angles are in degrees.

The first design (design No. 1) had the following initial specifications:

1. Aperture D1 = 8.0″
2. Separation distance S12 = 42.0″
3. Mirror blank diameters 8.0″, 6.0″ and 4.25″
4. Angle A3 such that the axis of the eyepiece will be perpendicular to the side of the box, or housing on which it will be mounted.

With these initial specifications, RC2 turned out to be nearly equal to −RC3. This suggested that RC2 could be made equal to −RC3 by fine tuning the design. The back focal length, S3F, was then varied by small steps until a value was found which made RC2 equal to −RC3. This will allow the telescope maker to use the concave secondary mirror as a match-plate for testing the convex tertiary.

When we study the numerical values for the first design, we find everything reasonable and satisfactory—except the value for W33, the residual uncompensated three-cycle coma. In this design it amounts to ±0.272 wavelength. This is too large for top optical performance. In order to correct this deficiency, let us go back and check the basic design rules for TCTs to see what we may have violated—or at least stretched a little bit too far.

The three cardinal rules for the design of any TCT are:

1. Make all angles as small as possible.
2. Make all radii of curvature as large as possible.
3. Make each mirror surface toroidal by the optimum amount.

Since the Solano is a TCT which employs non-toroidal surface curves only, we can be excused for violating Rule No. 3. If we should increase the separation distance S12, we will have to increase all radii of curvature and we will be taking heed of Rule No. 2. Design No. 2 (second column, Table 1) has the same design specifications as No. 1, except that the separation distance, S12, has been increased from 42 to 52 inches. As a result of this change, W33 is reduced to ±0.137 wavelength, a more acceptable value.

When we look into the possibility of reducing the residual three-cycle coma through the application of Rule No. 1, we find that in the basic design, angles A1 and A2 are as small as they can be made with the separation distances and mirror blank diameters chosen; but angle A3 is quite large. Thus, to improve the performance of the basic design, we should try to reduce angle A3. In designs 3, 4 and 5 the aperture and overall length of the first basic design have been retained, but angle A3 has been progressively reduced. Note that with every reduction in A3, W33 is reduced. In modification C the residual three-cycle coma amounts to only ±0.065 wavelength. This is so small that this design could safely be scaled up to

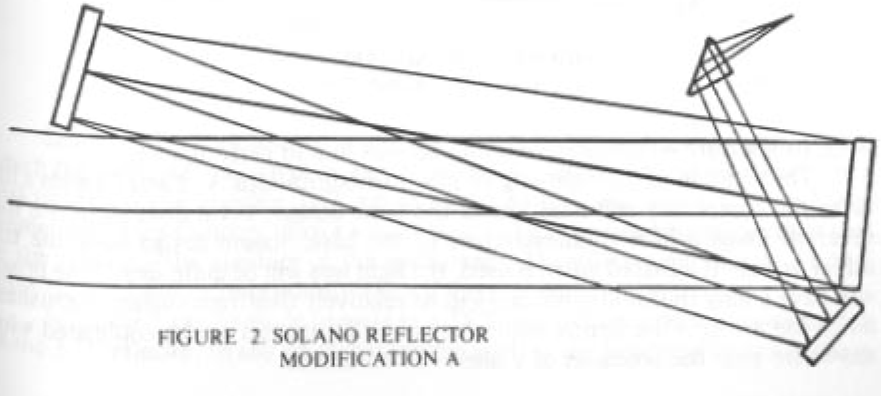


FIGURE 2. SOLANO REFLECTOR MODIFICATION A

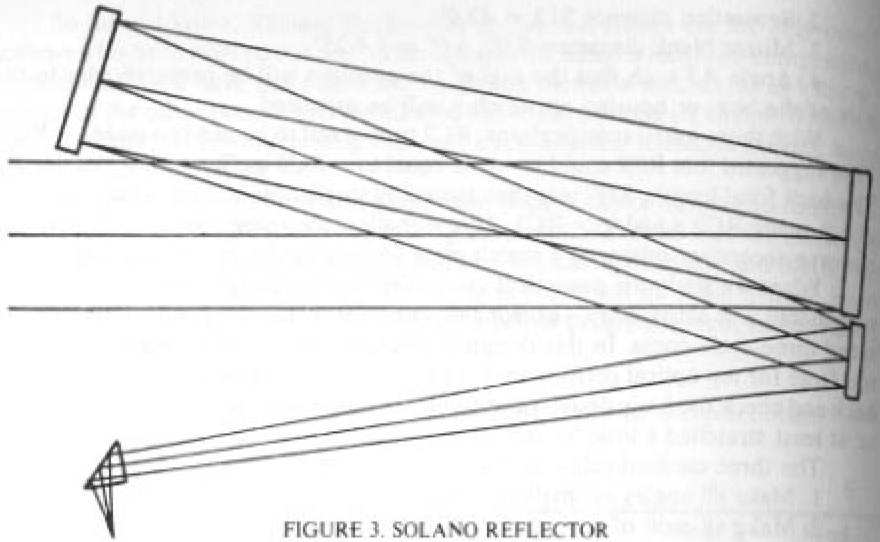


FIGURE 3. SOLANO REFLECTOR
MODIFICATION B

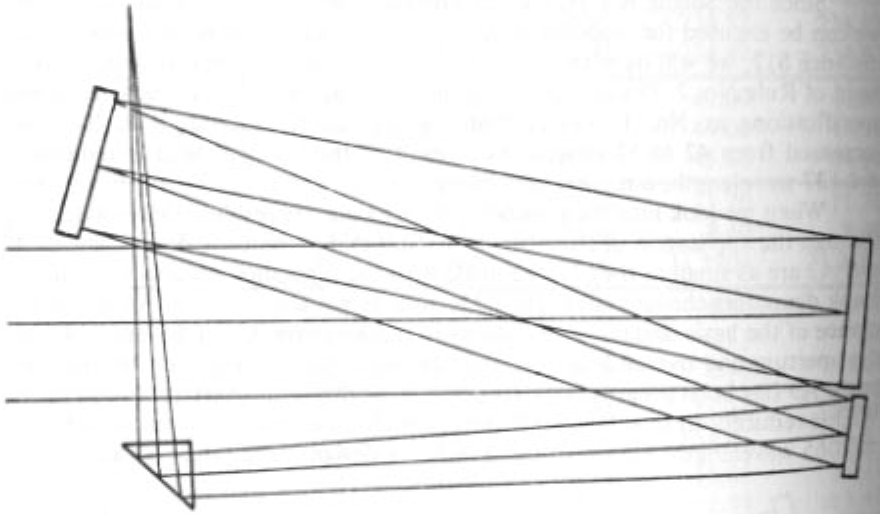


FIGURE 4. SOLANO REFLECTOR
MODIFICATION C

twice its aperture—16 inches—without serious loss in performance.

The addition of the right-angled prism (modifications A, B and C) adds a little to the complexity and light loss of the basic design, but it does eliminate the reversed image which is characteristic of the basic Solano design—and the tri-schief as well. If a coated prism is used, the light loss will be quite small. The prism will have a long useful lifetime and will be relatively free from surface blemishes. Since the prism is the optical equivalent of a flat, it need not be collimated with anywhere near the precision of a tilted curved mirror.

In designs 4 and 5, the angles A3 have been carefully adjusted to make RC2 equal to −RC3. If we would be willing to forego the advantage of being able to use the secondary mirror as a match-plate for the tertiary, W33 could be reduced to values somewhat smaller than those given.

Asphherization

In theory, the primary mirror should be a paraboloid of revolution and the secondary and tertiary mirrors, hyperboloids. However, the radius of curvature of each mirror is so great compared with its diameter that very little aspherization would be required on any of the mirror surfaces. To simplify the problems of the optician, the designs presented here call for the primary to be aspherized (parabolized) by an amount sufficient for all three mirrors, and the secondary and tertiary made spherical. The value of −K1, given in Table 1, is the amount of parabolization required on the primary mirror of each design. Although 29.08 times the amount required to turn a sphere into a paraboloid (design No. 5) might seem a lot, it is actually quite small and is equal to the amount required to produce an 8-inch, f/14.25 paraboloid from a sphere.

A Word of Caution.

This article is intended to cover only the optical design of the Solano reflector, present some of the forms it might take, and to give some idea of its performance capabilities. It does not touch on the problems of mechanical design and collimation procedures. Any telescope maker who plans to build one of these instruments should plan carefully for this part of the project before starting construction.

Other Possible Three-Mirror Designs.

In Table 2 are listed all possible ways in which three curved mirrors can be arranged in sequence:

Table 2. Possible three-mirror sequences.

Sequence	Primary	Secondary	Tertiary
1	Concave	Concave	Concave
2	Concave	Concave	Convex
3	Concave	Convex	Concave
4	Concave	Convex	Convex
5	Convex	Concave	Concave
6	Convex	Concave	Convex
7	Convex	Convex	Concave
8	Convex	Convex	Convex

Sequence 8 cannot be used in any kind of telescope because there is no way in which the three radii of curvature can be adjusted to make the combination form a real image. In any possible TCT which might employ sequences 5, 6 or 7, the diameter of the secondary mirror would have to be considerably greater than that of the primary—the aperture of the instrument. Therefore sequences 5, 6 and 7 must be ruled out as impractical—even if they could be made to work.

Sequence 1 can be made to work in a TCT, but only in a skewed system such as the 3-D reflector. In any co-planar system such as the Solano or tri-schief there is no possible combination of radii of curvature which will allow the astigmatism (on-axis) to cancel out. This disposes of sequence 1. Sequence 2 is employed in the Solano, and sequence 3 in the 3-mirror schief and the tri-schief.

I have tried to put together a workable TCT system employing sequence 4, but so far have been unsuccessful. I would not go so far as to say that there cannot be any combination of radii of curvature, separation distances, and tilt angles which will yield a workable TCT using this sequence, but I do feel that if any workable combination is found, it will not be really competitive with the better Solano and tri-schief designs. Therefore, the Solano and tri-schief mirror sequences appear to be the only really useful three-mirror co-planar configurations which can be used in TCT designs.

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3. R.A. Buchroeder, "Design Examples of Tilted Component Telescopes (TCTs)", OSC, University of Arizona, Technical Report 68, May 1971.
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5. Anton Kutter, "A New Three-Mirror Unobstructed Reflector", *Sky & Telescope,* Jan. & Feb. 1975, Vol. 49, Nos. 1 & 2, pp. 46-48 and 115-120.
6. Oscar R. Knab, "Making the Kutter Tertiary", *Sky & Telescope,* Jan. & Feb. 1975, Vol. 49, Nos. 1 & 2, pp. 48-49 and 121.

A VISUAL WRIGHT TELESCOPE
by Edgar Everhart, PhD.

The Wright telescope at f/5 is the best possible design for low power, wide field visual use. Such a telescope is also a camera with a flat field and superb definition.

Comparison with Other Systems.

The optical system was invented by Franklin B. Wright in 1935, (P.A.S.P. 47, 300, 1935; Amateur Telescope Making—Advanced, *Scientific American Inc.,* New York, 1952, p. 401). It is related to the Schmidt system in that both use a corrector plate. The Wright corrector, however, is twice as strong as the corresponding Schmidt corrector and is located at the focus rather than at the center-of-curvature of the mirror. Another difference is that the Wright primary is an oblate spheroid rather than a sphere.

It is easy to understand the rationale for the Wright design. The oblate

spheroidal primary is made to have exactly twice as much spherical aberration as a spherical mirror would have and therefore the corrector must be twice as strong to cancel this. Balancing the aberrations in just this way, with the corrector at the focus, turns out to eliminate coma completely. A detailed description of both Schmidt and Wright systems has been given by Linfoot (E.H. Linfoot, *Recent Advances in Optics,* Oxford University Press, London, 1955, p. 272 ff.). The Newtonian, Schmidt and Wright systems are compared in Table 1 and the geometrical aberrations off-axis are shown in Fig. 1. The fine performance of the Wright system at f/5 approaches the perfection of the Schmidt system, and this is achieved with a short tube and flat focal plane.

f/5	Newtonian	Schmidt	Wright
tube length	F	2F	F
coma	very bad	none	none
astigmatism	bad	none	negligible
field width	narrow	very wide	wide
focal surface	flat	curved	flat

The Maksutov-Bowers design has similar characteristics to the Schmidt.

Table 1. System Comparison.

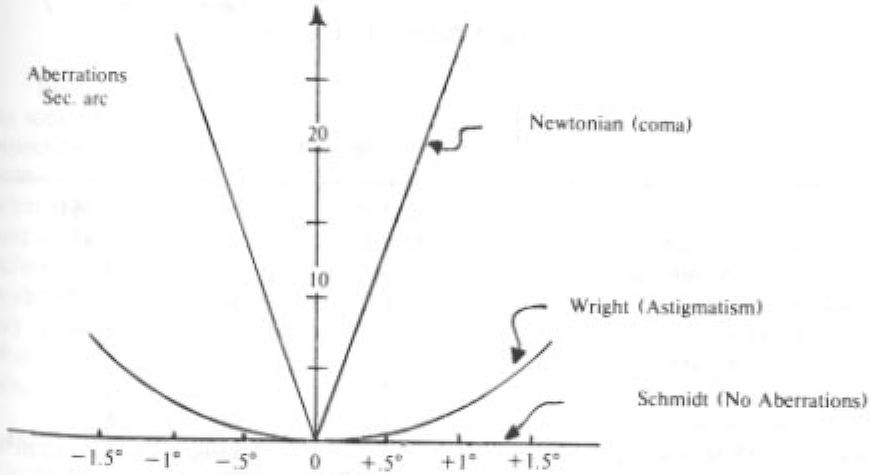


Figure 1. Off-axis aberrations of several f/5 systems.

A rich field visual telescope should be close to f/5 proportions in order that the optimum ¼" exit pupil can be obtained with available 1¼" focal length Erfle eyepieces. An f/4 design would invite serious eyepiece problems, but a permissible variation would be an f/6 design with a 1¼″ giant Erfle eyepiece. The diagonal mirror in this case would have to be even larger to cover the field of this large eyepiece.

A recommended 11¼″ Wright design which has been built and tested is shown in Fig. 2, and Table 2 gives dimensions for this and two smaller instruments. The focal plane is set in close in order to minimize the size of the diagonal needed. The eyepiece holder must be considerably larger than the standard size in order to utilize the full field of the 1½″ Erfle eyepiece and accommodate its very considerable bulk. To cut down the eyepiece's field with an adaptor or to use orthoscopic eyepieces would defeat the wide-angle capabilities of the design.

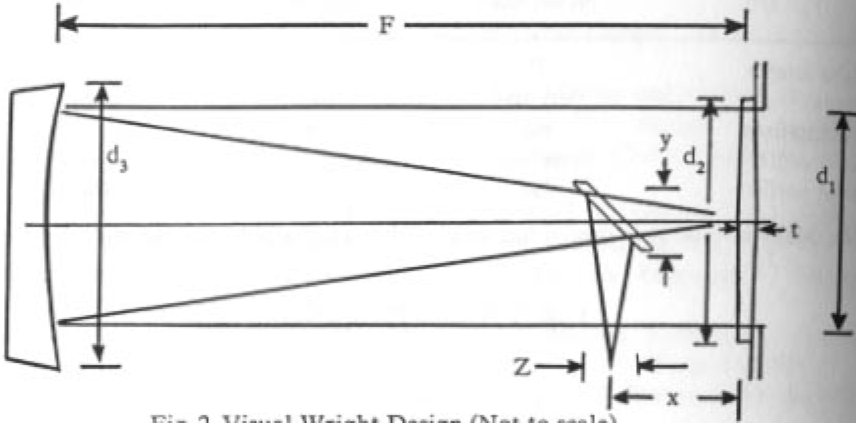


Fig. 2. Visual Wright Design (Not to scale)

Table 2. Wright designs.

clear aperture d_1	11.25″	9.00″	7.25″
dia. of corrector disc d_2	11.75″	9.50″	7.87″
dia. of primary mirror d_3	12.50″	10″	8″
thickness of corrector t	0.625″	0.500″	0.375″
focal length F	56.25″	45″	36.25″
cone interception x	7″	6″	5″
diagonal mirror minor axis y	2.75″	2.50″	2.25″
field stop, eyepiece z	1.25″	1.25″	1.25″
pressure differential (approx.) p	5.5 lbs/in²	5.5 lbs/in²	4.4 lbs/in²
deflection of plate h	0.00171″	0.00143″	0.00127″

Neither the oblate spheroidal primary mirror nor the corrector plate offers serious difficulties using the tests and procedures to be described.

Primary Mirror.

The figure required on the mirror is *exactly* the opposite of the corresponding paraboloid. It could be measured by zonal testing simply reversing the sign of the knife-edge setting for the paraboloid.

Unlike the paraboloid, the outer zones focus closer to the mirror than the center zone and the "doughnut" figure of the Foucault test is reversed and appears with a high center and turned-up edges.

There is introduced here, as a better alternative, a useful null test for the mirror. The oblate spheroid required in the Wright design is obtained by rotating the ellipse shown dotted in Fig. 3 about its minor axis OV. This ellipse has an eccentricity of 0.71 and is in proper proportion when OV, OA and OB are all equal to F, the focal length. Here A and B are conjugate foci and are the proper locations for pinhole and knife-edge respectively. After measuring F in the usual way, one makes a rather accurate layout, within ¼ inch, for this null test.

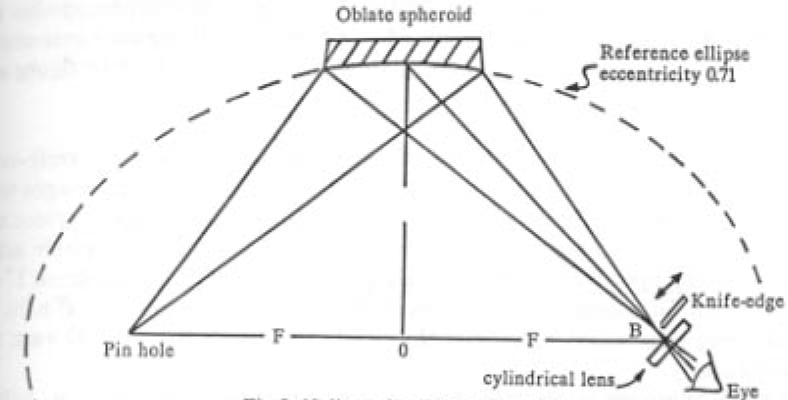


Fig. 3. Null test for oblate spheroidal mirror for Wright Telescope

Instead of seeing the mirror flooded with light as in the usual Foucault test, one sees only a thin bright line on the horizontal diameter of the mirror. For visual inspection, this line of light must be spread out vertically, and this is done with a plano-cylindrical lens between the knife-edge and the eye. A focal length of a few inches is suitable with the axis of the lens horizontal. One sees a broad horizontal band of light across the mirror. Starting with a spherical mirror and moving the knife-edge across the focus, one sees this band looking like a slice of the usual parabolic "doughnut." Distances AV and BV must be fairly nearly equal otherwise very unsymmetrical and misleading figures are seen. When the proper oblate spheroid is achieved, a uniform band is seen as the knife-edge cuts across the focus.

The image of the pinhole is highly astigmatic. It is brought to a focus at B in the horizontal plane, but not in the vertical plane. For this reason, the knife-edge at B must be accurately perpendicular, otherwise there is a skewed or oblique appearance to the edge of the band of light as the knife-edge cuts across. Despite these several peculiarities the test has proved to be quite satisfactory in practice.

The oblate spheroid is somewhat more difficult to achieve than a paraboloid because it has a high center and a turned-up edge. The author used a "rose-petal" lap (such a lap is pictured by H. W. Cox and L. A. Cox in *ATM III*) and also did some local work with sub-diameter laps. One must be careful not to go too near the center and also to stay away from the edge. The greatest depth is at the 0.7 radius zone. The result was the correct general shape and depth but with minor irregularities and an edge which turned up too much! Then a rather soft full-diameter lap was made and used with short strokes and with frequent cold pressing. This smoothed the irregularities and simultaneously reduced the turned up edge. Frequent testing was needed to stop at just the right point. Figuring took only a few hours, but making the test rig and thinking (mostly the latter) took several days.

Corrector Plate.

This is very easy to make if one follows the vacuum method. The desired correction is automatically achieved when one fine grinds and figures the corrector with a partial vacuum on one side of the plate. Table 2 gives the approximate values of pressure differential p needed for the designs presented and also the deflection h for the plate, it being assumed that both sides of the corrector will be figured. Fine grinding and polishing the corrector took eight hours. Its figure was correct and without zones when first tested.

Performance.

The completed 11¼" Wright telescope was tested outdoors with a knife-edge null test using light from Polaris. At low and intermediate powers the images seen were excellent—in fact, the aberrations seen were entirely due to the eyepiece and imperfections in the observer's eye. There was neither coma nor detectable astigmatism when the eyepiece was bodily moved laterally so that it was centered 1° off the optical axis. Of course, the eyepieces themselves have aberrations off axis. Of the many eyepieces tested, Edmunds No. 5160 and Jaegers No. 1E2670 were the most satisfactory.

An f/5 telescope is not intended for use at high powers. However, with a short focal length eyepiece the diffraction disc of stars is seen, and powers to 150x are usable, on the moon and planets. There is, however, some flair to the star images noticeable at this power which is due entirely to imperfections of execution and not in the design.

The completed telescope has been magnificent for sky-sweeping, comet searches, faint variables and deep sky observing. The star images are such that if it were set up as a camera, the resolution at the edge of a three-inch diameter circle would be better than the photographic plate can resolve.

PREDESIGNED DOUBLETS

by R. A. Buchroeder

Some computer-designed, coma-free astronomical objectives are given in the tables with "normalized" focal lengths. If these data are multiplied by the focal lengths you desire, then any size design is available and will still be optimized. Designs faster than f/8 are intended for R.F.Ts, and experimental or laboratory use. Those slower are well suited for telescopes.

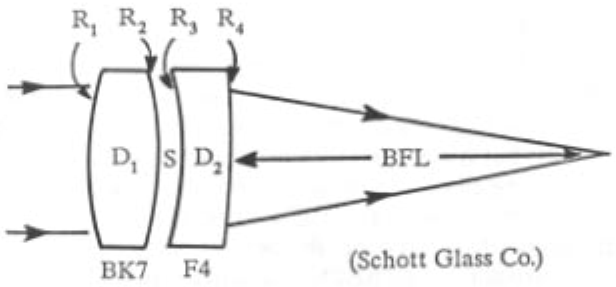
Two groups were computed. The upper one is for color correction F to C (hydrogen blue and red). Baker, Kitts and the current Carl Zeiss (West German) are of this correction. The lower list is for ones in which the blue is over-corrected (achromatized more to the red). This was the choice of Clark, Brashear and most of the old masters. The reader is left to make his choice, either type is well corrected.

For tolerance, 0.1% on radius and .004" on thickness are customary. Diameters of the elements are a few percent larger than the design aperture, of course. Because of the identical inside curvatures, coating the lenses is recommended; this will also improve the transmission 12% and darken the sky background.

Example.

Design a 6" f/8 with the "Clark-type" achromatization.

Look in the lower table and find f/8. The lenses all look like the sketch and the sense of curvature is shown. A negative radius is one that bends to the left; a positive to the right.



EFL = .5738786 x 48" = 27.546"
R_2 = R_3 = −.3457343 x 48" = −16.595"
R_4 = −1.6280643 x 48" = −79.147"
D_1 = .015625 x 48" = .750"
D_2 = .0177187 x 48" = .562"
S = .0035622 x 48" = .171 *nominal;* adjust as required.
BFL = .9776662 x 48" = 46.928" nominal; take what you get.

Telescope Objectives, Aplanatic.

dFC EFL = 1.0

Speed	R_1	$R_2=R_3$	R_4	D_1	S	D_2	BFL
f/2.5	.4563057	−.4335834	−7.1723772	.1250000	cemented*	.0375000	.8852328
f/5	.5841218	−.3592279	−1.5815394	.0312500	.0026378	.0187500	.9684933
f/8	.5816707	−.3551441	−1.5979841	.0156250	.0029742	.0117187	.9794070
f/10	.5806793	−.3540666	−1.6044717	.0125000	.0030548	.0093750	.9819099
f/12.5	.5800109	−.3534947	−1.6096165	.0100000	.0031071	.0075000	.9839507
f/15	.5796336	−.3532560	−1.6129772	.0083333	.0031360	.0062500	.9853302

*Not aplanatic

Clarke-type Achromatization (.5150-.6563μ)

f/2.5	.4400397	−.4307301	−15.6571140	.1250000	cemented*	.0375000	.8807615
f/5	.5752874	−.3504293	−1.6190800	.0312500	.0031308	.0187500	.9668104
f/8	.5738786	−.3457343	−1.6280643	.0156250	.0035622	.0117187	.9776662
f/10	.5731011	−.3445286	−1.6331737	.0125000	.0036630	.0093750	.9801488
f/12.5	.5725627	−.3438798	−1.6375123	.0100000	.0037271	.0075000	.9821834
f/15	.5722596	−.3436964	−1.6404310	.0083333	.0037634	.0062500	.9835602

*Not aplanatic Glass: BK7, $N_d = 1.516798$, $V_d = 64.143$
F4, $N_d = 1.616588$, $V_d = 36.612$

Note by Ed: In the U.S.A. the most readily obtainable glass for doublets is from Schott. The above tables give a very easily computed design for any size of telescope that is likely to be built by the amateur, without the bother of trigonometric tracing. Mr. Buchroeder has done it all for you on the large computer available to him.

THE HOUGHTON CAMERA
by R. A. Buchroeder

The Houghton Camera, shown in Fig. 1, is an all-spherical substitute for a Schmidt camera. This particular design, computed by the writer for the utmost convenience with amateur methods, lacks the perfection possible in a fully-optimized design (see James Houghton's patent No. 2350112, 1944), but is quite satisfactory as can be seen from Fig. 3. Due to the simplification of having all curvatures equal, the color is a bit undercorrected but its oblique spherical aberration is about 25% worse than that of a comparable true Schmidt. If this simplicity is foregone, the designs based on the Houghton principle of the afocal corrector can surpass true Schmidts, particularly in the Schmidt-Cassegrain versions, where it excels.

The advantage of the Houghton over the Maksutov, which also uses only spherical curves, is that field correction is superior and tolerances are much more lenient. In a Maksutov, one obtains corrective spherical aberration as the differential between the front and rear surfaces of the meniscus lens, and the near-concentricity of the lens minimizes the astigmatism in the field. However, the fact that the lens is non-concentric in order to be achromatic means that it cannot avoid off-axis aberration. In the Houghton, the "work" is done by the curvatures of the lenses, and the lens thicknesses are consequently no more important than the air spaces, against which they can be traded off. If the lenses were infinitely thin, and if the curvatures didn't bump into each other, the performance of the Houghton would be *identical* to that of the true Schmidt. But even with the thick lenses, the difference is not great. Color is self-cancelling because the net power of the corrector group is zero. Field aberrations, as in the Schmidt, are cancelled (to the third order) by the symmetry of the design. As in the Schmidt, it is limited by an aberration known as "oblique spherical aberration" (also known in some quarters as cubic astigmatism), against which we have no convenient cure.

I started building my Houghton camera back in 1967 with the help of Mr. Al Bowen (now at Wollensack in Rochester). We finished the optics in late 1968, but it was only recently that I got around to making a tube and lens cells. The instrument was first tested on January 1, 1972. The results were good enough to convince me that the Houghton camera is simple to build, quite forgiving of errors, and might be of interest to fellow ATMs who, like me, feel that a true Schmidt

6-INCH APERTURE, f/3 HOUGHTON CAMERA
10° Total Field

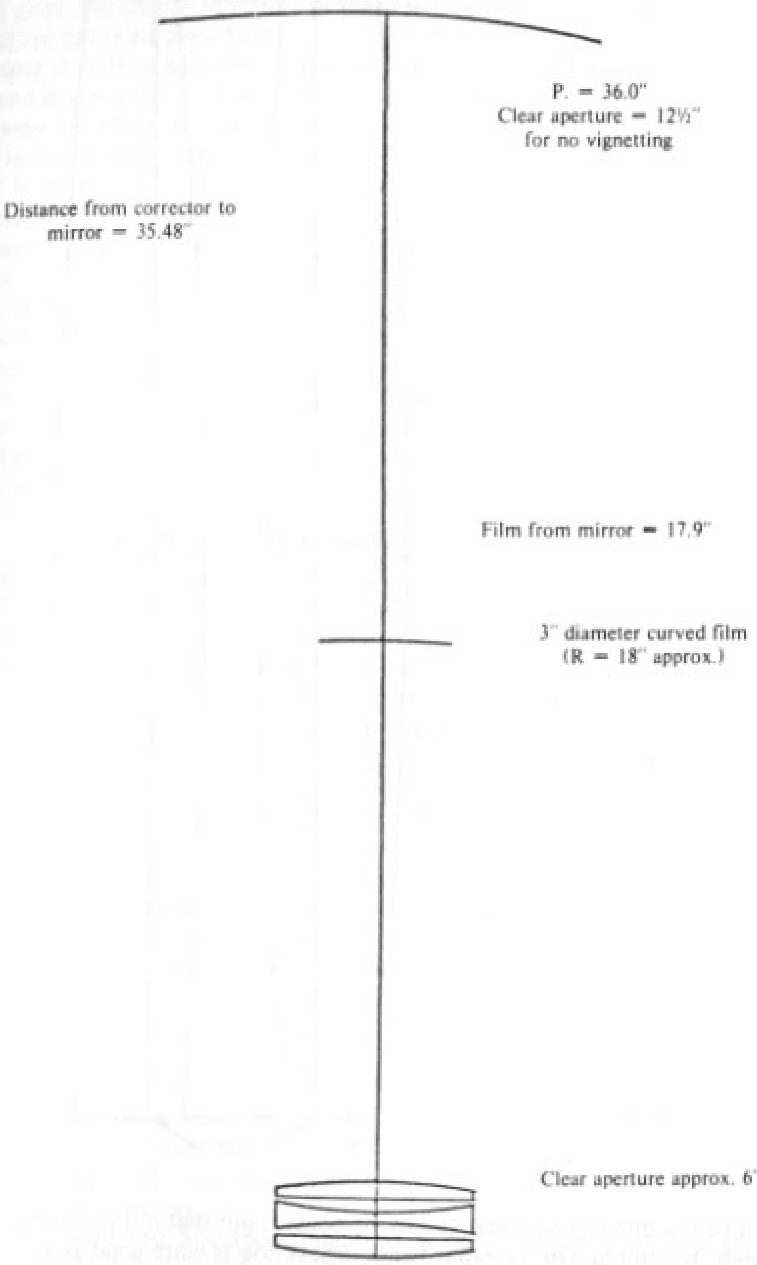


FIGURE 1

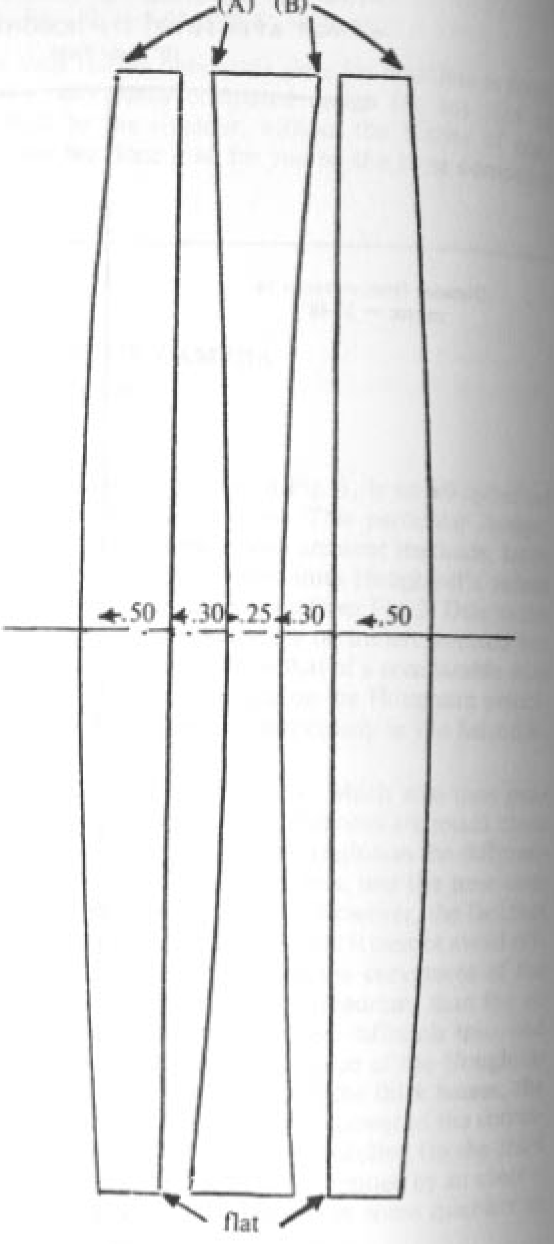


FIGURE 2

would be too difficult to make. It may be pointed out that if one *can* make a true Schmidt, he should. On the other hand, unless one is quite good at aspherics, he will get a better performance by making this spherical design. The tradeoff here is hard work versus mastery of the optician's art.

Fig. 2 shows the details of the corrector. Normally the design is computed for BK-7, but *any* kind of glass may be directly substituted so long as every lens is of the *same* kind of glass. By grinding the lenses against each other, all with the same curve, the color is automatically cancelled. Unless one goes to some quite peculiar kind of glass, the change in refractive index will be either negligible, or cancellable by readjusting the air gaps. Note in Fig. 2 that the curves which are ground against each other should be assembled *opposite* from each other. This automatically cancels coma in the corrector group, regardless of mismatch in the ordinary curves. If coma were noted in the assembled unit, respace the entire corrector unit with regard to the mirror; by this means any error in coma can be corrected completely.

It is assumed that the mirror will be made to within half an inch of the 36" specified. If it is off worse than that, then one is well-advised to alter the corrector curvatures in the same ratio; if the mirror comes out long, make the corrector radii a bit long; the opposite if it comes out short. Now, if the assembled unit shows under-corrected spherical aberration, the lenses should be spaced more closely. If overcorrected, increase the air gap between the lenses. This is a privilege that one does not have in a Maksutov, and a decided advantage if one wants a well-corrected system without repeated rework. (There is, in fact, a two-lens afocal corrector that is equivalent to the Maksutov; an air gap becomes equivalent to the single shell Maksutov; the drawback is that it, like the Maksutov, has field aberrations.)

One always wonders how well something has to be made to work adequately, so Fig. 4 is an approximate method of estimating your performance. Assuming the curves are smooth, then if the corrector is too weak, the spherical aberration will be undercorrected and the blur size large. If the corrector is too strong, the spherical aberration will be overcorrected and again the blur size too large. The rate at which the blur size increases is indicated on the graph. Now, it is in fact better to err on the weak side on the corrector. The reason is that then the axial spherical aberration will compensate the aforementioned oblique spherical aberration and the edge of the field will be improved compared to the nominal design. The amount required is only a percent or so, and it is probably best to ignore it.

First test photos were taken with the camera unguided and pointed to the celestial pole. Flat IIaO glass plates were held onto my incomplete film-holder using double-sided tape. The camera was adjusted for centering by viewing in and looking at the reflections, and focused on a mountain. At night, a 15-second exposure (the moon was full that night and my neighbourhood is "blessed" with abundant mercury lighting) gave a "sky-limited" exposure. Measuring the plates the following day, the sharply focused areas where the curved image surface intersected the flat plates showed spot sizes that were under 50 microns in diameter. Because the corrector radii turned out to be 7% too weak, and we didn't bother to rework them, this is not far from the computed size of 25 microns.

No indications of ghost images, although my lenses are all uncoated, were detected, so they must be comfortably so far out of focus as to be negligible. Coating will increase the transmission by about 30%, but since the camera is f/3, we have light to spare. The user will decide whether he can afford the luxury of magnesium fluoride coatings.

A few words on tolerances might be in order, although no real study of "practical" defects has been made. The lenses should be well centered, if possible, although our camera has the lenses taped together, which could be considered intolerably sloppy. If the mirror is tiltable, and the film-holder too, then there should be no need to tilt or adjust the corrector lenses, so long as they were reasonably set in line in the first place. Thicknesses on the lenses may be disregarded, but it is better to go on the thin side rather than on the thick. Plate glass, if you can find any without serious striation, should do quite nicely. It has a slightly higher index than BK-7, which is desirable, and its dispersion is low enough for it to work well. Ophthalmic Crown, once available from Coulter Optical, is desirable as it is of higher purity than plate glass. As for the flat sides of the lenses, they needn't be terribly flat (say 5 fringes or so), but like all the surfaces they should be smooth to a fringe or so. This specification isn't far from what the polished surface of plate glass can boast, over the small area of interest. Turned edges may be disregarded so long as they are not too severe. On the concave lens, this will cause some zonal undercorrection which can be balanced by re-spacing the elements. On the corrector lenses, it is desirable to use black paper aperture stops to prevent glistening edges from fogging the image. My concave lens is ground flat over the last 1/8 inch and this makes a nice contacting surface.

I might mention that we *never* tested any of the optical surfaces for figure. We took it for granted that, being rather strong, they would tend to be smooth and spherical. This seems to have been the case, judging from the test photos. The ATM may find it fun to test-plate the lenses one against the other, just to see how they are going.

As yet, I haven't made a curved film-holder. However, the type used by Celestron is most attractive, using magnets to hold the film retainer to the spider.

A few comments on making a "Schmidt" may be of value. First be sure you have a nice, dark sky, for these cameras are so fast and efficient that fogging is a real problem. Second, you'll need sturdy, well-aligned drive, for field rotation due to misalignment will be a problem in a camera such as this which covers 10°. Fine grained, red-sensitive emulsions may be preferred to minimize sky fogging. Finally, making the optics may be only half as much trouble as making the cells, film-holder, tube and access system. My delay in assembling the Houghton is attributable not to the difficulty in making the optics, which we finished three years ago, but to the mess of making the mechanical devices.

One might ask whether a field-flattening lens could be used to avoid the curved image surface. The answer is "yes". It can be a plano-convex lens. Its radius will be:

$$R = \frac{n-1}{n} \times 18''$$

for BK-7 or BSC-2, R = 6.13″
for plate glass, R = 6.17″

It should be as thin as possible, and as perfectly polished as you can make it. Assuming your nominal Houghton is made as perfectly as you can, you'll find your image quality will improve a bit if you *increase* the air gap in the corrector (do it evenly in both gaps), as this compensates the spherical aberration from the field flattener.

I would advise *against* the use of a field flattener. It adds extra losses, and the slightest defects on the lens will record on the emulsion as shadows and imperfections. There is also the possibility of ghost images unless you oil the emulsion onto the flat side of the lens, even then you may get a ghost image.

I haven't any immediate plans for my Houghton camera. The problem is one of lights. Although Tucson is in the middle of the desert, it is a modern city and so severe is the light problem that even the professionals on Kitt Peak, 50 miles to the west, are becoming alarmed by it. It is quite impossible to use a Schmidt anywhere within fifteen miles of the city, and consequently I haven't the inspiration to put the instrument to work.

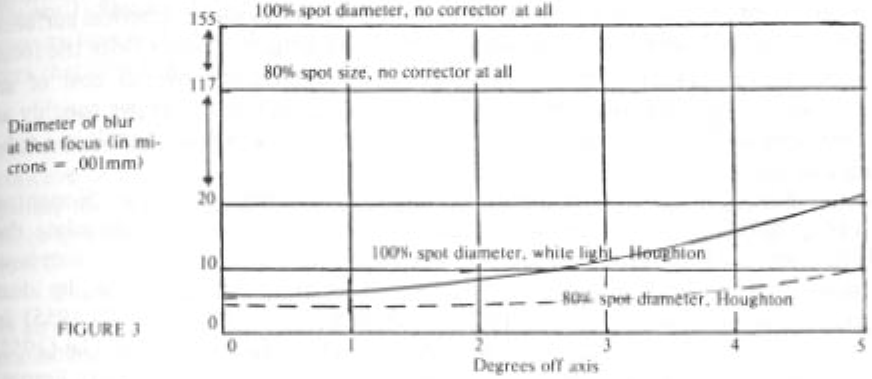


FIGURE 3

EFFECTS OF ERROR ON THE CORRECTOR

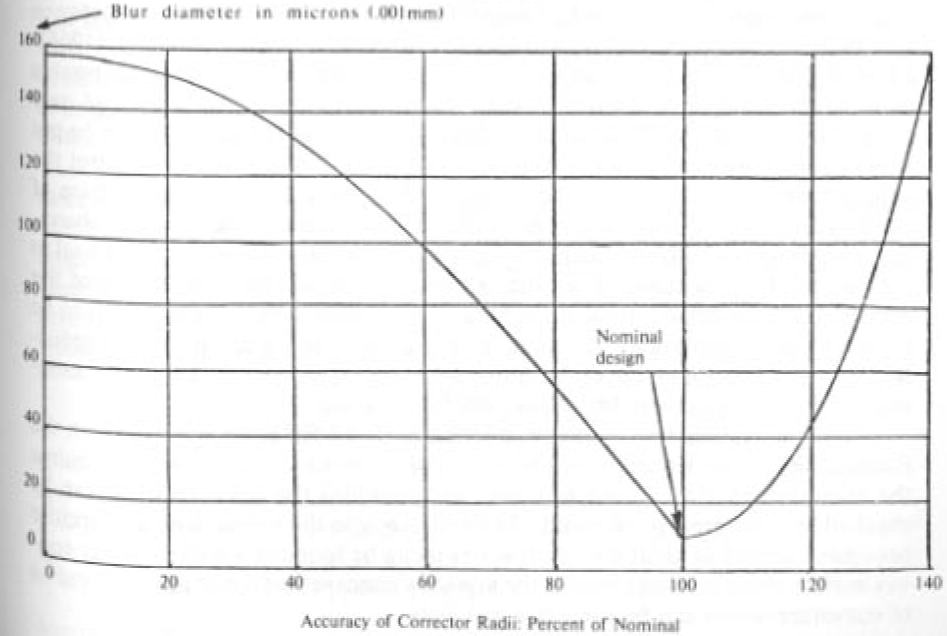


Figure 4.

A SIMPLE HOUGHTON CAMERA

by N. J. Rumsey

The Schmidt camera is conceptually elegant and has a remarkable performance, but it suffers from several practical disadvantages. Two of these concern us here. First, there are very few craftsmen who are competent to make the aspheric correcting plate of the Schmidt camera compared with the number of those competent to make spherical surfaces of high quality. Second, the Schmidt system is very long; it exceeds twice the focal length of the system. Brown (1970) pointed out that the overall cost of an astronomical instrument, together with its building and dome, grows roughly as (tube length)$^{2.5}$. Thus even a modest reduction in tube length can result in a substantial reduction in cost.

Addressing himself primarily to the first of these problems, Houghton (1942, 1945) in Great Britain pointed out that it is possible to simulate the behaviour of a Schmidt correcting plate with a thin group of lens components having spherical surfaces only, the overall power of the group being zero. Similar ideas seem to have occurred independently to Arnulf (1955, Arnulf et al. 1955) in France and Volosov (1948) in Russia. They have been followed up by Gaj (1958, 1959) in Poland, Gelles (1963) in America, Bayle and Espiard (1966) in France, and recently by Wynne (1972) in England.

If one wishes to simulate the behaviour of a Schmidt correcting plate as closely as possible, it is advisable to use a symmetrical group of three lens components. The group may consist of a negative component between two weaker positive components, as favoured by Houghton, or of a positive component between two meniscus negative components, as favoured by Bayle and Espiard (1966). However, even if the group consists of only two lens components (with powers equal in magnitude but opposite in sign), the designer still has more control over the primary aberrations than he has with a Schmidt plate, for the group can be put at almost any distance from the spherical mirror and the designer can control the coma as well as the spherical aberration of the system by the correct choice of bendings for the two lens components. On the other hand, if the spherical aberration and coma are both corrected, the astigmatism of the system is proportional to the square of the distance of the lens group from the center of curvature of the mirror. Thus the system must be as long as a Schmidt if the astigmatism is to be corrected; but a moderate shortening of the system that results in a useful reduction in overall cost may entail the introduction of so modest an amount of astigmatism that such a possibility should not be ruled out.

During manufacture, concave spherical surfaces can be tested easily with the Foucault test or the Ronchi test. The testing of a convex surface normally requires the manufacture of a concave test plate against which the convex surface can be checked by interference and could add significantly to the overall cost. It therefore becomes a matter of great interest if systems can be found in which for every convex surface there is somewhere in the system a concave surface of the same radius of curvature which can be used as a test plate.

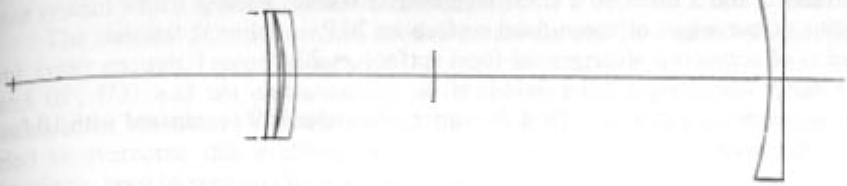


Figure 1. Simple Houghton camera with the same radius of curvature for the two convex lens surfaces as for the (concave) mirror. The overall length is three-quarters that of a Schmidt camera of the same focal length.

I have been able to design a Houghton camera in which there are just two convex surfaces, with the radii of curvature equal to each other and to that of the concave of the spherical mirror. The system can therefore be made without test plates, the mirror substituting for them, as shown in Fig. 1. The tube length is three-quarters that of a Schmidt of the same focal length so, applying Brown's (1970) formula, we expect the cost to be about half.

The astigmatism is not zero. In the most oblique pencil examined, coming in at an angle of 3°.2 to the axis of the system, the blur patch produced by the astigmatism at the mean focal surface corresponds to an angular subtense of 7.5 sec. of arc on the sky. The relative aperture is f/3. For a large scale system, say comparable to that of the Mt. Palomar Schmidt, this astigmatic blurring is greater than that produced by an atmospheric tremor at a good site and the limiting resolution of the photographic emulsion, and therefore is not acceptable. However, if the system is confined to an aperture not much exceeding half a metre, the astigmatic blur becomes comparable with the resolution of many of the emulsions likely to be used. For the smallest aperture likely to be considered, 150mm, the astigmatic blur circle has a diameter of only 1/60mm. For a spectrograph camera the small amount of astigmatism is of no significance at all so long as the photographic emulsion lies in the focal surface for tangential focal lines.

The spherochromatic aberration is almost identical to that of a Schmidt of the same aperture and focal length. The wavelength of best correction for the version of the system given in Table 1 lies between the Hβ and Hδ lines, but closer to the latter. Thus the best performance would be obtained with blue-sensitive emulsion. However, in the modest sizes of instrument to which this design is likely to be restricted, the spherochromatic aberration is of little significance and the system would give good results even with red-sensitive emulsions.

Table 1.
Specifications for a simple Houghton camera.

$r_1 = -180$	$t'_1 = 0.75$	BK-7
$r_2 = -36$	$t'_2 = 0.104$	air
$r_3 = -20$	$t'_3 = 0.50$	BK-7
$r_4 = -36$	$t'_4 = 25.65$	air
$r_5 = -36$	$l'_5 = -17.9714$	air

aperture = 6

relative aperture = f/3
surfaces 2 and 3 meet on a circle of diameter 6.086
radius of curvature of mean focal surface = 20.9
radius of curvature of tangential focal surface = 22.8
for image diameter of 2 the field is 6°.4
for no vignetting over this field the mirror diameter is 9 (compared with 10 for a Schmidt).

In summary—for systems not exceeding about half a metre the performance of this simple Houghton camera is not significantly inferior to that of a Schmidt of the same aperture, focal length and field of view, while the overall cost of manufacturing and housing the Houghton camera is likely to be about half that of the Schmidt.

A specification for one of these simple Houghton cameras is given in Table 1. If a unit length of 25mm is used in the table, the design produces a camera of the smallest size likely to be of interest. If a unit length of 100mm is used, the design applies to a camera of the largest size for which the astigmatism may be considered to be still acceptably small over a total field of 6°.4.

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SIMPLE HOUGHTON CAMERA, CONSTRUCTION AND OPERATION

by Garry R. Nankivell

In the foregoing paper Norman J. Rumsey described a system based on a concept originated by J. L. Houghton way back in the days of World War II. Houghton endeavoured to replace the elegant Schmidt correcting plate by a system of thin spherical lenses of net zero power. Over the years this theme has been explored by many investigators, with varying degrees of success. The system to be described here is the result of an investigation into two and three lens correctors, stimulated by Buchroeder's three lens system which appears earlier in this chapter.

The classical Schmidt camera needs no introduction to readers of this book, but, oddly enough, I recently installed the *first* Schmidt of modest size in New Zealand (6", f/3) and am endeavouring to demonstrate its capabilities. The plate seems to be the main deterrent to making a Schmidt and Norman Rumsey has tried to overcome this problem and, at the same time, introduce features of simplicity, both in general dimensions and construction. The camera was based on the following specification:

aperture	6.0 inches
relative aperture	f/3
focal surface diameter	2.0 inches (field 6°.4)

One disadvantage of the Schmidt is its long tube length. For small cameras this is not too much of a problem, but it becomes of considerable importance when the instrument is large. Again when the instrument is relatively slow, so as to minimize the effects of sky fog, to improve its magnitude limit and increase its plate scale, we are always looking for ways of decreasing tube length and minimizing flexure, as well as convenience in operation and site portability.

A shorter tube length has been achieved in this design by trading off the introduction of some astigmatism against the usual tube length of double the focal length. By making the tube length only three-quarters that of the Schmidt, the amount of astigmatism introduced at an off-axis angle of 3°.2 will give rise to a DCL (disc of least confusion) subtending 7.5 arc seconds on the sky. For our 6" aperture instrument this amounts to a value of 0.00066 inches, comparable to and even exceeding the resolution of many emulsions available today.

The afocal corrector consists of two elements. The first element is of positive power, and is meniscus in shape; the second element is of negative power and is more meniscus. However, the two elements' paraxial powers are zero when considered as a unit, with the individual bendings arranged to produce correction for spherical aberration and coma. The system as designed is "self-testing," eliminating the necessity of making extra test plates etc., and the need for elaborate setups for testing on the completed instrument.

Construction Notes.

An instrument of the above dimensions has been under construction for the Wanganui Observatory as a photographic assist to the normal observational work. It appears, as time goes on, that it is becoming increasingly difficult to get suitable emulsions on glass at a reasonable cost for astronomical purposes. The range on film base is, however, more readily obtainable and lends itself to use in an instrument with a convex focal surface. Moreover, the economics are far better compared with the cost of plates.

The Wanganui instrument has a primary mirror of 9.25 inches clear aperture. This was available as a blank in plate glass of 1.5 inches thickness, formerly the property of J. T. Ward, founder of the observatory in 1903, and a prolific mirror maker. The use of plate glass may be questioned, but at least it got the project off to a good start, without the usual long lead time in procuring pyrex. The curve was milled in rapidly, and the fine grinding carried out with WCA grits on a 5/6 tile tool with the Draper. Polishing was carried out with the same sized tool and the surface brought to an accurate sphere of 36.00 inches radius. Even with plate glass no difficulty was experienced. Final work was done with slowest speed with Barnesite 924. The resultant surface came up to a very fine polish. Ronchi testing confirmed the spherical figure—this surface now forming a concave test plate to check the two convex surfaces.

With the normal Schmidt configuration, a 10-inch mirror would have been required to avoid vignetting. The 9-inch mirror blank called for in the specification is a "non-preferred" size, although I did see that a 9¼ x 1.62" blank is listed in the 7740 F.A. pyrex range. The mirror should be finished off symmetrical when viewed across a diametral section—it is helpful in final positioning and collimation. Also the aluminizing should be held over until the convex surfaces of both lens elements have been figured against it by interference. Do not forget to use three thin spacers between the surfaces during testing to overcome the risk of odd scratches.

The lenses are made of BK-7, but any other borosilicate crown equivalent such as BSC-2 will work as well. It is desirable, however, to use glass from one melt to achieve zero paraxial power and thus keep the longitudinal colour balance under control. The first surface is very shallow and was produced on a plano tile tool, using the classical mirror strokes. The sag on the 6.25" blank is only 27.1 thou., requiring 220 grit to rough in. The second surface was milled in to the required curve and worked up to the pre-polish on a tile tool. Although I have access to a reasonably complete range of brass optical tools, with radii increments according to T. Smith's list of preferred radii, I still like to block up a tile tool when working large surfaces. The wets grind down much better and far more evenly, but, more important, one can get right on to the desired radius with prudent machine setting. It is *much* more difficult to "force" the curve in an unchanneled metal tool. For prototype and on-off jobs where one has such a large variation in tool and glass diameters, it is difficult to obtain the ideal kinematic conditions for even wear. If you are sure of your spherometer technique, you can bring the second and fourth surfaces through to matching the curve on the primary mirror and hopefully find that the curves agree to within about 7-10 rings!

I still find that it saves a lot of time to give the surface a quick flash polish with Cerium and check the matching. It is then simply a matter of extending the final grinding in the direction as indicated by the ring appearance until you are within the 7-10 ring limit. It is certainly worth while to have a close match. I have seen the effects of pulling a surface which may be up to 50-70 rings out—overextended polishing time, frequent lap retrimming and the ever-present risk of surface damage due to impatience and "risky" technique. The first and third surfaces should be worked along in the same progression as the other ones, keeping grit sizes in step. The elimination of wedge is made during the fine grinding operations. The shapes of the individual lenses are such that final mechanical-optical centering and edging would be a costly and wasteful business, very similar to the conditions obtained with a Maksutov meniscus.

Testing the very long first surface may present some difficulty. The test is tantamount to making a 6" f/15 mirror check. The angle subtended is quite small, but with a good illumination system, no trouble should be experienced. The tertiary of a tri-schiefspiegler would be a bigger headache! A small viewing telescope could be used to advantage, but I had no difficulty in obtaining a smooth sphere. The third surface is just the dead opposite! The problem is getting all the light from every part of the surface into the observer's eye. An on-axis tester is advisable to escape any off-axis horrors introduced with the more conventional test setup. With strong curvatures there is a tendency for the surface to polish out precisely spherical, providing that no violations are present to upset the even wear conditions. After obtaining four polished surfaces of good figure, and two lens elements showing both negative and positive power, it comes as a sort of shock when they are placed together and then viewed through! There must be an easier way to make a "window". Now place the lens combination up against your newly aluminized mirror and Ronchi test—behold the "raison d'être." When all the surfaces have been completed, it is then necessary to remove the outer edge of the third surface by carefully grinding on a plane tool until the clear diameter is reduced to 6.086 inches. This operation allows the interior to form a closed ring contact, keeping out dust and reducing the risk of mechanical maladjustment. Both components were mounted in a cast aluminum alloy cell, using precisely the same methods as for a refractor objective.

I do not propose to give the actual camera construction in great detail since methods and resources vary tremendously. However, some comments on a few components may be of help. The film holder can be turned from extruded alloy rod and subsequently anodized to a rich black shade. I find that this type of finish looks good and wears well; all that is required for these smaller components is a rectifier bridge to give 10 amps at 50 PIV. This is run off the low tension supply to my vacuum plant via a variac. Another point is forming the curved focal surface—in this case the tangential focal surface is 22.8 inches. There is a certain degree of roughness with a turned metal surface along with slight contour variations. I make up a concave metal tool of the appropriate curvature using a radius bar in the lathe. Then I make a trepanned disc of black vitrolite about 0.2 inches thick and grind in the curve as if I were making a convex lens. No need to polish—simply finish up with 15 micron grits. The disc is fixed to an alloy backing with epoxy which, in effect, is the film-holder. The backing is tapped to allow a drawbar to pull it up to a shoulder on the focusing shaft. If you are going to make a range of film-holders to save time in re-loading, the axial distance of each holder must be identical to eliminate constant re-focusing adjustment. All trace of "wedge" must be removed to prevent defocus across an arbitrary diameter, even if the focus is perfect on axis. For multiple exposures where you might end up with 6 to 8 films during an observing run, a "high rise" tank made of perspex or lucite dividers is a must. For these small catadioptric cameras, I have standardized on a film circle size of 60.0mm diameter, which provides a clear usable diameter of 55mm.

Positioning the components in the camera and collimating is exactly the same as for a Schmidt. I will not tramp over this aspect but would draw your attention to a very useful paper on Schmidt collimation: *Adjustment and Testing of Schmidt Telescopes,* by J. Anderson and J. V. Clausen, Astron & Astrophys 34, 423-429 (1974).

Although slanted towards the larger size of Schmidt, many of the details can be utilized to advantage when putting a smaller instrument into operational shape. I would recommend the use of a reflector focused for parallel light to do the focusing of the camera. Simply draw a rough grid with a ballpoint pen onto a disc of film and load it into a holder. Then place the holder in the camera and illuminate it with an incandescent lamp (auto bulb 12V) placed off axis. Observe the image through the reflector until the grid is in sharp focus. The tolerance seems to be about

±0.0015 inches. You can also check the film-holder squaring on by moving the reflector across the front of the camera and viewing the opposite edges.

With these f/3 systems of 6 inches aperture I have had very good results with Ilford FP4 sheet film run for 10 to 15 minutes and developed in MWP-2 for 10 minutes. A cutting die to punch the 60mm circles is a very convenient method of film preparation.

Unlike systems based solely on refracting elements, the Houghton and Schmidt can produce images of exquisite quality. It goes without saying that the tracking capabilities of the drive must be likewise. In experimenting with these types of systems, I am constantly struck with the fine definition produced. The resultant negatives, on first casual examination, look somewhat empty; upon examination with a 10x triplet magnifier, the images are seen as fine needle-sharp points. Even globular clusters such as 47 Toucanae, close by the small Magellanic Cloud, can be resolved away from the center.

I have also made up some selected filters which fit into the film-holders to enable taking of fields in specified wavelength bands.

Finally, a comment on film handling. Any careless storage, processing, enlarging, etc., will obviously mar the emulsion, giving rise to scratches, pinholes and those other tribulations that visit an unwitting worker. The remedy is obvious. The circular border allows a serial number to be marked on the film, using a draftsman's tubular pen and Indian ink. Small card pockets can be folded up and stapled to store the film discs, and can simultaneously record the exposure details.

COMPOUND SCHMIDT TELESCOPE DESIGNS WITH NONZERO PETZVAL CURVATURES

by Robert D. Sigler

A variety of aplanatic and anastigmatic Schmidt Cassegrain and Schmidt Gregorian telescope designs with nonzero Petzval curvatures are investigated. Relaxing the Petzval constraint permits the development of high performance photovisual instruments which are capable of diffraction limited imaging over fields of view of 1-2°.

Introduction

Compound catadioptic telescope designs of the Schmidt type have the capability of very high optical performance over a large field of view while employing a minimum number of optical elements. Configurations that have zero Petzval curvature (i.e., a flat image surface in the absence of astigmatism) and essentially no Seidel or chromatic aberrations have been quite thoroughly described.[1,2] These flat field configurations are primarily astrophotographic cameras and can cover fields of view of 6° or more with very high quality images. It is also unfortunately true that the flat field designs, due to the Petzval constraint, have large secondary obscuration ratios, small secondary magnification, and frequently an awkwardly positioned image surface. These constraints are not too serious for strictly photo-

graphic instruments where the secondary obscuration is frequently as large as $T = 0.5$ without unduly affecting performance. However, for photo/visual instruments, the large field of view, and low effective focal ratio are sacrificed for higher secondary magnification radius (i.e., greater effective focal length) and the highest possible resolution over a somewhat smaller field of view, typically 1° or 2°. The attainment of high resolution, especially in the intermediate spatial frequencies of the MTF curve, is facilitated by having the smallest possible secondary obscuration ratio.

Designs with Nonzero Petzval Curvature

When the Petzval curvature is allowed to become nonzero, many interesting photo/visual instrument designs possessing good optical performance, but not the configurational drawbacks of the flat field designs, become possible. These nonzero Petzval curvature designs have not been nearly as thoroughly described in the literature as the flat fielded designs, and several of the designs described herein appear not to have been previously discussed.

The defect of Petzval curvature in a photo/visual instrument is not as serious as in a strictly photographic one and, if deemed necessary, can be eliminated with field correcting lenses, or its effect can be mitigated by using a suitable curved image receiving surface when used as a camera.

The configuration and aberration equations describing compound Schmidt systems are presented in Table 1. These equations result from the combination of the third-order aberration equations of Schwarzchild[3] and the seesaw theorem for aspheric plates of Burch.[4] In these equations, an expression for distortion, while easily obtainable, has been ignored as it is quite small in compound Schmidts and is usually not considered a serious aberration. In the absence of spherical aberration and coma, which is the case in all the designs presented here, the position of the stop has no effect upon the Seidel aberrations (distortion excluded).

Table 1. Third-Order Equations for Compound Schmidt Telescopes

Configuration Equations		Aberration Equations	
$R = \frac{M - E}{M + 1}$,	(1)	$B = \frac{1}{8f_1^3}\left\{1 + b_1 - \left[b_s + \left(\frac{M+1}{M-1}\right)^2\right]\frac{(M-1)^3(1-R)}{M^3} - G\right\}$,	(5)
$E = M - (M+1)R$,	(2)	$F = \frac{1}{8f_1^2}\left\{\frac{2}{M^2} + \left[b_s + \left(\frac{M+1}{M-1}\right)^2\right]\frac{(M-1)^3 R}{M^3} - GD\right\}$,	(6)
$T = \frac{1 + E}{M + 1}$,	(3)	$C = \frac{1}{8f_1}\left\{\frac{4(M-R)}{M^2(1-R)} - \left[b_s + \left(\frac{M+1}{M-1}\right)^2\right]\frac{(M-1)^3R^2}{M^3(1-R)} - GD^2\right\}$,	(7)
$S = \frac{M(1-R)}{1-M}$,	(4)	$J = 1 + \frac{1}{S}$,	(8)

where

B = spherical aberration

F = coma

C = astigmatism

M = f/f_1- secondary magnification ratio;

R = primary to secondary separation divided by f_1;

D = primary to corrector plate separation divided by f_1;

G = ratio of figuring depth on corrector plate compared with that required on corrector plate of a Schmidt camera with a primary of focal length f_1;

T = ratio of minimum, unbaffled, secondary diameter to diameter of the primary for axial images;

E = back vertex distance ratio, or the distance from the primary to the image plane divided by f_1
S = secondary focal length divided by f_1
f = focal length [subscript denotes surface referred to (i.e., 1 = primary, 2 = secondary)];
b = conic constant, which is a measure of the surface asphericity (sphere = 0, parabola = −1.0); and
J = product of Petzval curvature and primary focal length f_1.

A variety of aplanatic and anastigmatic designs with nonzero Petzval curvatures have been plotted in the attendant figures. Both configuration and aberration data for each design have been combined on the same figure so that the tradeoffs between configuration and performance can be rapidly evaluated. For comparison, a representative flat field design (after Linfoot) is included as Fig. 2(A). Those designs, which have been designated as being compact, have the corrector plate position fixed relative to the secondary position ($R = 0.95D$) so that with relatively fast primary focal ratios, the secondary can be directly mounted to the corrector and thus avoid the diffraction effects associated with the usual secondary mounting vanes. This also results in a much shorter over-all length. With these same primary focal ratios, a convenient placement of the image surface (i.e., at about one primary diameter behind the vertex of the primary) is obtained by fixing the value of E at $E = 0.4$. As spherical mirror surfaces are considerably easier to produce than aspheric ones, some attention was given to finding solutions that had one or both mirrors spherical.

The figures are rather self-explanatory, but a few comments on each design is in order.

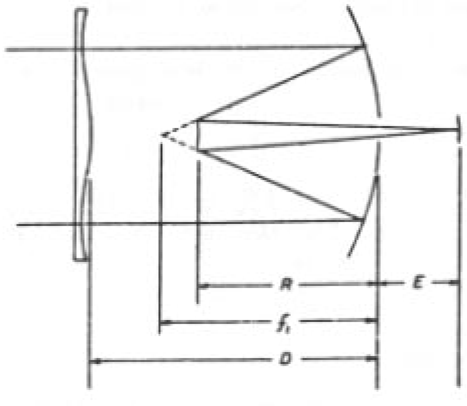

Fig. 1. Compound Schmidt telescope configuration.

Schmidt-Cassegrain Anastigmat with Spherical Mirrors [Fig. 2(B)]

This is a monocentric design of Linfoot[5] and Wayman[6] that has its corrector positioned at the common center of curvature of the mirrors. Both mirrors are spherical. The design is in many respects similar to the flat field design of Fig. 2 (A) in that it has a widely varying image surface placement as a function of secondary magnification ratio, and it has a very small value of Petzval curvature. In terms of secondary obscuration, it is about midway between the flat field designs and the nonzero Petzval curvature designs for which the image position has been fixed. Note that in this monocentric design the image surface is in a conveniently accessible position for only a very narrow range in the value of M.

Schmidt-Cassegrain Aplanat with Spherical Mirrors [Fig. 2(C)]

In this design, the image surface is fixed at $E = 0.4$, and both the primary and secondary are spheres. There is very little astigmatism for moderate secondary magnification ratios, and the design is an anastigmat for $M \simeq 2.5$. The secondary obscuration ratio is rather small, especially for large values of M. Another feature of this design is that the corrector is positioned well inside the radius of curvature of the primary, resulting in a quasi-compact configuration from the standpoint of over-all length. When it is considered that in the vacuum deformation technique[7,8] of making Schmidt plates, the required aspheric surface on the corrector is accurately produced by the generation of a spherical surface, these designs with spherical mirrors can be considered a kind of all spherical catadioptic telescope design. An aplanatic version of this design, as described by the third-order equations with $M \simeq 3.4$, was the basis for the ray tracing results shown in Fig. 3. From the spot diagrams it is clear that the dominant aberrations are chromatic and third-order astigmatism as would be expected. These results, while reasonably good, can be further improved with computer optimization programs.

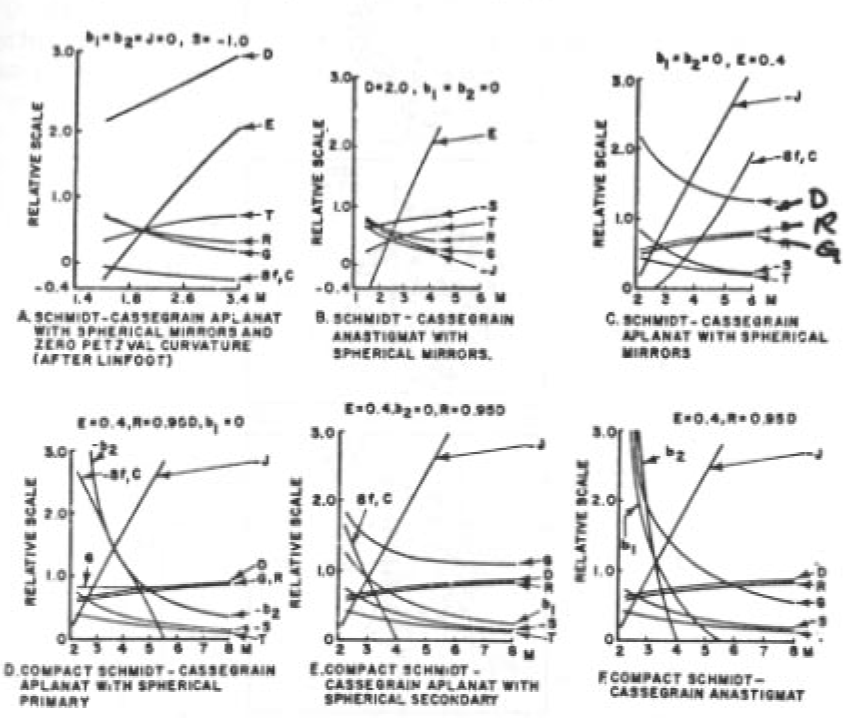

Fig. 2. Schmidt-Cassegrainian aplanats and anastigmats.

Compact Schmidt-Cassegrain Aplanat with a Spherical Primary [Fig. 2(D)]

This is a compact design with $R = 0.95D$ and the image surface fixed at $E = 0.4$. It was described in a previous paper[9] and is included here for completeness.

Several commercially manufactured telescopes for amateur astronomers and 35-mm cameras are based upon this design. Note that an anastigmatic solution exists at $M \simeq 5.61$. At the anastigmatic solution the secondary obscuration ratio is only about $T = 0.22$, resulting in a very high performance system.

Compact Schmidt-Cassegrain Aplanat with a Spherical Secondary [Fig. 2(E)]

This is a type of Dall-Kirkham Schmidt that is rather similar to the previous example. It also has an anastigmatic solution, but at $M \simeq 4.1$. Note that the required corrector plate strength is considerably greater than the spherical primary case. As can be seen from the curves, these nonzero Petzval curvature Schmidt-Cassegrainian designs can have quite small secondary obscuration ratios in combination with a conveniently placed image surface.

Compact Schmidt-Cassegrain Anastigmat [Fig. 2(F)]

These are anastigmatic solutions that result from setting aberration Eqs. (5), (6), and (7) to zero. The figuring strength required on the mirrors and the corrector become very large for small values of M, and for very large values of M, G approaches zero, and the mirrors approach a parabola. In the compact anastigmatic design, an increase in either E or the value of R/D has the general effect of shifting the aberration curves to the right (i.e., toward larger values of M).

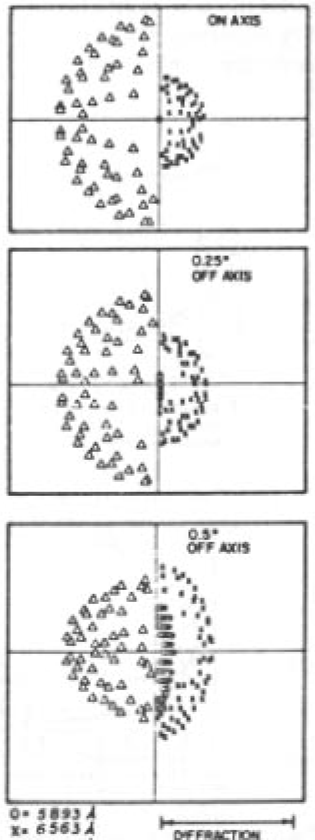

Fig. 3. Half-pupil ray trace of Schmidt-Cassegrainian aplanat with spherical mirrors. Third-order aberration theory solution (30-cm aperture, $f/6.8$, $M = 3.4$, $E = 0.4$). Images shown are on Petzval surface.

Schmidt-Gregorian Aplanat with Spherical Mirrors [Fig. 4 (A)]

Schmidt-Gregorian designs have much larger Petzval curvatures than the Cassegrainian forms, although of opposite sign. Inverse Gregorian forms, in which the secondary is larger than the primary, although configurationally possible with a folding mirror, have not been considered in this paper. The Schmidt-Gregorian aplanat with spherical mirrors is unusual in that it has its secondary outside the corrector-primary space, but close enough to the corrector so as to be mounted on a short tube. The major drawback to this design is the large value of the astigmatism that is plotted at 1/8th of the scale used for the Cassegrainian forms.

Compact Schmidt-Gregorian Aplanat with Spherical Primary [Fig. 4(B)]

Except for the more conventional placement of the secondary and the very strong corrector, this design is rather similar in performance and configuration to the previous Schmidt-Gregorian design.

Compact Schmidt-Gregorian Aplanat with Spherical Secondary [Fig. 4(C)]

Of the Schmidt-Gregorian designs with one or more mirrors spherical, this design has the weakest corrector and the smallest astigmatism, although that astigmatism is still quite large. It is unfortunate that the Schmidt-Gregorian aplanats have so much astigmatism associated with the larger values of M, where they are

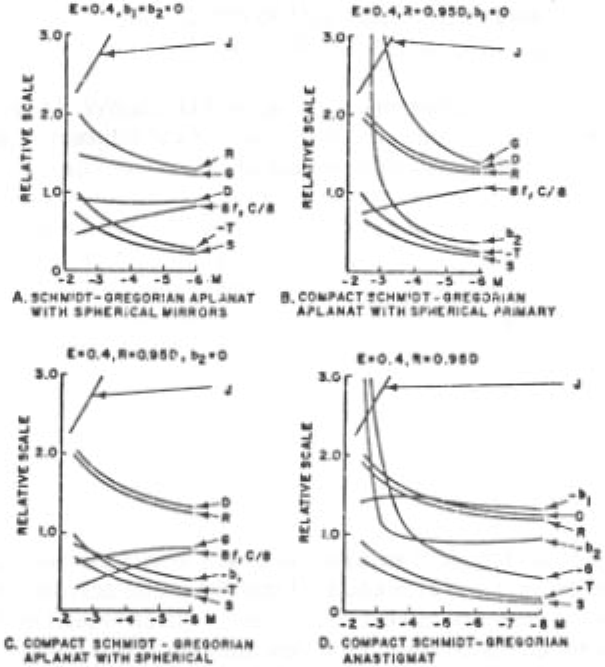

Fig. 4. Schmidt-Gregorian aplanats and anastigmats.

more configurationally attractive, as to make them of questionable value as a photovisual instrument.

Compact Schmidt-Gregorian Anastigmat [Fig. 4(D)]

These designs require very large figuring strengths on all surfaces when the secondary magnification is small. At large secondary magnifications, the mirrors approach a pair of confocal parabolas with no corrector, as do the Schmidt-Cassegrainian forms. A rather interesting development of the anastigmatic Schmidt-Gregorian forms is the inverse corrector profile on the Schmidt plate. Perhaps these could be fabricated with a deformation technique using pressure rather than a vacuum. The aberration curves for these designs are also generally shifted toward the right with larger values of either E or R/D.

If the compact requirement is ignored, Schmidt-Gregorian anastigmat designs with a spherical secondary are possible, but they have rather awkward configurations. An example of this is where $b_2 = 0$, when $M = 10.5$, and $E = 2.0$, $R = 0.25D$, $b_1 = -1.05$, $G = 0.223$, and $T = -0.32$.

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Chapter 5
SPECTROHELIOSCOPES

SPECTROHELIOSCOPES
by Fredrick N. Veio

One of the biggest objects in the sky is the sun. In white light you can study the solar granulation, a variety of sunspot shapes and changes, and the faculae near the solar limb. In H-alpha light, which is 6562.8 Angstroms wave length, the solar disc presents an entirely different appearance. Solar features of interest will be filaments, flares, plages and prominences. Surge activity of filaments and prominences is easily detected and displays startling releases of solar energy. The solar spectrum itself can be viewed in very fine detail. Only the spectrohelioscope can give a variety of solar events to the solar observer. An instrument constructed by the amateur himself will cost about $350 (1974 prices); the cost from an optical company would be several times that value. Two other techniques to do solar research involve the use of a birefringence filter of approximately 5 Angstroms pass-band, and these are expensive, or a Fabry-Perot etalon combined with an interference filter—average price being $1,000. Birefringence filters and Fabry-Perot interference devices require much experience and shop facilities; a spectrohelioscope is the only choice left for the solar enthusiast. Fortunately, only common shop equipment is needed and simple construction is possible.

There is a considerable amount of detail that can be seen on the solar disc in H-alpha light with a medium-sized spectrohelioscope; this consists of a 9-feet focal length telescope and a 6-feet focal length spectroscope, mounted end-to-end. The reason is quite simple; the average resolution of a spectrohelioscope depends on the diameter of the sun image on the entrance slit and upon the width of the slit. A 9-foot f/1 telescope will produce a 1-inch diameter sun image; with a slit width of 0.005″, a section of the sun of 10″ arc passes through the slit. Calculation:

$$\frac{0.005'' \text{ slit}}{1'' \text{ sun image}} \times 32$$

min. arc = 10″ average resolution sun in sky

The shape and brightness (flare) or darkness (filament) of the solar feature determines the true resolution. A bright flare of about 5″ arc can be detected about as easily as a faint flare of about 10″ arc. Filaments that are small but very dark will be equal to a filament that is large but very faint. Most details on the solar disc and at the solar limb average about 5″ to 10″ arc or larger. That is why a medium-sized spectrohelioscope will give good performance. A professional spectrohelioscope is twice the dimensions and uses an 18 foot focal length telescope with about a 13 foot focal length spectroscope. To observe the solar disc features and the prominences on the limb, no occulting disc is required; both the solar disc and the limb are seen together with a comfortably bright image. For acceptable contrast of the detail on the solar disc in H-alpha light, the passband must be about 0.8 Angstrom, for excellent contrast the passband must be about 0.6 Angstrom.

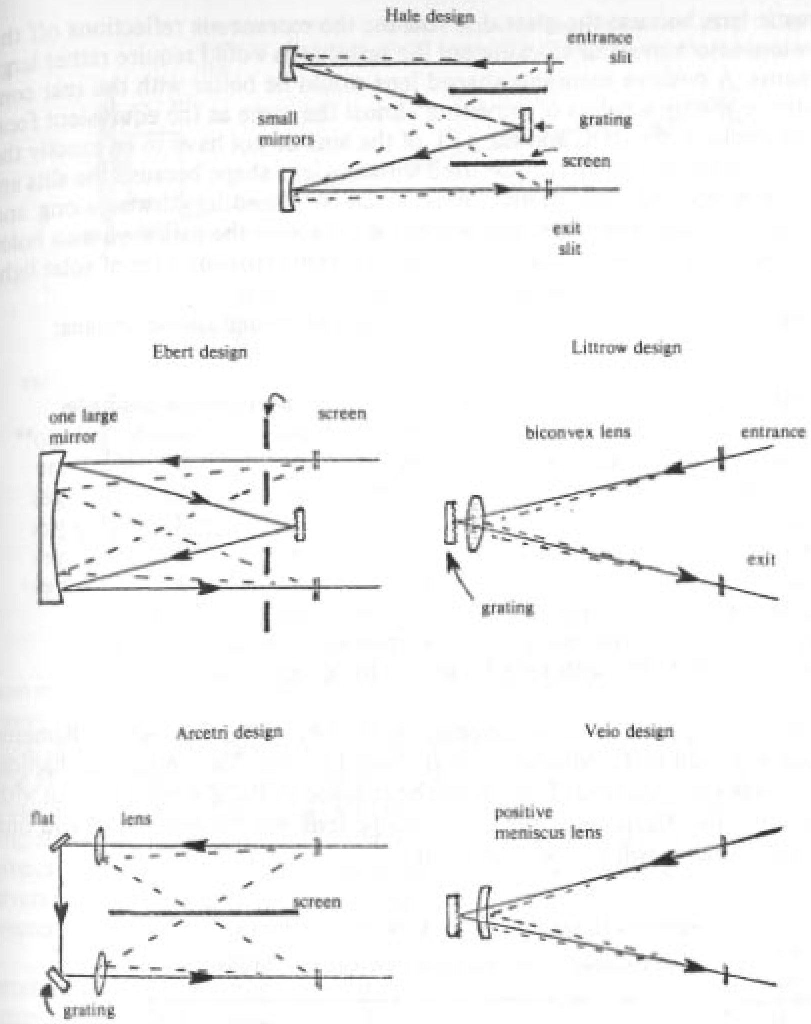
Professional solar observatories use a 6-inch circle in which to draw the solar features, this will give sufficient room to draw the details without any crowding. For the filaments, use wide or narrow black lines; for the flares and plages, have closed circles or elongated areas; for the sunspots use a round black dot for only a few large umbrae—omit the penumbrae to avoid confusion. For the sun in white light, have a separate drawing of the sunspot groups.

A spectrohelioscope will not be seriously affected on a day of average atmospheric seeing of about 1" arc since the resolution of the instrument is about 5" arc or more. Only on a poor day of seeing will the resolution be harmed. For spectroscopic study of 1" arc detail, the seeing will alter the visibility of the spectroscopic detail because the 1" arc detail will be about the same as the 1" arc seeing conditions.

There are five types of solar image synthesizers: Anderson prisms, Hale's oscillating slits, Seller's vibration slits (like a tuning fork), Arcetri slits, and Veio's simplified rotating glass disc. Not all types of synthesizers can be used with any spectroscope design. Only Anderson prisms and the rotating glass disc have no vibration problems. A set of Anderson prisms will cost about $500, a pair of rotating glass discs will be about $50. The latter method will be emphasized in this chapter.

Anderson prisms are two separate square prisms, about 1¼" on the side. They are mounted on the ends of an axle which rotates in front of two fixed slits. Arcetri slits are set on a metal bar that uses a sideways motion. Hale's slits are placed on a metal bar that oscillates back and forth. Seller's slits are a mechanical spring mechanism that moves in and out relative to each other. The Veio glass disc has 24 slits cut in the paint on the face of a 4¼" glass disc; the disc is placed on the output axle of a motor that rotates one revolution per second.

There are several spectroscope designs for a spectrohelioscope. The Arcetri design has two lenses of almost the same focal length, one optical flat and a reflecting grating all arranged in the form of a U-shape. The solar light passes through the entrance slit to one lens, reflects off the optical flat to the grating and through the other lens to the exit slit. There is an even number of reflections including the grating itself. The rotating glass disc will not work with the Arcetri design because the spectrum is inclined at a 45° angle to the exit slit; rotating the grating will not correct the situation.



SPECTROSCOPE DESIGNS

These are some common spectroscope designs, particularly the Littrow. Crossing over of extraneous light is blocked out by a screen placed along the optical axis. Or the screen with holes can be located across the optical axis. Dotted lines are the light crossing over. For the Littrow (Veio) design, the positive meniscus lens shape is best because the two lens reflections are more easily blocked out than with a plano-convex lens or related shape.

All the following spectroscope designs have an odd number of reflections.

The Ebert design has one large spherical mirror. The off-axis Ebert design has two spherical mirrors made separately and of almost the same focal length.

The Littrow design has one lens of biconvex or other related shape, or even an achromat. With the biconvex Littrow design, the lens has two extraneous solar relections which must be removed. One small piece of black tape placed on the rear surface of the lens and a small diaphragm a short distance from the rear surface of the lens will remove the reflections. If the shape of the lens is a positive meniscus, the two reflections can be more easily removed; the rear concave surface sends one reflection back to the side of the box near the exit slit while the other reflection off the front convex surface is blocked out by a small diaphragm about one foot behind the lens.

The rotating glass disc cannot be used with a biconvex, plano-convex or achromatic lens because the glass disc rotates; the extraneous reflections off the Littrow lens also move and blocking out the reflections would require rather large diaphragms. A positive meniscus shaped lens would be better with the rear concave surface having a radius of curvature almost the same as the equivalent focal length of the lens; the ROC and the e.f.l. of the lens do not have to be exactly the same. Only Anderson prisms can be used with any lens shape because the slits are fixed. The Ebert and Hale designs need a screen placed lengthwise along and parallel to the optical pathways, or a screen placed across the pathways with holes in the screen in the proper places. The screen prevents crossing over of solar light from the entrance slit, off the mirrors and into the exit slit.

The table gives a summary of the possible spectrohelioscope designs:

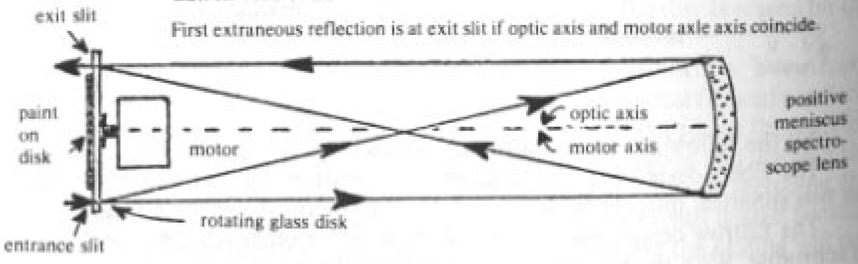
synthesizers	slit motion	spectroscope design			
		Arcetri	Hale	Littrow*	Veio**
Arcetri slits	sideways	yes	no	no	no
Anderson prisms	fixed	no	yes	yes	yes
Hale's slits	oscillating	no	yes	R	yes
Seller's slits	vibrating	no	yes	R	yes
Veio disc	rotating	no	yes	R	yes

* Lens shape is an achromat, plano-convex, biconvex, long f/1 best.
** Lens shape is a positive meniscus only; minimum about 6 feet f/1.
R—Recommended only with long focal lengths; about 12 feet f/1.

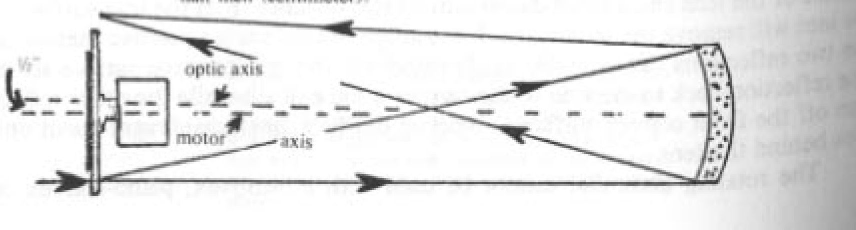
The rotating glass disc was invented in 1912 by F. Stanley. An 8" diameter glass disc was used by G. Mitchell; it had about 150 slits. The optical-mechanical mounting was very involved. The disc can be reduced to 4¼" diameter and cut with 24 slits. Off-axis effects from the spectroscope lens will be minimized and one degree angle prisms will not be mandatory.

ELIMINATE SPECTROSCOPE LENS REFLECTIONS

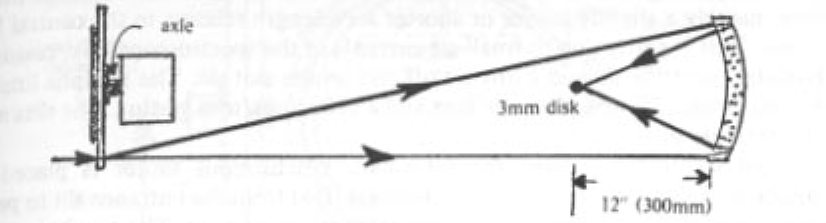
First extraneous reflection is at exit slit if optic axis and motor axle axis coincide.



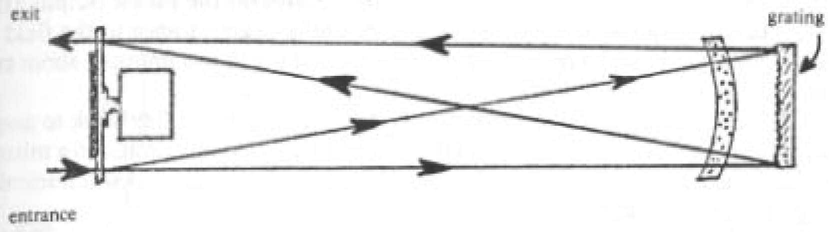
Remove first extraneous reflection by off-axis tilt of the spectroscope lens by half inch (centimeter).



Remove second extraneous reflection by blocking out with a 1/8" (3mm) diameter diaphragm placed about 12" (300mm) behind the spectroscope lens.



Sun light to and from the grating in order to observe the solar spectrum and the solar disk in H-alpha light.



A small top-quality grating has a considerable amount of resolution, which can easily be calculated. Just add up the total number of lines and divide it into the wave length of interest. For example, a 32mm grating with 1200 lines/mm has a total of 38,400 lines. The latter, divided into 6563 Angstroms wavelength, which is the H-alpha line, gives 0.17 Angstrom resolution in the first order. For excellent contrast of the sun in H-alpha light, 0.6 Angstrom passband is preferred. The grating should have a resolution of about one-third of that of the passband, namely about 0.2 Angstrom. That is why small gratings will give good performance; an average quality grating will have about 0.4 Angstrom resolution and they are not recommended for best results.

The basic procedure to set up a spectrohelioscope is quite simple. First mutually align the optical axes of the telescope and spectroscope lenses. Then move the grating mounting sideways to reflect the solar spectrum back to the spectroscope lens and finally focus the telescope lens. Now turn the micrometer which tilts the grating in order to place the H-alpha line in the center of the field of the eyepiece. Put the rotating 24-slit glass disc on the output axle of the motor, turn on the motor and observe the sun in H-alpha light.

The focusing mounting for the spectroscope lens must be free from play and wobble—slight spring tension is desirable. A slight shift of the spectroscope lens will move the H-alpha line a little so that the line will not coincide with the exit slit. The grating in its cell must be shimmed snug on the sides with cork or thick paper, this prevents any slight accidental cant of the grating which would again displace the position of the H-alpha line off the exit slit. The high f/ratio of the lenses will give great depth of focus so that the mutual focusing of the lenses is not critical. Depth of focus of an f/44 lens is about ¼-inch; depth of focus of two such lenses focused together is half, about 1/8-inch. For comparison, a 6" diameter mirror of f/8 has about 0.006" depth of focus.

When observing the solar disc in H-alpha light, most of the field of view will be dark H-alpha light. The extreme top and bottom of the field will be a little brighter, namely a slightly longer or shorter wavelength relative to the central H-alpha line. This is partly due to small air currents in the spectroscope box, causing the H-alpha line to be moved a tiny bit off and on the exit slit. The H-alpha line is 0.006" wide with a 75" spectroscope lens and a 1200 lines/mm grating. The slits are about 0.005" wide.

About six inches behind the 60 r.p.m. synchronous motor is placed a diaphragm with two 1¼" holes to allow the solar light from the entrance slit to pass to the spectroscope lens and grating, then back to the exit slit. The two holes are covered with good quality reticle glass. The diaphragm prevents stirring up air currents in the spectroscope box as the 24-slit disc rotates on the motor output axle. The air current diaphragm helps to give a very uniform appearance to the field of view of the sun in H-alpha light. Contrast of the solar detail will improve about two times.

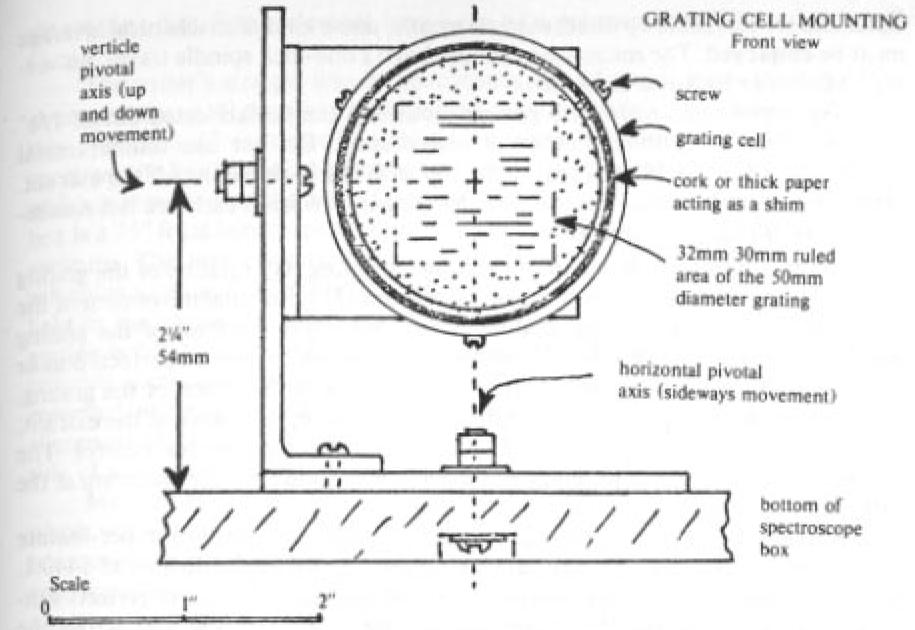
The front door of the spectroscope box must be painted flat black to avoid reflections of the sun off the door and into the eyes in a manner similar to a mirror. The spectroscope box should be painted a dull color, not white; this will minimize solar glare off the instrument and into the eyes.

Use a Bodine 10-watt synchronous motor, about 3 x 3 x 3 inches, weighing 2.2 pounds. The warming of the motor will not create any problems and no insulation is required. Some brands of motors have slight vibrations; never use them for such tiny vibrations shake the spectroscope box and ripple the air inside—this causes the H-alpha line to shimmy on and off the exit slit and presents a messy H-alpha view of the solar disc. Always buy a smooth-turning motor—the only motor that I know of without any vibration is by Bodine—they also have no significant eccentricity on the output axle. Small 3-watt motors have too much axle eccentricity; this causes the glass disc to wobble as it rotates. A trace of wobble in the glass is acceptable, too much results in an uneven up and down motion in the field of view of the sun.

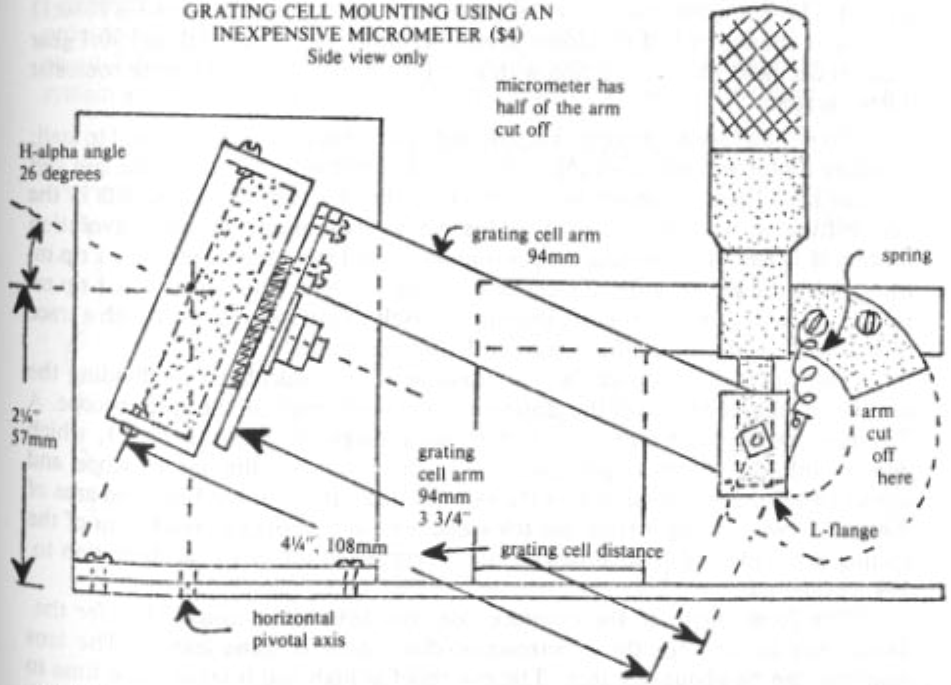
A piece of square glass about 1¼" x 1¼" and 3/16" thick is placed near the exit slit of the spectroscope box. Tilting it will move the spectrum up or down a small amount so the solar disc can be studied at different wavelengths off the H-alpha line—it is called the line-shifter. Do not buy commercial glass because it is seldom of good quality; best quality is obtained from reticle glass which can be picked up from a war surplus store. As a double check on the quality, it should be checked by the autocollimation technique; an achromatic lens of about 10 to 20 inches focal length and 1" to 2" diameter is adequate, also use a small optical flat about 1/8 wave and about 1" diameter. The glass to be tested is placed between the optical flat and the achromat; a Ronchi screen with 100 lines/inch will yield straight lines if the glass is of good quality.

Dust is the enemy of a diffraction grating. When the spectroscope is not in operation, always put a cover over the grating. Never touch the surface of the grating—any slight finger-mark will be permanent because the surface is very delicate. The ruled surface of the grating will not be seen; it will appear as an ordinary optical flat, but the lines definitely are there. Never blow with the mouth at any particle on the surface of the grating, there is a high chance that a bit of saliva will be scattered onto the grating; just leave the dust "as is" for a few specks of dust will cause

GRATING CELL MOUNTING
Front view



GRATING CELL MOUNTING USING AN
INEXPENSIVE MICROMETER ($4)
Side view only



no harm.

A low-cost micrometer head is used to control the vertical tilt of the grating easily and precisely. The H-alpha line must be placed precisely at the narrow exit slit; it must be understood that tilting the grating at the proper angle for the H-alpha line is impossible by direct manual means, some kind of mechanical leverage must be employed. The micrometer should have a one-inch spindle travel; no vernier, ratchet or lock-nut is needed.

The various pieces for the grating mounting can be fabricated out of 1/8" thick aluminum, anything thicker is unnecessary. Do not use thinner metal because any slight bending of thin metal will shift the H-alpha line off the exit slit. Never put any mechanical pressure on the grating. Precision parts are not necessary except for special purposes.

There are three motions to the grating mounting: (1) rotation of the grating cell, (2) vertical movement of the grating cell and (3) horizontal movement of the whole grating mounting. The rotation of the cell aligns the lines of the grating parallel to the exit slit, this mutual parallelness does not have to be perfect, plus or minus two degrees will not result in any serious loss of resolution of the grating. The vertical movement of the cell shifts the spectrum up and down at the exit slit; this motion is extremely delicate and requires a micrometer for control. The horizontal movement of the whole grating assembly positions the spectrum at the exit slit.

The RA drive for an equatorial mounting needs a one-revolution-per-minute motor with a 96:1 and a 15:1 gear ratio. This gives a total gear reduction of 1440:1. Now if a telescope is mounted horizontal to the ground and a mirror reflects sunlight into the telescope, the mirror *doubles* the motion of the sun across the ground. The RA drive must have the gear reduction doubled (2 x 1440 is 2880:1) in order to reduce by half the doubled motion of the sun. Thus 96:1 and 30:1 gear ratios equal 2880:1 total reduction with a 1 r.p.m. motor for a heliostat or coelostat mirror system.

Do not use 3-watt motors. They do not have enough torque and tend to stall; a stalling motor will not drive the gears, so the mirror does not follow the sun and will not keep the solar image on the entrance slit. A stalling motor results in the sun drifting on the entrance slit and this can be most annoying. Slow revolution motors of 1/15 to 1/30 revolution per minute are not recommended, use a 1 r.p.m. motor with the proper gears. Traces of backlash are quickly taken up by a 1 r.p.m. motor so that the mirror follows the sun precisely. Slow speed motors with a trace of backlash can have a drifting sun on the entrance slit.

The working f/ratio of the spectroscope lens is calculated by dividing the diagonal of the ruled area of the grating into the focal length of the spectroscope. A 30mm x 30mm ruled area on a grating has a diagonal of 44mm (1.7"), which divided into 75" focal length gives f/43. The f/ratio of the spectroscope and telescope lenses should be almost the same in order to cover the full ruled area of the grating with sunlight from the telescope lens so that the full resolution of the grating is maintained. The lenses should be corrected for spherical aberration to 1/4 wavelength.

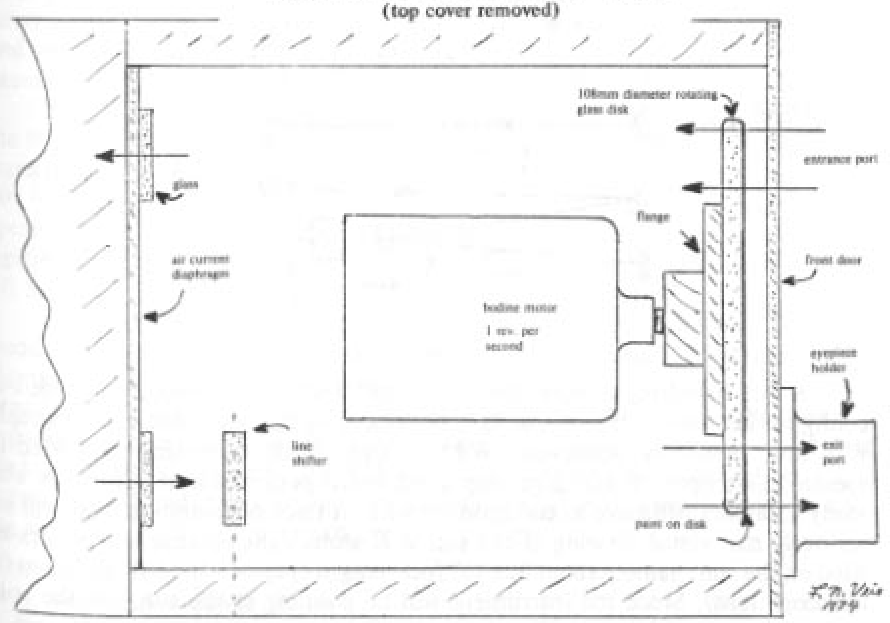
The focal length of the eyepiece does not have to be exactly 4½" for the 24-slit disc or 2½" for the spectroscope disc, there is some leeway. The lens diameter can be about one inch. The eye relief is high and it takes some time to become accustomed to it. The spectrum has much fine detail and an eyepiece with about 2" to 2½" f/1 is best. The solar disc in H-alpha light requires a longer focal length eyepiece because short focal lengths give too much power, this reduces the contrast of the solar disc in H-alpha light. About 4½" to 5" f/1 is best with the 24-

slit rotating disc. Single element lenses can be purchased from Edmund Scientific Corp.

The writer's straight-line design consists of a 9 foot f/1 telescope lens of 2.5" clear aperture. A 4" diameter pyrex mirror reflects sunlight into the telescope, and this projects a 1" diameter sun image onto the entrance slit of a 7 foot long spectroscope box. Inside the front of the box is a 4¼" diameter rotating glass disc which is mounted on the axle of a Bodine synchronous motor. At the rear of the box is a 75" focal length spectroscope lens of positive meniscus shape and 2" clear aperture. The rear concave surface of the lens has 73" radius of curvature. A reflecting grating of 30 x 30mm ruled area with 1200 lines/mm diffracts the sunlight in the various wavelengths of the spectrum; the blazed wavelength of the grating is 5000 Angstroms. The spectroscope box is supported by two wood and concrete piers, each weighing about 70 lbs. The heliostat and telescope lens are mounted on a wood board which is bolted on top of a 40" high third pier. Absolute alignment of the optical system is necessary when it is set up for observing; the side of a concrete patio or sidewalk can be a useful help here.

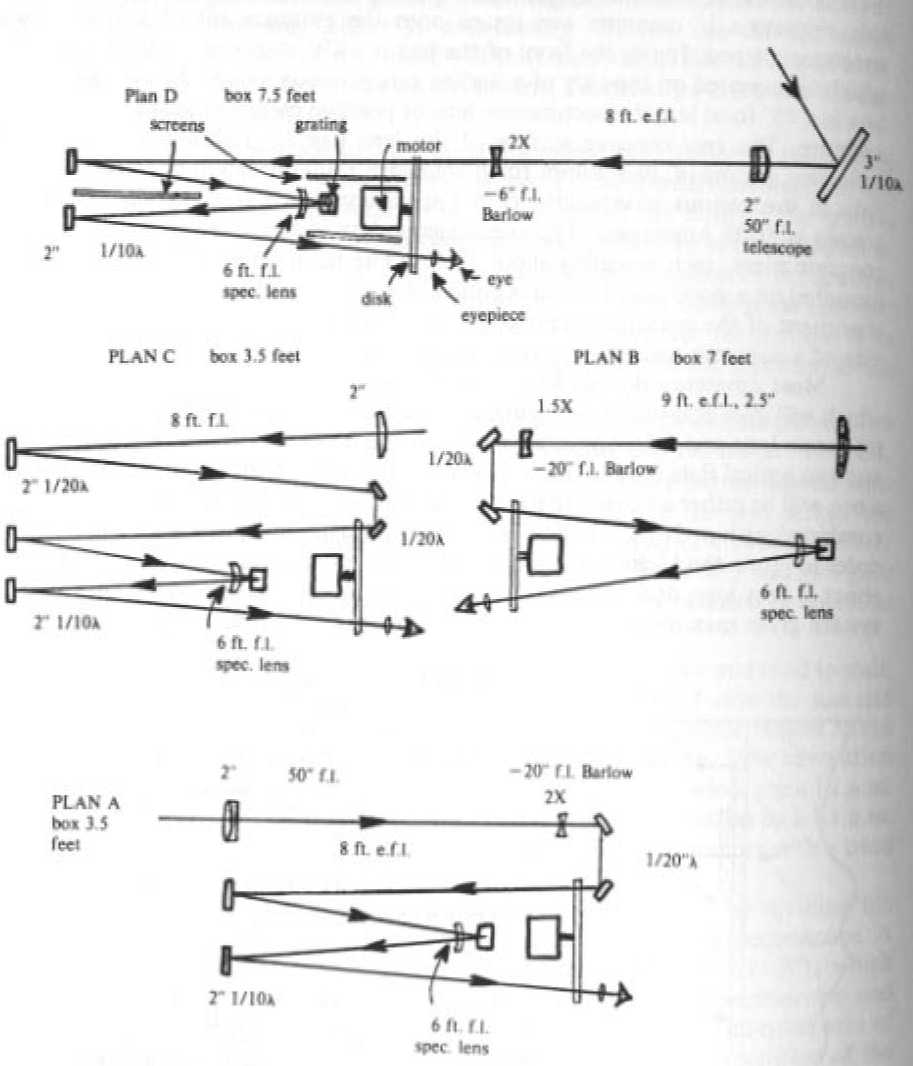
Most amateurs do not have much space. There are other optical designs which will give equivalent performance. The heliostat with the 9 foot focal length telescope lens and 6 foot spectroscope lens can be mounted in a 9 foot long box and two optical flats used to fold up the system into a U-form. Unfortunately, such a box will be rather awkward to handle. Instead, a 6 foot focal length telescope lens combined with a -20" f/1 Barlow lens can be adjusted to produce a 9 feet e.f.l. in order to retain the 1" diameter sun image on the entrance slit. The box will now be about 7 feet long and only two piers will be needed for support. The box-pier system gives maximum stability without a trace of vibration, therefore photogra-

FRONT OF SPECTROSCOPE BOX - top view
(top cover removed)



phy will be possible. The piers are very cheap to make, certainly less so than making a very rigid fork mounting of equivalent stability.

COMPACT SPECTROHELIOSCOPE DESIGNS



A fork mounting is recommended to hold a spectroheliosope in a folded-up configuration. Unless the mounting is heavy and rigid, good detail in photography will not be easily achieved. With a light fork mounting a folded-up spectroheliosope will still give very good visual performance, and this is what many amateurs will have to compromise with. A trace of mounting sway will not seriously mar visual viewing of the sun in H-alpha light because low powers are used on the sun, namely about 22x (5" focal length eyepiece divided into 9 feet f/1 telescope lens). Since the instrument will be pointing at the sun, not the polar regions, an equatorial mounting is unnecessary.

The folded designs are not meant to be absolute but merely to serve to make the amateur aware that he does not have to mount the spectroscope and telescope in a straight line as do professional spectroheliosopes. Other arrangements are quite in order so long as the optical elements are of high quality. The more optical flats in the system, the higher must be the quality per individual surface.

In plan A to save some money, an Edmund achromat of 50" focal length and 2" diameter can be employed for the telescope system. A -20" f/1 Barlow lens must be used to give sufficient projection distance (10" from the Barlow lens, off the two optical flats and onto the entrance slit). The Barlow lens is adjusted for 2x to give 8 feet e.f.l. as a bare minimum. The spectroscope has the usual 6 feet f/1 with two optical flats of 2" diameter to fold up the focal length of the spectroscope by about half. The 2" pyrex flats must be at least 1/10 wave flatness. The other optical flats are used to bend the telescope in a U-form with the folded spectroscope system; the extra flats must be of quartz and about 1/20 wave. This doubled, folded-up system is very compact, requiring about a 3½ foot box. A 6 foot focal length spectroscope must be used to maintain high linear dispersion of the grating, namely 4 Angstroms/mm in the first order.

In plan B the 6 foot f/1 spectroscope lens is not folded up. The 2.5" diameter telescope lens is 6 feet f/1 in combination with a -20" f/1 Barlow lens adjusted for 1.5x, or 9 feet e.f.l. Two quartz flats of 1/20 wave fold up the system in a box 7 feet long. This design is less critical to keep in adjustment than plan A. Plan B can be mounted along the side of a large reflecting telescope or a 5" refractor, so one equatorial mounting supports two instruments, one for daytime and one for night.

With plan A you will need a star diagonal to observe the sun. In plan C no star diagonal is needed for the sun is behind the observer. The 2" diameter telescope is 8 feet f/1 and folded up with one 2" diameter quartz flat of 1/20 wave. Two 1/8 wave pyrex flats of 2" diameter fold the focal length of the spectroscope lens. Two other quartz flats of about 1¼" diameter and 1/20 wave fold up the spectroscope and telescope with respect to each other. A box of about 3½ feet long is all that is necessary.

Plan D is a polar heliostat straight-line design with the box inclined so that the RA axle points to the north pole. A 3" heliostat mirror of pyrex and about 1/10 wave reflects the sun into a telescope consisting of an Edmund 2" achromat lens of 50" focal length combined with a -6" Barlow (Edmund) giving 8 feet e.f.l. The spectroscope focal length is folded up as in plans A and B. This design has excellent rigidity for photography, it is also compact and of low cost. The box must be about 7½ feet long.

Boxes for all the designs should be at least 1/2" thick oak wood. Nails and wood screws should be used to guarantee holding together of the planks. An aluminum tube of about 5" diameter and 1/8" thickness might have a slight tendency to bend; aluminum rings would have to be placed inside to guarantee rigidity because any trace of bending in the tube could easily tilt the grating to a different angle and throw the H-alpha line off the exit slit. Wood is recommended because it is easy to work and cheap. Screens should be installed in the box to prevent crossing over of light from the entrance slit.

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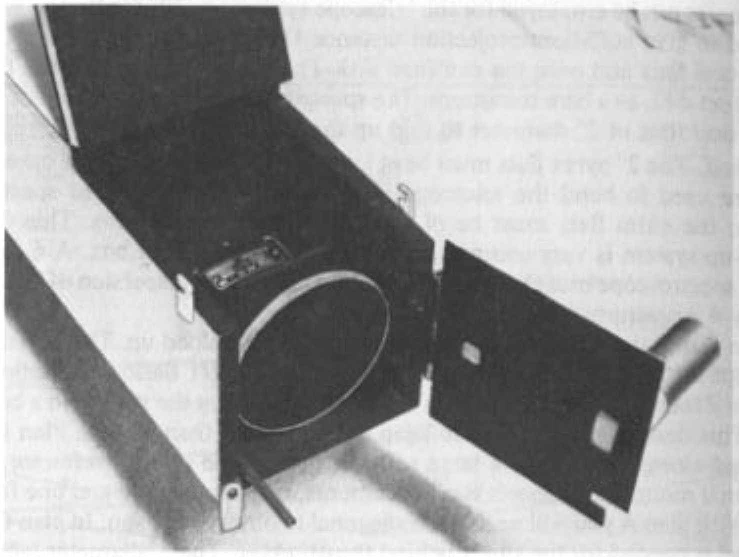
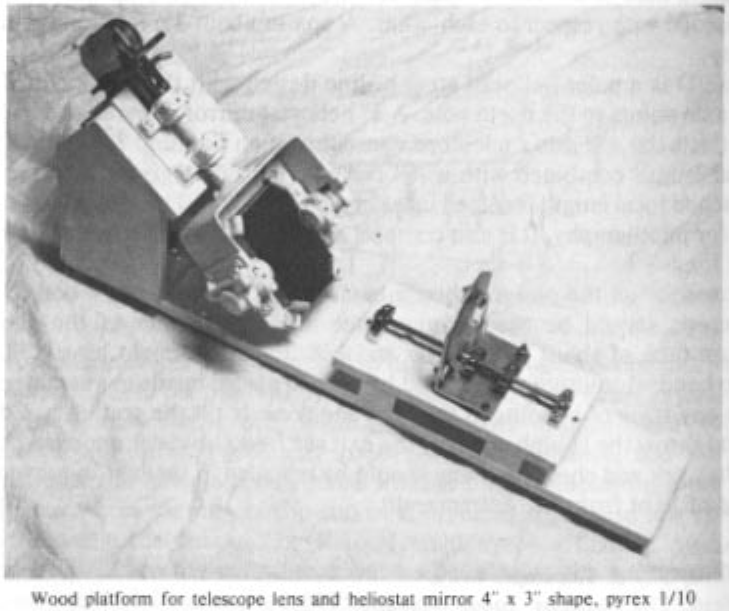
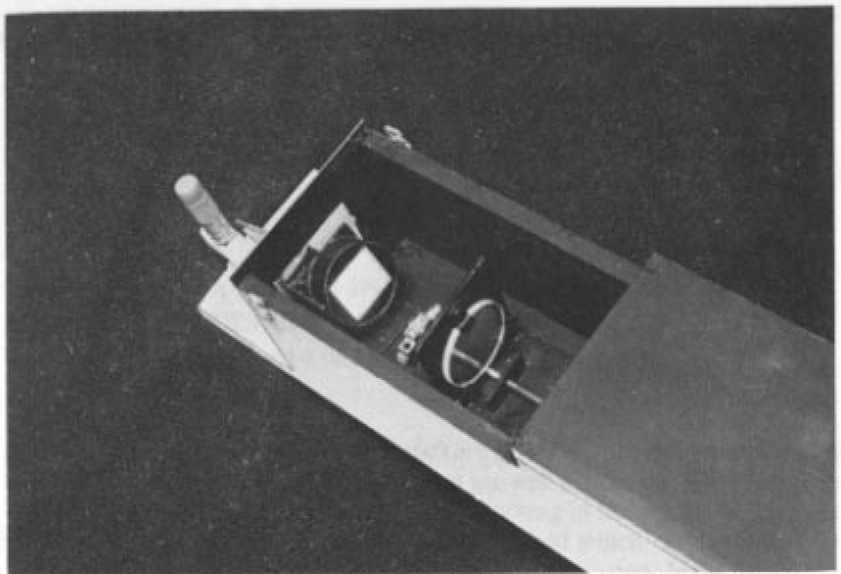


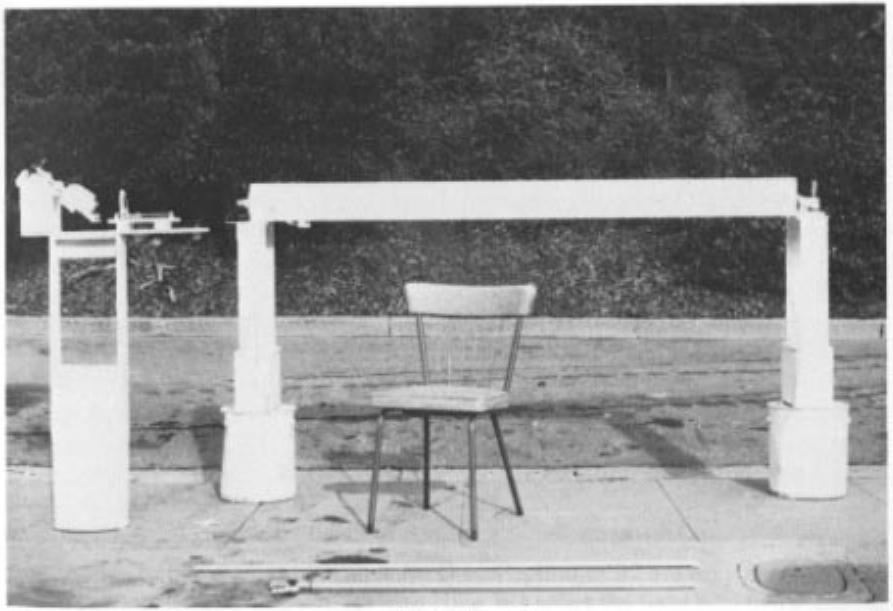
Front of the spectroscope box. Front door is open with eyepiece seen and entrance and exit ports visible. Door latch and focusing rod on left. Rotating glass disc on output axle of Bodine motor.



Wood platform for telescope lens and heliostat mirror 4" x 3" shape, pyrex 1/10 wave. RA drive and bearings with aluminum fork mount.



Rear of spectroscope box. Top cover folded back. Spectroscope lens and grating seen. Micrometer head behind grating.



Ready for work!

Chapter 6
INTERFEROMETERS

A SIMPLE INTERFEROMETER FOR TESTING ASTRONOMICAL OPTICS
by Karl-Ludwig Bath

Amateur telescope makers test their optics by a number of methods; most of these are well written up, with the exception of interferometry on which there is almost nothing in the available literature. In the following article, an interferometer is described which can be assembled from normally available materials and which is easily adjusted. Most of the elements can be found in any inexpensive prism binocular.

Highlights of the interferometer:

It is applicable to all common F/D ratios and to all focal lengths down to about 20cm. White unpolarized light can be used. The interferometer provides a bright image. When working with laser illumination and exit A2, up to 50% efficiency is available, sufficient to project the image to 10″ diameter. Contrast of the image is high and at exit A1 is always 100%. The image is free from disturbing light. Exit A1 is complementary to A2. At A1 the zero order fringe is bright, at A2 it is dark.

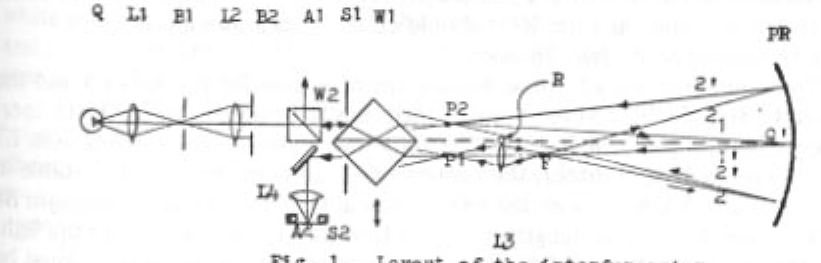


Fig. 1. Layout of the interferometer.

Principle.

In Fig. 1: The elements from lamp Q to diaphragm B2 are only necessary if a laser is not available. The beam divided cube W1 splits the light into two coherent parts, 1 and 2. Beam 1 produces a small image of the light source at Q′—then, having been reflected, it passes through a small biconvex lens L3 and forms an undisturbed spherical reference light wave with the center P1. Beam 2 leaving the cube W1 meets lens L3 and as a spherical wave fills the whole aperture of the optical system under test (PR). The reflected wave has all the deviations of PR, thus forming a second light wave at P2. Cube W1 recombines the two waves, which can be observed at A1 or A2.

Elements of the Interferometer.

1. The source at Q: Any common light source will do, preferably a projector lamp—best is a laser. With a laser, each surface should be cleaned thoroughly and, after aligning, care should be taken to remove all dust particles from the surfaces hit by the narrow beam to avoid interference. If the beam of the laser is too narrow and does not illuminate the whole aperture of PR, a simple negative lens is placed between the interferometer and the laser—the small amount of divergence does no harm.

2. The lens L1. A photographic lens of about f = 50mm, a binocular ocular or the like.

3. Diaphragm B1. A strip of aluminum foil provided with pinholes of various sizes.

4. The lens L2. Another corrected lens whose focal length should be long enough to produce an image Q' of B1 smaller than 1/10th of PR's diameter.

5. Beam dividing cube W2. This is only needed for exit A1 and should be removed when exit A2 is used (A2 provides four times the brightness of A1). A thin microscope cover plate or two Porro prisms "cemented" with water may be used as well.

6. The cube W1. To get sufficient dispersion of P1 and P2, at least a 25mm cube should be used. I obtained the same results by replacing W1 by two Porro prisms luted with sunflower oil. While most available cubes have one unpolished black face, the home-made cube leaves all faces accessible as needed for exit A2.

7. Lens L3. This is a symmetric biconvex lens with a focal length smaller than 1/20th of PR's. To get a small angle between the beams 1 and 1' at Q', the diameter of L3 should not exceed 10mm. If necessary, it may be ground to near half-moon shape. The aberrations of L3 are compensated even when it is tilted in the beam. If L3 is assymetric (for instance a plano-convex) it should be adjusted with some care, and in this case the ratio R/D should equal 10 as a minimum.

Construction of the Interferometer

Three-dimensional adjusting devices are necessary for the lens L3 and the optics to be tested (PR). At least one of them has to be adjustable in height (perpendicular to the plane of Fig. 1). The focusing device of any camera with L3 mounted on it will do. Further, the centers of all elements must be adjustable to the same height. We begin with the light source at Q and then place diaphragm B1 at approximately 4.5 focus lengths of L1 in front of Q. Then we center the light cone emerging from B1 to PR before putting the lens L1 in its place. Q must be focused on the diaphragm B1.

Lens L2 images the diaphragm B1 on PR at Q'. The diaphragm B2 should have a diameter of 5 to 10mm and it should be adjustable in the plane perpendicular to the beam.

Setting the cubes is not critical. Cube W1 is a plano-parallel plate with respect to beam 2. Beam 1 will be recentered by turning the cube.

The distance of the emerging beams 1 and 2 should not exceed 10mm, otherwise we get additional astigmatism and coma. Beam 2 is set to the desired position by moving diaphragm B2. The distance of beam 1 from beam 2 is set by shifting cube W1 in the direction indicated by the arrow in Fig. 1.

Lens L3 is centered into beam 2 at one focal length from cube W1. In case the system PR has a ratio of less than 10 after having finished the adjustment of the interferometer, in order to avoid vignetting by the cube, cube W1 must be shifted nearer to lens L3.

No light should miss lens L3 and light cone 2 must illuminate the whole aperture of PR. These two conditions are met by adjusting the diameter of diaphragm B2 and its position perpendicular to the beam.

Distance L2—PR equals the imaging distance of PR (called R, see Figs. 1 and 4).

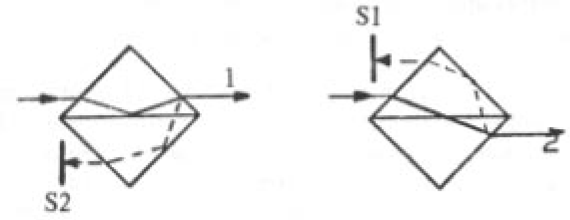


Figure 2.

Adjusting the Interferometer.

We produce some strips of fairly stiff paper. One strip underneath each beam dividing cube provides easy turning by small angles.

At first we move lens L3 or diaphragm B2 until the light cone 2 is centered on PR. If PR is an objective lens, the plane mirror (Fig. 4) is obscured with black paper and the axis of the lens adjusted with regard to the interferometer axis (marked by the dashed line) with the beam reflected by the lens surfaces.

At P2 (one focal length away from L3) we insert a strip of slightly transparent white paper into beam 1 and adjust the image of F (Fig. 1) to exactly opposite P1 and centered on beam 1. This is done by moving PR (Fig. 1) or the plane mirror in case of an objective lens.

Finally, looking into the interferometer at exit A1 or A2, we see several bright spots. The one caused by cube W2 can be removed by turning this cube slightly. Another is caused by cube W1 (see Figs. 2 and 1). Occasionally lens L3 produces reflections which are easily removed by turning the lens (see above under "Lens L3").

Having adjusted fairly carefully, we find two bright discs corresponding to points P1 and P2. P2 appears only on PR and is identified by moving the head some inches backwards.

We now have to: (1) make the two discs of equal size and (2) make them coincide. The size of the discs can be varied by changing the distance L3—PR. The discs are brought into coincidence by turning and inclining the concave mirror (or the plane mirror if a lens is being tested). Another approach would be to change the height of L3 carefully and to turn the cube W1 by small angles. During the last procedure, beam 1 will move over PR but should not leave it. This second method is more convenient but may result in only partial illumination of PR.

Having brought the two discs to the same size and coincidence, we can expect to see interference fringes. In order to get experience with the fringes, we repeat all adjusting steps and vary them by very small amounts. We find the paraxial focus by centering the ring system first and then focusing the distance L2—PR. Unintentional maladjustments necessitate going through all the steps described—it is useless to look for fringes in a maladjusted system.

The Fringes.

If PR is a perfect spherical mirror, the interferogram for the center of curvature is a uniform bright (exit A1) or dark disc (A2). In this case, we move P1 and P2 horizontally or vertically against each other and see straight fringes emerging; these are parallel and without deviation no matter what the direction is. Any deviation of wavefront 2′ deteriorates the fringe pattern (compare interferograms 2 and 1).

The focus of a certain part of the test piece PR is identified by parallelism of the fringes more conveniently than by making the fringes vanish. For instance, if the fringes are straight at the center of the test piece, then deviations from the straight line give the aberration of the zone very exactly (in interferograms 3-5, spherical aberration is shown). In example 4 the central fringe at the edge is displaced by 4.0 fringes, corresponding to approximately 4 rings in example 3. In No. 5 the interferometer focus P2 coincides with the focus of a zone of the test piece in No. 3.

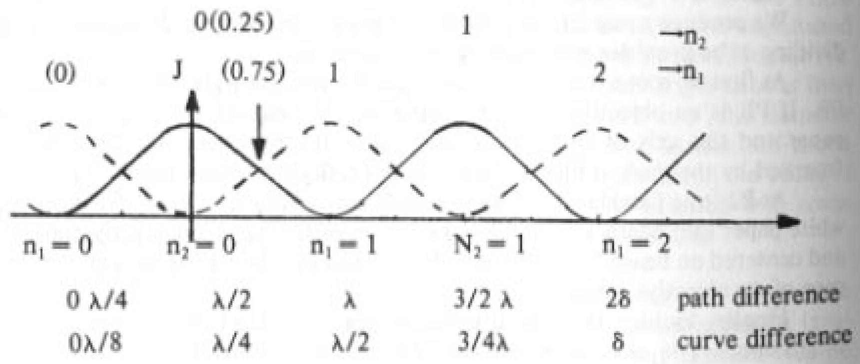


Figure 3.

Some Applications.

Concave mirror: elliptical, paraboloidal and hyperboloidal mirrors are flattened at the edge compared to a reference sphere, and therefore produce a pattern similar to the test object in interferograms 3 to 5. We get these fringe radii from the difference between the curve under test and the reference sphere (beam 1′). At first approximation:

$$\delta = \frac{h^4}{8R^3}(\epsilon_1^2 - \epsilon_2^2)$$

where h = distance of the point with reference to the optical axis
R = radius of curvature
ϵ = eccentricity.

For a paraboloid, $\epsilon_1 = 1$, and reference sphere, $\epsilon_2 = 0$, we derive the well-known formula

$$\delta = \frac{h^4}{8R^3},$$

and from this the value of h if δ and R are given.

From Fig. 3 we see that the path difference $2\delta = (2n_1 - 1)\frac{\lambda}{2}$, with n_1 being the number of the dark ring considered (center bright, A1). So we get:

$$\frac{2h^4}{8R^3} = (2n_1 - 1)\frac{\lambda}{2}, \text{ or}$$

$$h = \sqrt[4]{(4n_1 - 2)\lambda R^3} \quad (2)$$

For A2 we find in the same way:

$$h = \sqrt[4]{4n_2\lambda R^3} \quad (3)$$

With these formulas we can further compute the half diameters h of spherical mirrors, which will work as paraboloids within the Rayleigh tolerance of $2\delta = \lambda/4$. In Fig. 3 the arrow follows the diameter of such a spherical mirror:

$$D = 2h = 2\sqrt[4]{4(0.75-2)\lambda R^3} \quad \text{where } n_1 \text{ is } 0.75 \quad (2a)$$

and $$D = 2\sqrt[4]{4(0.25)\lambda R^3} \quad \text{where } n_2 \text{ is } 0.25 \quad (3a)$$

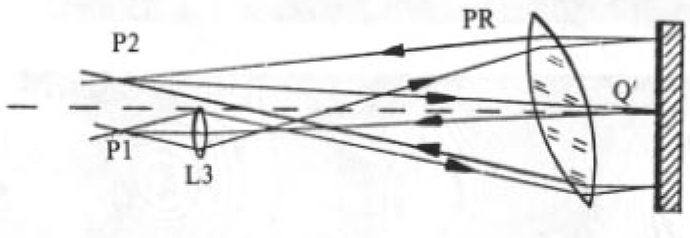


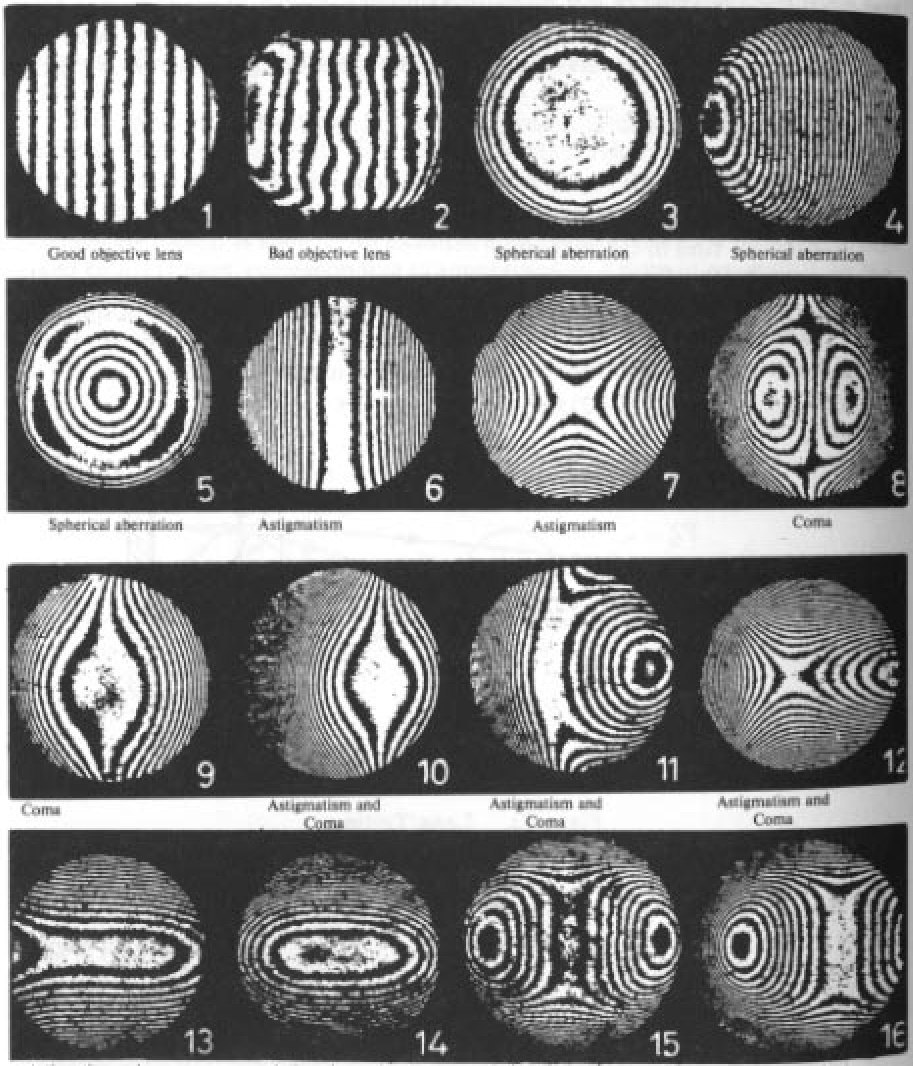
Figure 4. Lens Testing

When testing the entire telescope, the flat mirror must be of high quality. Moreover, we should pay attention to the 'scope's axis (Fig. 4) otherwise we will introduce additional astigmatism and coma. With a telescope containing lenses of not first rate chromatic correction, the interference fringes will appear only on a part of PR. This effect is caused by light of short coherence length and is avoided only by use of a laser.

Some Notes on Photography.

Lens L4 is to be focused on PR. Bad focusing causes an indefinite edge of the image (see interferogram No. 13). For a 2cm diameter image, the focal length of L4 has to be approximately 2R/D, measured in cm. Cube W1 causes an elliptical image (astigmatic imaging of PR, because in most cases the light cone is assymetric with respect to the cube. Interference is not affected). We get a circular image if the beam traverses an additional Porro prism (not drawn) of W1 size lying with its hypotenuse face in the plane of the drawing between the camera and W1.

If PR is a lens, there are some more reflections which can be stopped by suitable diaphragms at P1 and/or P2.



1 Good objective lens; 2 Bad objective lens; 3 Spherical aberration; 4 Spherical aberration; 5 Spherical aberration; 6 Astigmatism; 7 Astigmatism; 8 Coma; 9 Coma; 10 Astigmatism and Coma; 11 Astigmatism and Coma; 12 Astigmatism and Coma; 13 Astigmatism and Coma; 14 Astigmatism and Spherical aberration; 15 Astigmatism and Spherical aberration; 16 All three aberrations together

All photographs are taken in the meridional plane.

A PRACTICAL SOLUTION TO THE COMMON PATH INTERFEROMETER

by A. E. Aeppli

My first experimental setup of the interferometer was on a strip of wood onto which the loose lenses were stuck into small lumps of plasticine to make them stand up and to give them the right height. Although I did not know what to look for, I succeeded in seeing interference fringes with this crude setup (after half a day of frustrating trials!). After this first success, I built the interferometer shown in the photos which works so well that so far I have saved the effort of building one that looks a little more professional.

My concept of the interferometer was different from the one described by Mr. Bath. I wanted to have all the optical elements fixed once they were aligned. If necessary, I wanted to be able to exchange lenses of different focal lengths, and therefore change spacing, without having to rebuild anything. The whole job had to be done in an afternoon, using only a hand drill.

A piece of wood was cut into squares about 3″ x 3″. All squares were stacked on top of each other and clamped together. A hole was drilled into each corner to accept an 8mm threaded rod. A small hole was drilled through the center of the stack which would later serve as a guide when the individual large center holes for the optical parts were made. This ensured good enough alignment since the squares were used the same way round and in the same order in which they were drilled. When assembling the interferometer, each square carried one optical element which could be moved and fastened anywhere along the optical axis. Because the optical elements could not be adjusted as described in the article, when the interferometer is used to test a mirror, the whole unit has to be mounted on a cross-slide. Various cross-slides have been described in *Sky & Telescope* in past years either for Foucault or caustic testers (X-Y axis). For the Z axis (up and down movement) I use the center column of my heavy photographic tripod which I always use as a stand, or I adjust one of its legs. For fine adjustment of this setup, I put small weights in front or at the back of the support table, or onto the interferometer itself. This changes the tilt very slightly.

Using My Interferometer.

Testing a spherical mirror only takes about ten minutes when starting from the beginning. Re-checking after a spell of polishing takes about two minutes of adjusting the screws on the cross-slide and the weights for the Z axis, if the mirror stand is sturdy enough.

At the approximate radius of curvature, the reference beam of the interferometer is directed towards the center of the mirror, just like a torch. The returning beam, which is caught onto a white card mounted all around the beam-splitter, is focused by moving the interferometer to and from the test mirror until one of the beams forms a sharp point, just as in Foucault testing. By moving the interferometer sideways, the beams are made to re-enter the beam-splitter and lens L3.

Now we have to move to the observing point of the interferometer at A2. If we sit back one or two feet, we see two bright points, P1 and P2. One of them can be moved by moving the interferometer (to make them stand out brightly among other reflections, I advise using a coated mirror for the first test). These two points are moved until they cover each other perfectly. If one of them is larger than the other, the interferometer is focused to or from the mirror until both look the same size. If we now move the eye as close as possible to the interferometer, we see the whole mirror illuminated brightly (as in Foucault testing). By pressing on the support table, we see interference rings flashing across the mirror. We now adjust the cross-slide and vertical axis until the rings remain visible. There may be 10, 20 or more rings—by fine focusing we obtain the desired straight fringes if the mirror is perfectly spherical.

For me, testing for spherical wave fronts is the main way in which I use the interferometer. Any fault can be seen at a glance with high accuracy, especially if a positive eyepiece is used with a piano wire stretched across its field to serve as a reference straight line. On strong aspherical surfaces, I use the interferometer to measure zones—the peaks of the fringes accurately point to the zone in focus.

Spherical wave fronts are obtained if a perfect surface or system is tested of the following specifications:

1. A spherical mirror at its center of curvature.
2. A plane mirror against a spherical mirror.
3. A parabolic mirror at its focus against a plane mirror.
4. A complete optical system (such as a Maksutov) against a plane mirror.
5. A telescope objective against a plane mirror.
6. A hyperbolic Cassegrain secondary against a plane mirror (Norman test).

On visiting the astronomical workshop of Zeiss in Western Germany, I was shown their use of interferometers for final quantitative testing of all their large astronomical mirrors and objectives. I think that making up the described interferometer from surplus lenses and eyepieces will appeal to any optical amateur. Purchasing a good quality beam-splitter cube, however, will save a lot of experiment time and will ensure quick success.

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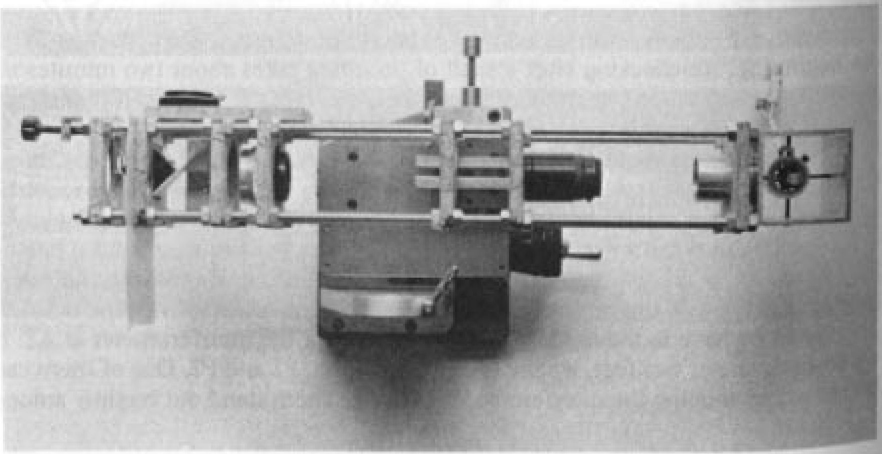
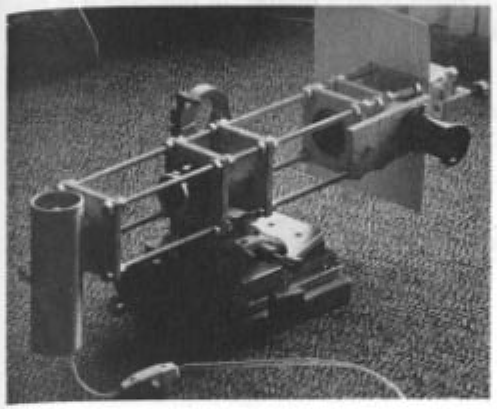
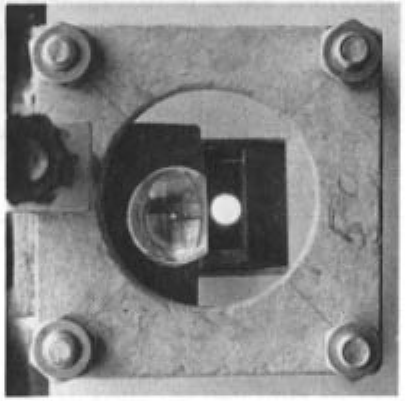


Interferometer — Top View



Side View



View Prom 'PR'

THE SCATTER-PLATE INTERFEROMETER
by Richard E. Sumner

I've been interested in the scatter-plate interferometer for about ten years and followed its development with interest. The first reference I can find is dated 1954 when Dr. James Bauch first published his findings at the National Physical Laboratory in England.

In his first unit he used two identical plates as shown in Fig. 1.

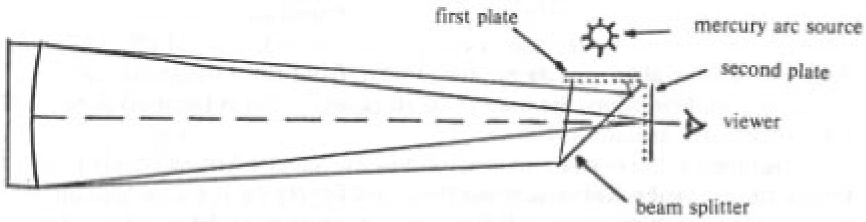


Figure 1.

All I can say is that it must have been one hell of a unit to align. Since then scatter-plates have been made by superimposing two images on a piece of plastic; a master pattern is pressed and then rotated 180° and pressed again.

Current technology uses high resolution photographic plates, namely Kodak

649F, the scatter pattern again being formed from a master. In this case it is the speckle pattern formed from a ground piece of glass, see Fig. 2.

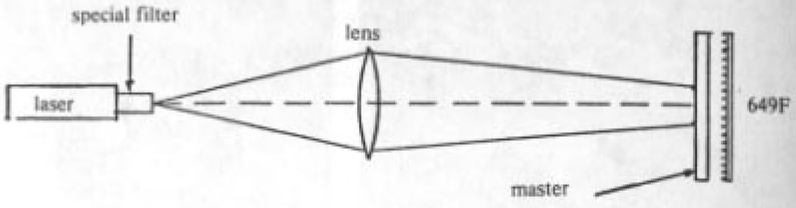


Figure 2.

Two exposures are made, one rotated precisely 180° from the other; the better the 180° are held, the higher the contrast. The finer the grind, the larger the scatter-cone (the angle of scatter light). This determines how fast a mirror you can test.

The film is developed, bleached and fixed. A small fiducial mark is usually included to mark the physical center of the plate—very important for lining up the plate and the reflected image.

The usual configuration used is as in Fig. 3:

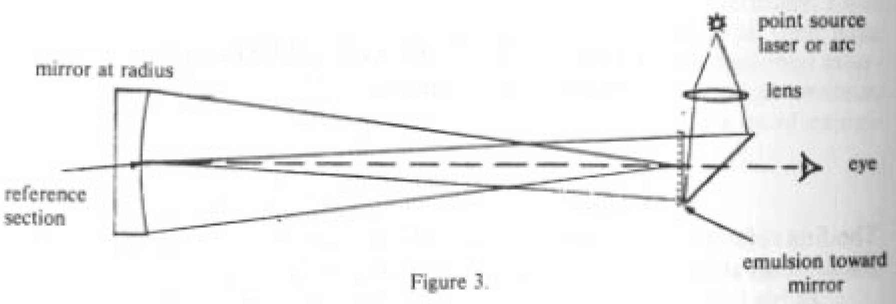


Figure 3.

The scatter-plate interferometer is a common path two beam system. The whole of the mirror under test is compared against the small reference section. Since the scatter-plate gets its reference wave front from the scatter points which are caused by diffraction, the unit's overall quality factor is reported to be theoretical (somewhere around $\lambda/100$).

Included at the end is a drawing of how Diffraction Limited made their unit. I found this out when Xerox sent me their unit for repair. It seems that the scatter-plate now joins salt prisms and diffraction gratings as an endangered species. Xerox has a technician who was successful in cleaning that transparent film off the window in the interferometer!

Another method developed at Edmund Scientific and reported to me by Mike Simmonds is as shown in Fig. 4:

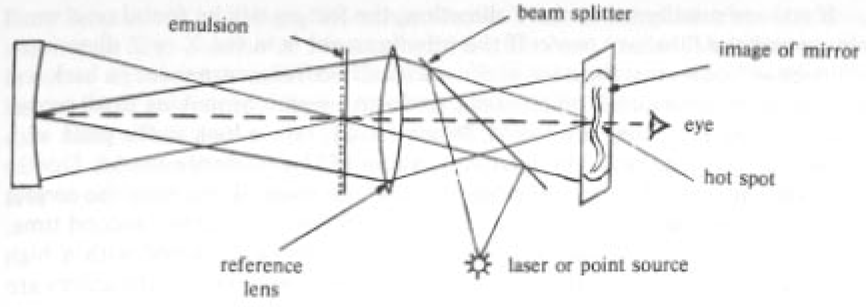


Figure 4.

This method has one tremendous advantage: it keeps the user from viewing the laser directly (if one is used). Secondly, it allows you to place an occulting disc at the focal plane to block the bright reference spot.

The ultimate quality of the interferometer is based on all the information generated by the scatter-plate and brought to focus in the final image. When you view the mirror with your eye, the fringes will be seen on the surface of your mirror under test. For long focus mirrors this is a good test, but for fast mirrors the fringes you see are not real. This can be proved by moving your eye from side to side and observing the fringes changing shape. But if you use a highly corrected camera lens and bring all the energy to a common focus, the fringes will become real, as viewed in the finder or in the final print.

Alignment of the plate is critical. It must be held firmly and be able to be moved in three directions, X, Y and Z. See Fig. 5:

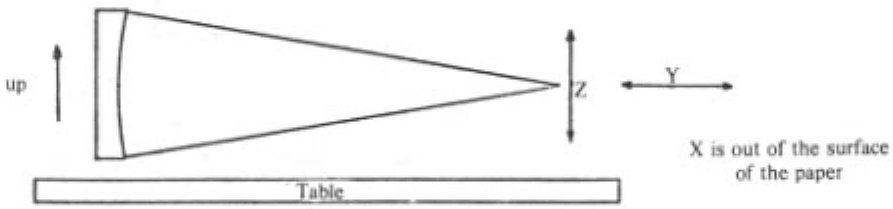


Figure 5.

A misalignment of ½mm will make the fringes very hard to find. The plate must be at the radius of the mirror under test. The amount of misalignment is not so critical for long focus systems.

On setting up the unit, the first thing to be done is to focus the reference spot on the mirror—adjust the mirror to bring the reflected beam back to the scatter-plate. Measure for correct spacing and place a ruler across the mirror to block the reference beam. Look at the scatter-plate with a lens so that you can see the fiduciary mark clearly, viewed from the back. Adjust the unit till the image formed of the scatter-plate is in best focus. Now remove the ruler and align the unit in the X and Z planes till the image of the fiduciary mark is directly on top of the original in the emulsion. Remove the viewing lens and observe for fringes.

If you are misaligned in the Y direction, the fringes will be found on a small circle around the fiduciary mark. If the misalignment is in the X or Z directions, the fringes will be seen at the edge of the mirror. If no fringes are seen, go back and check the setup for errors. If all else fails, perform a search by making small movements in X and Z till they are found. When found, take a look at the plate with your viewing lens and note the relative position of the reference marks. Due to small variations in each plate, they do not come out even. If you note the correct position for your unit, you will have no trouble in finding fringes a second time.

In my opinion the most beautiful fringes are those produced with a high intensity arc source with white light, using an aluminized mirror—the colors are something to behold.

Caution. This is an interferometer and very sensitive to vibration and bending of supports. Be sure you use a firm table, free from vibration and jiggles.

SCATTER-PLATE INTERFEROMETER BY DIFFRACTION LIMITED (from Xerox)

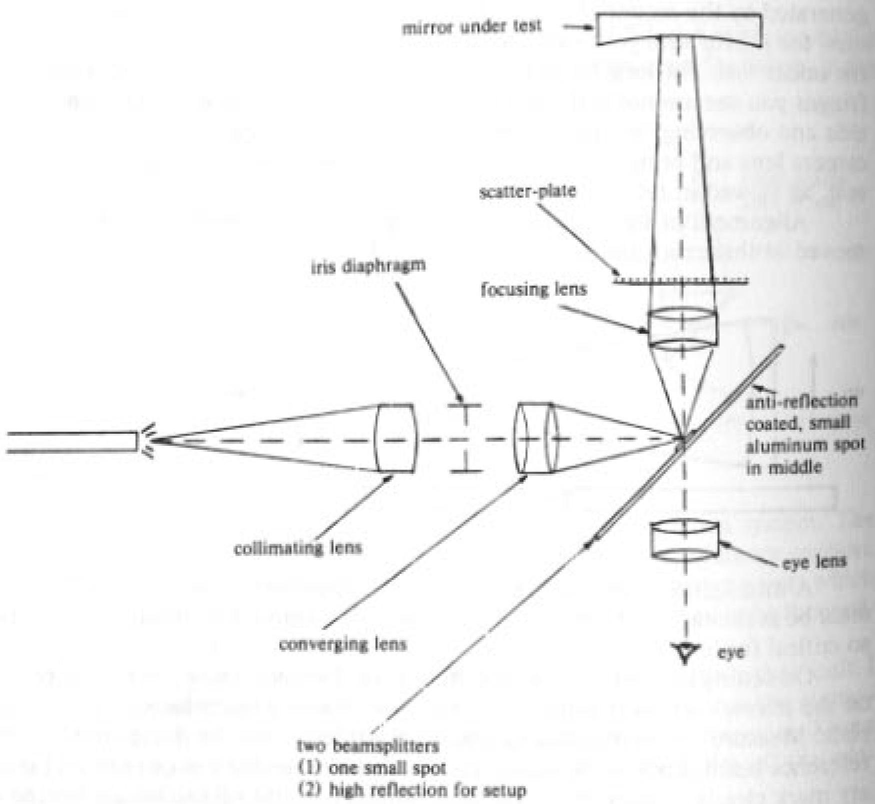


Figure 6.

Be cautious in using a laser, they are not a known quantity when it comes to the human eye—this is why I recommend the Edmund method. Another approach is to use a view camera (like a 4 x 5) and view the image on the ground glass. It helps to use an aluminized mirror when you are getting started.

Mike Simmons of Edmunds has informed me that scatter-plates will be offered for sale in the Fall 1976 catalog (they are not easy to produce without proper equipment). Catalog number will be 30,782.

Chapter 7
CALCULATOR PROGRAMS FOR TELESCOPE MAKERS

Introduction by Ed.

In the 1950s when the Maksutov Club was formed, computers were still in their infancy. They were huge machines and expensive to operate. Solid state components, which are the heart of a modern computer, had hardly been invented and were still very primitive. Very few amateurs had access to a computer except at an excessive cost in computer time. There were such things as desk calculators (Friden, Monroe and such) but they were little more than adding machines; in the early 1950s they were mechanical, in the later 1950s they began to be electrically powered.

In the 1960s, true electronic desk calculators began to appear and the large computers were solid state machines that were designed to be more compact. In 1968 the department in which I work bought an HP9100B desk calculator at a cost of well over $6,000 (far beyond the budget of most TNs); it is a powerful machine but weighs over 80 lbs. and looks like an oversized typewriter.

In the 1970s, hand-held calculators began to appear. At first these were adding machines with multiplying and dividing capacity and they cost $400 and up. Hewlett-Packard were the pioneers and they had a free market until firms such as Texas Instruments and others began to be interested in the potential market; after this, prices began to drop rapidly and the calculators became more and more complex and with much greater capacity for problem solving.

Now (1976) there are a number of hand-held calculators on the market that offer a full range of functions. Most of them have a single memory register only but some of them have multiple memories—Texas Instruments and Hewlett-Packard offer a series of calculators that have 20 memories. To illustrate the extraordinary complexity of these little instruments, a user recently discovered another 30 memories hidden away in the SR-52 calculator (Texas Instruments), to the complete surprise of the manufacturers! At least two of these more complex calculators are programable with magnetic cards (the SR-52 by Texas Instruments and the HP-65 by Hewlett-Packard); both of these have 224 possible steps on the cards and with the SR-52, at least, it is possible to connect one card with another, thus giving almost unlimited çapability to the calculator.

During the 1960s, a number of computer programs were collected in the Maksutov Club Circulars, but these have been abandoned in this book because TNs who have access to a large computer are still in the minority. Hand-held calculators are now well within the budget of most amateurs although only the more expensive ones are capable of solving all the problems to be met with in telescope making.

Competition in the field of hand-held calculators must be enormous and prices are dropping every week; the calculators are being made with more and more capacity and by the time these remarks appear in print they will probably be quite out of date, but the card-programable calculators enable anybody to do a ray-trace quickly and easily (as opposed to the old method with 7-place tables) and so telescope designing is now within the range of all amateurs.

Many people feel that they have not got the mathematical ability to write programs, so the following are given for those who don't like to write their own—they have been found to work and to give the right answers. They are written for the SR-52 and the HP-25, both of them multiple-memory jobs, but they can be adapted to single-memory calculators with the addition of pencil and paper.

They are split in two sections: those for the Texas Instruments series, and those for the Hewlett-Packard. Within these divisions they are presented in order of increasing complexity. In this way it is hoped that an amateur who has newly bought a calculator will be encouraged to build his own programs without too much brain-fag.

Program

For computing the diameter of successive rings to be cut when generating a cast-iron tool in the lathe.

SR-52 — by A.M. 10/7/76

Key	*Code*	*Comments*	*Registers*	
LBL A	11		01	increment
RCL 03	03		02	R
+	85			
RCL 01	01			
)	54	$sagitta_1$		
STO 03	03			
rtn	56		*Labels*	
LBL B	12		A and B	
2	02			
X	65			
RCL 02	02			
X	65			
RCL 03	03	2RS		
x_2	40			
)	54	$2RS - S^2$		
$\sqrt{x}$	30	$\sqrt{2RS - S^2}$		
X	65			
2	02	$2\sqrt{2RS - S^2}$		
)	54			
rtn	56			

Procedure:
- Store in 01 increment to be used
- Store in 02 R (radius desired)
- Hit A for sagitta
- Hit B for diameter
- Hit A and B successively for increasing sagitta, increments are automatic.

Example:

It is desired to generate a tool with radius 80 inches with increments on the sagitta of .005.

Enter .005, STO 01
Enter 80, STO 02

Hit A	Display .005
Hit B	" .1264911064
Hit A	" .01
Hit B	" .2529822128
Hit A	" .015
Hit B	" .3794733192

and so on until the B key displays the full diameter of the tool you are going to use.

The equation for the S, R and d relationships is a quadratic of the form, $S^2 + 2RS - (d/2)^2 = 0$. From this,

$$d = 2\sqrt{2RS - S^2}$$

and this can be measured directly on the lathe with a vernier caliper.

Program

For computing x and y axes for the caustic test.

SR-52 — A.M. 10/7/76

Formulas $y = 3r^2/R$ $x = 4r^3/R^2$

Key	*Code*	*Comments*	*Registers*	
LBL A	11		01	r
RCL 01	01		02	R
x^2	40	r^2		
X	65			
3	03	$3r^2$		
÷	55			
RCL 02	02			
)	54	$3r^2/R$		
rtn	56		*Labels*	
LBL B	12		A and B	
RCL 01	01			
y^x	45			
3	03	r^3		
X	65			
4	04	$4r^3$		
÷	55			
RCL 02	02			
x^2	40	R^2		
)	54	$4r^3/R^2$		
rtn	56			

Procedure:
- Store R in register 02
- Store r in register 01

Hit A for y axis
Hit B for x axis

Since r has to be recorded on the caustic chart in any case, the increments are not automatic and r has to be stored for each entry. R is the same all through, so it only has to be stored for the initial entry.

Example:

We want the readings for a 12½" mirror at f/5 for a Newtonian. The increments on the radii of the caustic masks are .600. R in this case is 125.

Enter 0	STO 01	y axis display		x axis display
Enter 125	STO 02			
Enter 0	STO 01	y axis display	0	x axis display 0
" .600	"		.00864	.000055296
" 1.200	"		.03456	.000442368
" 1.800	"		.07776	.001492992

and so on until the last entry occurs at 6.000.

Program

For finding (1) sagitta of a sphere, formula $R - \sqrt{R^2 - r^2}$
(2) sagitta of a paraboloid, formula $r^2/2R$
(3) the difference between the two.

SR-52 A.M. 10/7/76

Key	*Code*	*Comments*
LBL A	11	
RCL 02	02	
x^2	40	R^2
−	75	
RCL 01	01	
x^2	40	r^2
)	54	
$\sqrt{x}$	30	
)	54	$\sqrt{R^2 - r^2}$
STO 03	03	
rtn	56	
LBL B	12	
RCL 02	02	
−	75	
RCL 03	03	
)	54	sag. of sphere
STO 04	04	
rtn	56	
LBL C	13	
RCL 01	01	
x^2	40	r^2
÷	55	
RCL 02	02	R
)	54	r^2/R
÷	55	
2	02	
)	54	sag. of paraboloid
STO 05	05	
rtn	56	
LBL D	14	
RCL 05	05	
−	75	
RCL 04	04	
)	54	difference
rtn	56	

Registers

01	r
02	R

Labels

A, B, C, D

Procedure:
STOre r in 01
STOre R in 02
hit A for $\sqrt{R^2 - r^2}$
hit B for spherical sagitta
hit C for paraboloidal sagitta
hit D for difference

Example:

We have a 12½" f/5 mirror. We want to find the reading on a 12" spherometer which will sit just inside the rim of the mirror for our grinding and we want to find the difference between the sagittae of the sphere and paraboloid because this will give us an approximate guide as to how long it should take to parabolize. r in this case is 6 and R 125.

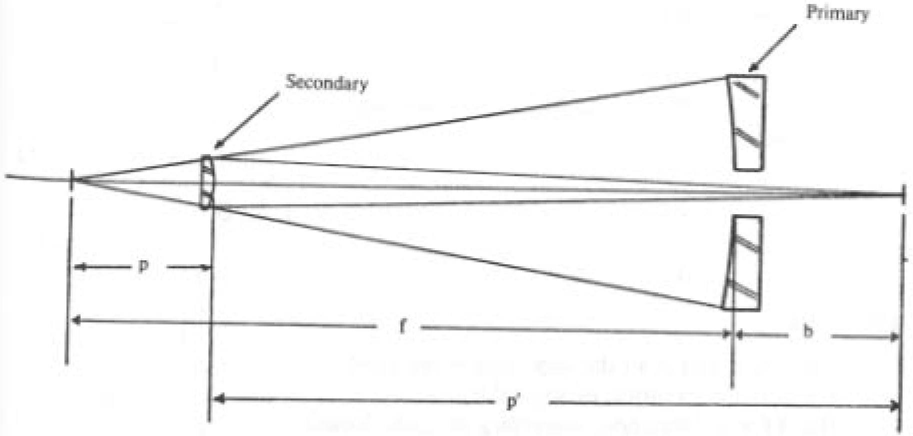
	display
Enter 6	6
STO 01	6
Enter 125	125
STO 02	125
Hit A	124.855917
Hit B	.1440830397
Hit C	.144
Hit D	−.000830397

the − simply means that the sphere is deeper and has no significance.

Program

For finding the parameters of a Cass. telescope.

SR-52 A.M. 10/8/76



Equations for the linear parameters are to be found in Hindle's article in *A.T.M. I*, p. 216. The equations for eccentricity are based on R.E. Buchroeder's article in this book.

Key	*Code*	*Comments*	*Key*	*Code*	*Comments*
LBL A	11		RCL 06	06	
RCL 01	01		X	65	
+	85		RCL 05	05	
RCL 02	02		)	54	
)	54		÷	55	
STO 04	04		(	53	
÷	55		RCL 06	06	
(	53		−	75	
RCL 03	03		RCL 05	05	
+	85		)	54	
1	01		=	95	radius, secondary
)	54		rtn	56	
=	95	p	LBL D	14	
STO 05	05		4	04	
rtn	56		X	65	
LBL B	12		RCL 03	03	
RCL 04	04		+/−	94	
−	75		)	54	
RCL 05	05		+	55	
=	95	p'	(	53	
STO 06	06		RCL 03	03	
rtn	56		−	75	
LBL C	13		1	01	
2	02		)	54	
X	65		x^2	40	

Cass. program (contd.)

Key	*Code*	*Comments*
=	95	(K+1)
−	75	
1	01	
=	95	eccentricity, secondary
rtn	56	

Registers		*Labels*
01	f	A, B, C, D
02	b	
03	A	

Procedure:

Enter f, b and A in the appropriate registers
Hit A for p (position of secondary)
Hit B for p' (distance, secondary to Cass. focus)
Hit C for radius, Cass. secondary
Hit D for eccentricity, secondary, in terms of paraboloid

Example:

We are making a Cass. telescope of 12½" diameter and decide on f/4 primary focal length (f = 50) with an amplification of 4 (A = 4). We want the final focal plane to lie 12 inches behind the surface of the primary.

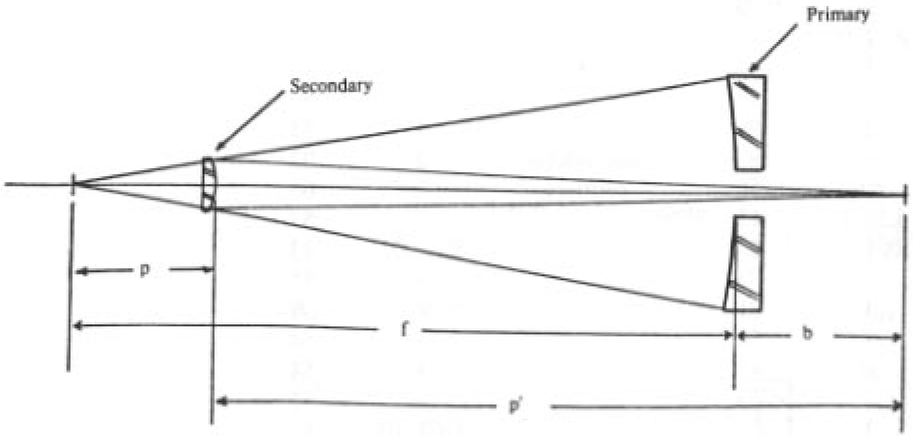
		display
Enter 50		50
	STO 01	50
Enter 12		12
	STO 02	12
Enter 4		4
	STO 03	4
Hit A		12.4
Hit B		49.6
Hit C		33.06666667
Hit D		−2.777777778

The primary, of course, is a paraboloid and has an eccentricity of −1.

Program

For finding the parameters of a Ritchey-Chretien telescope.

SR-52 A.M. 10/8/76



Origin of the equations is the same as for the Cass. program

Key	*Code*	*Comments*	*Key*	*Code*	*Comments*
LBL A	11		RCL 05	05	
RCL 01	01		)	54	
+	85		÷	55	
RCL 02	02		(	53	
)	54		RCL 06	06	
STO 04	04		−	75	
÷	55		RCL 05	05	
(	53		)	54	
RCL 03	03		=	95	radius, secondary
+	85		rtn	56	
1	01		LBL D	14	

Key	Code	Comments
)	54	
=	95	p
STO 05	05	
rtn	56	
LBL B	12	
RCL 04	04	
−	75	
RCL 05	05	
=	95	p'
STO 06	06	
rtn	56	
LBL C	13	
2	02	
X	65	
RCL 06	06	
X	65	
X	65	
2	02	
+/−	94	
+	55	
RCL 07	07	
)	54	(K+1)
−	75	
1	01	
=	95	eccentricity, primary
rtn	56	
LBL E	15	
RCL 03	03	
−	75	
1	01	
)	54	
y^x	45	
3	03	
)	54	
STO 10	10	
(	53	
(	53	
(	53	
4	04	
X	65	
RCL 03	03	

Key	Code	Comments
RCL 03	03	
y^x	45	
3	03	
)	54	
STO 07	07	
RCL 01	01	
−	75	
RCL 05	05	
)	54	
STO 08	08	
RCL 06	06	
+	55	
RCL 08	08	
)	54	
STO 09	09	
X	65	
(	53	
RCL 03	03	
−	75	
1	01	
)	54	
)	54	
+	85	
2	02	
X	65	
(	53	
RCL 03	03	
+	85	
RCL 09	09	
)	54	
)	54	
+	55	
RCL 10	10	
+/−	94	
=	95	(K+1)
−	75	
1	01	
=	95	eccentricity, secondary
rtn	56	

Registers

01	f
02	b
03	A

Labels

A, B, C, D, E

Procedure:

Enter f, b, and A in the appropriate registers
Hit A for p (position of secondary)
Hit B for p' (distance, secondary to R-C focus)
Hit C for radius, secondary
Hit D for eccentricity of primary
Hit E for eccentricity of secondary

Example:

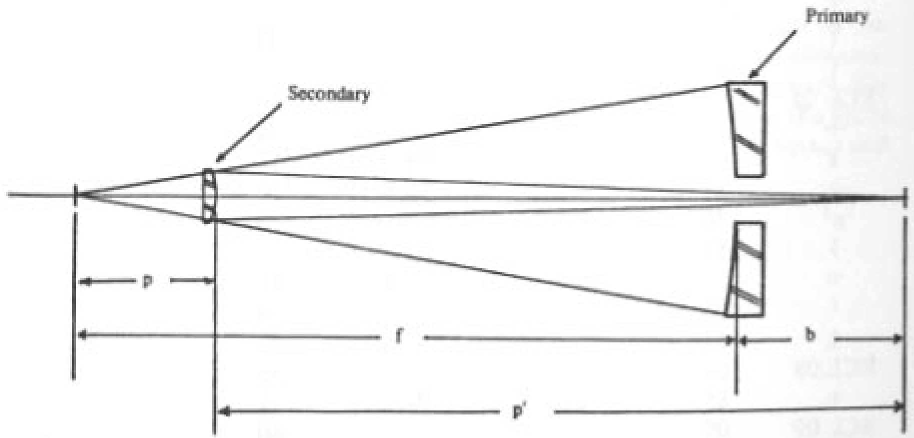
We are making a Ritchey-Chretien telescope of the same dimensions as the Cass. telescope In this case, both mirrors are other than paraboloids and we want to know the eccentricity.

Enter 50		display 50
	STO 01	50
Enter 12		12
	STO 02	12
Enter 4		4
	STO 04	4
Hit A		12.4
Hit B		49.6
Hit C		33.0666667
Hit D		−1.041223404
Hit E		−3.17178881

Program

For finding the parameters of a Dall-Kirkham telescope.

SR-52 A.M. 10/8/76



Origin of the equations is the same as for the Cass. telescope

Key	*Code*	*Comments*	*Key*	*Code*	*Comments*
LBL A	11		(	53	

RCL 01	01	
+	85	
RCL 02	02	
)	54	
STO 04	04	
÷	55	
(	53	
RCL 03	03	
+	85	
1	01	
)	54	
=	95	p
STO 05	05	
rtn	56	
LBL B	12	
RCL 04	04	
−	75	
RCL 05	05	
=	95	p'
STO 06	06	
rtn	56	
LBL C	13	
2	02	
X	65	
RCL 06	06	
X	65	
RCL 05	05	
)	54	
÷	55	
X	65	
(	53	
(	53	
RCL 08	08	
+	85	
1	01	
)	54	
x^2	40	
)	54	
÷	55	
(	53	
(	53	
RCL 08	08	
+	85	
RCL 09	09	
)	54	
X	65	
RCL 08	08	
y^x	45	

RCL 06	06	
−	75	
RCL 05	05	
)	54	
=	95	radius, secondary
STO 07	07	
rtn	56	
LBL D	14	
RCL 06	06	
÷	55	
RCL 05	05	
=	95	
STO 08	08	
RCL 06	06	
÷	55	
(	53	
RCL 01	01	
−	75	
RCL 05	05	
)	54	
=	95	
STO 09	09	
X	65	
(	53	
RCL 08	08	
−	75	
1	01	
)	54	
LBL A'	16	
RCL 07	07	
÷	55	
RCL 10	10	
)	54	
STO 11	11	
RCL 10	10	
√x	30	
X	65	
RCL 11	11	
)	54	
STO 12	12	
(	53	
RCL 11	11	
x^2	40	
−	75	
RCL 12	12	
x^2	40	
)	54	

3	03	
)	54	
=	95	(K+1)
STO 10	10	
−	75	
1	01	
=	95	e, primary
rtn	56	

√x	30	
STO 13	13	
RCL 11	11	
−	75	
RCL 13	13	
=	95	short conjugate
rtn	56	
LBL B'	17	
RCL 11	11	
+	85	
RCL 13	13	
=	95	long conjugate
rtn	56	

Registers

01	f
02	b
03	A

Labels

A, B, C, D, A', B'

Procedure:

Enter f, b, and A in appropriate registers

Hit A for p
Hit B for p'
Hit C for radius of secondary
Hit D for eccentricity of primary
Hit A' for short conjugate
Hit B' for long conjugate

the eccentricity of the secondary is, of course, zero.

Example:

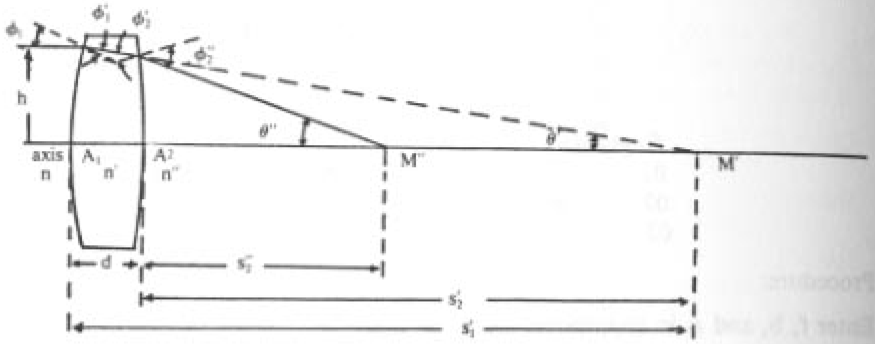
We are making a Dall-Kirkham telescope of the same dimensions as the Cass. on page 295. Here, the secondary is a sphere and the primary is an ellipsoid. We shall want the dimensional parameters and the eccentricity of the primary. We will also probably be figuring the primary by putting the light source at the short conjugate of the ellipse and the knife edge at the long conjugate (or vice versa) and so we shall want to know the conjugates.

	display
Enter 50	50
STO 01	50
Enter 12	12
STO 02	12
Enter 4	4
STO 03	4
Hit A	12.4
Hit B	49.6
Hit C	33.06666667
Hit D	−0.709375
Hit A'	17.94912411
Hit B'	209.6064314

In this case we will probably decide that the long conjugate is so far away that it will be easier to knife-edge the primary at center of curvature, using the value obtained from "D" and simply use the null test as a check on the c-of-c test.

Ray Trace Program
1st Surface

SR-52 A.M. 10/7/76



This program is based on the ray trace procedure in *Fundamentals of Optics*, by Jenkins & Wright, p. 126 (McGraw-Hill).

Key	*Code*	*Comments*	*Key*	*Code*	*Comments*
Meridional rays			+	85	
LBL A	11		RCL 01	01	
RCL 04	04		)	54	s'
÷	55		HLT	81	
RCL 01	01				
)	54	sin φ	Paraxial ray		
STO 05	05		LBL B	12	
INV	22		RCL 07	07	
sin	32	φ	−	75	
STO 06	06		RCL 05	05	
RCL 02	02		)	54	
X	65		+/−	94	sin θ'
RCL 05	05		STO 10	10	
÷	55		HLT	81	
RCL 03	03		INV	22	
)	54	sin θ'	sin	32	θ'
STO 07	07		HLT	81	
INV	22		RCL 01	01	
sin	32	φ'	X	65	
−	75		RCL 07	07	
RCL 06	06		÷	55	

)	54	θ'	RCL 10	10	
+/−	94		)	54	r − s'
STO 08	08		+	85	
HLT	81		RCL 01	01	
sin	32	sin θ'	=	95	s'
STO 09	09		HLT	81	
HLT	81				
RCL 01	01				
X	65				
RCL 07	07				
÷	55				
RCL 09	09				
)	54	r − s'			

Registers

01	r
02	n
03	n'
04	h

Labels
A and B

Procedure:

Store r, n, n', h in the appropriate registers—enter h successively in order 0.5, 1.0, 1.5, etc. (marginal ray last).

For meridional rays: hit A for θ'
hit RUN for sin θ'
hit RUN for s'

For paraxial ray: (marginal ray should be in register 04)
hit B for sin θ'
hit RUN for θ'
hit RUN for s'

Example:

r is +10.0, n is 1.0, n' is 1.523, h is successively 0.5, 1.0, 1.5

	display
Enter 10	display 10
STO 01	10
Enter 1.0	1.0
STO 02	1.0
Enter 1.523	1.523
STO 03	1.523
Enter 0.5	0.5
STO 04	0.5
Hit A	.9846288681
Hit RUN	.0171841698
Hit RUN	29.1047582
Enter 1.0	1.0
STO 04	1.0
Hit A	1.974427949
Hit RUN	.0344534486

Hit RUN	29.05756446
Enter 1.5	1.5
STO 04	1.5
Hit A	2.974712174
Hit RUN	.0518952002
Hit RUN	28.97859963
Hit B	.0515101773
Hit RUN	2.952622441
Hit RUN	29.12045889

2nd Surface
(meridional & paraxial rays)

Key	*Code*	*Comments*	*Key*	*Code*	*Comments*
LBL A	11		INV	22	
RCL 04	04		sin	32	ϕ''_2
−	75		+	85	
RCL 07	07		RCL 01	01	
+	85		−	75	
RCL 03	03		RCL 10	10	
)	54	$r_2 + s'_2$	)	54	
STO 08	08		+/−	94	θ''
X	65		HLT	81	
RCL 02	02		sin	32	sin θ''
÷	55		STO 12	12	
RCL 04	04		HLT	81	
)	54	sin ϕ'_2	RCL 04	04	
STO 09	09		X	65	
INV	22		RCL 11	11	
sin	32	ϕ'_2	+	55	
STO 10	10		RCL 12	12	
RCL 05	05		)	54	$r_2 - s''_2$
X	65		+	85	
RCL 09	09		RCL 04	04	
+	55		=	95	s''_2
RCL 06	06		HLT	81	
)	54	sin ϕ''_2			
STO 11	11				

	Registers	Labels
01	θ' from 1st surface	A
02	sin θ' from 1st surface	
03	d	
04	r_2	
05	n'	
06	n''	
07	s' from 1st surface	

Procedure:

Enter the appropriate quantities in registers 01 to 07
Hit A for θ''
Hit RUN for sin θ''
Hit RUN for s''_2

Note: 3rd, 4th and more surfaces may be worked with this program after the new parameters have been entered.

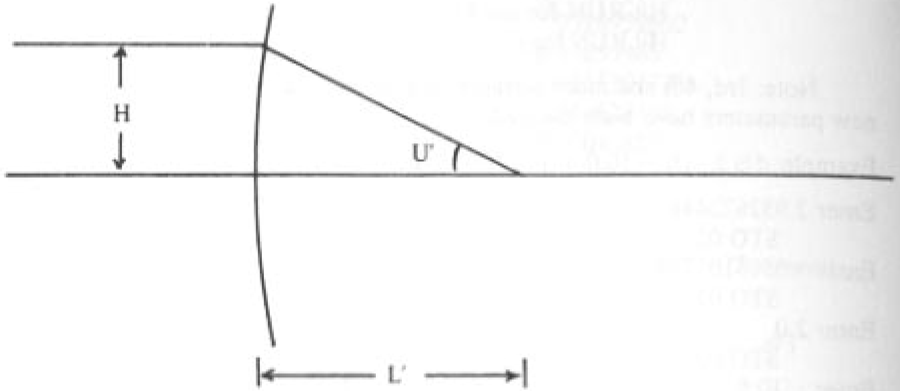
Example: d is 2, r_2 is −10.0, n' is 1.523, n'' is 1.0

	display	
Enter 2.952622441		2.952622441 (paraxial ray)
STO 01		2.952622441
Enter .0515101773		.051510773
STO 02		.051510773
Enter 2.0		2.0
STO 03		2.0
Enter −10.0		−10.0
STO 04		−10.0
Enter 1.523		1.523
STO 05		1.523
Enter 1.0		1.0
STO 06		1.0
Enter 29.12045889		29.12045889
STO 07		29.12045889
Hit A		−8.859734922
Hit RUN		−.1540160513
Hit RUN		8.907769528
Enter .9846288681		.9846288681 (0.5 merid. ray)
STO 01		.9846288681
Enter .0171841698		.0171841698
STO 02		.0171841698
Enter 29.1047582		29.1047582
STO 07		29.1047582
Hit A		−2.901586869
Hit RUN		−.0506206007
Hit RUN		9.183629148
		(1.0 merid. ray)
		(1.5 merid. ray)

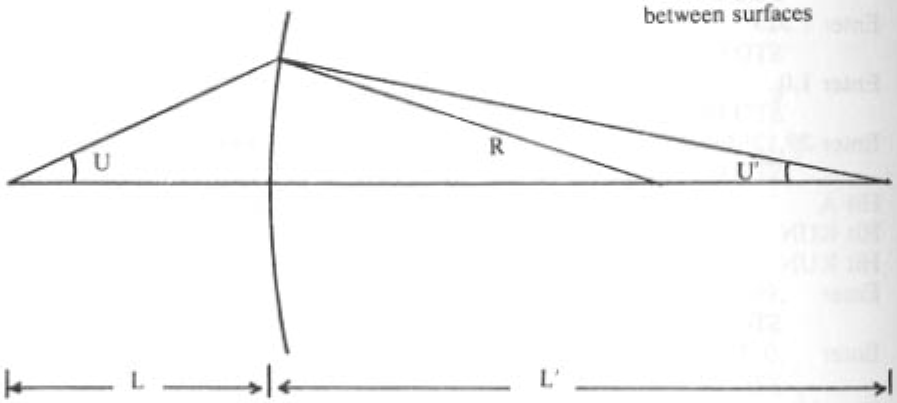
The 1.0 and 1.5 meridional rays can be worked by storing the proper quantities from the 1st surface in registers 01, 02 and 07.

Ray Trace Program
6 Surfaces

SR-52 I.H. Schroader 9/13/76



t is distance between surfaces



Key	*Code*	*Comments*	*Key*	*Code*	*Comments*
LBL	46		1	01	
A	11		9	09	
0	00		sin	32	sin U
EXC	48	H	)	54	sin I
9	09		INV	22	
7	07		sin	32	
if zro	90		)	54	I
0	00		SUM	44	(U+I in 19)
1	01		1	01	
9	09		9	09	
÷	55		sin	32	sin I
D	14	R	X	65	
STO	42		D	14	n/n'

9	09		)	54	sin I'
8	08		INV	22	
GTO	41	sin I	sin	32	I'
0	00		INV	22	
4	04		SUM	44	(U+I−I' in 19)
0	00		1	01	
D	14	t	9	09	
INV	22		sin	32	sin I'
SUM	44		÷	55	
1	01		RCL	43	U'
8	08		1	01	
RCL	43	L	9	09	
1	01		sin	32	sin U'
8	08		+	85	
÷	55		1	01	
D	14	R	)	54	1+ sin I'/sin U'
STO	42		X	65	
9	09		RCL	43	R
8	08		9	09	
−	75		8	08	
1	01		)	54	L'
)	54	(L−R)/R	STO	42	
X	65		1	01	
RCL	43	U	8	08	
INV	22		9	09	
dsz	58		9	09	
0	00		IND	36	
8	08		RCL	43	
3	03		9	09	
GTO	41		9	09	
0	00		rtn	56	
0	00		LBL	46	
0	00		C	13	
HLT	81		RCL	43	U'
LBL	46		1	01	
B	12	(surface by surface)	9	09	
1	01		HLT	81	
STO	42		LBL	46	initialize
0	00		E	15	
0	00		0	00	
GTO	41		STO	42	
0	00		9	09	
0	00		9	09	
0	00		HLT	81	
LBL	46	counter			
D	14				
1	01				
SUM	44				

Registers			Labels
00	N surfaces	A	N surfaces
01	R_1	B	stepwise
02	n/n' (1)	C	U'
03	t_2	E	initialize
04	R_2		
05	n/n' (2)		
06	t_3		
07	R_3		
08	n/n' (3)		
09	t_4		
10	R_4		
11	n/n' (4)		
12	t_5		
13	R_5		
14	n/n' (5)		
15	t_6		
16	R_6		
17	n/n' (6)		
18	L'		
19	U'		

Procedure:

			Display
1. Enter surface data (in order of recall)		STO R_{01} to R_{17}	
	N surfaces	STO R_{00}	
2. (a) for ∞ conjugate, enter H		STO R_{97}	
	U = 0	STO R_{19}	
(b) for finite conjugate, H = 0		STO R_{97}	
	L	STO R_{18}	
	U	STO R_{19}	Display
3. Initialize		press E	0
4. Result, for N surfaces		press A	L'
		press C	U'
5. Result, surface by surface		press E	0
		press B	L_1'
		press C	U_1'

alternate B and C to step through all surfaces.

(Note by ED.) This is a very sophisticated program. It is very convenient to use because once the initial entries have been made, the final answer can be obtained—if this is not satisfactory, the surfaces can then be stepped through to find out which surface is giving trouble. It is a beautiful example of what can be done with this very powerful calculator. It will be noticed that Mr. Schroader has made use of some of the 30 extra storage registers mentioned in the introduction.

Program

For finding the diameter of successive rings to be cut when generating cast iron tools in the lathe.

HP-25 by Robert E. Cox

Formulae: $S = R - \sqrt{R^2 - r^2}$ $d = 2\sqrt{2RS - S^2}$

Enter and store: R in register 1; r in register 0.
I (increment) in register 7.

Key

RCL 1
x^2
RCL 0
x^2
−
√
RCL 1
↻
−
STO 2
RCL 1
X
2
X
RCL 2
x^2
−
√
2
X
RCL 7
STO + 0
↻
RCL 2

First enter the program and store as indicated, then hit R/S and the first answers will be calculated; for further calculations just hit R/S and note the registers as indicated above.

The sagitta "S" is displayed in the "x" register and, upon exchanging x and y, the desired diameter will then be displayed in the "x" register. The program automatically increments S, through incrementing r, so all that is necessary is to read the "x" register for S and exchange registers and read d. If the next incremented r is desired, RCL 0.

Program

For computing the y and x axis for the caustic test.

HP-25 by Robert E. Cox

Formulae: $y = 3r^2/R$ $x = 4r^3/R^2$

Enter and store: R in register 1 r in register 0

If one wishes to automatically increment "r", then the program should be continued by dropping the last step (exchange register) and then continuing as in (2).

1	2
Key	*Key*
RCL 0	3
g x^2	RCL 0
3	f x=y
X	GTO 23
RCL 1	f x∠
÷ GTO 26	
STO 2	RCL 3
RCL 0	RCL2
3	GTO 00
f y^x	.
4	1
X	STO+0
RCL 1	RCL 3
g x^2	RCL 2
÷	
STO 3	
⇄	

In either case, x is in the "y" register and y is in the "x" register and to display x use the exchange register key.

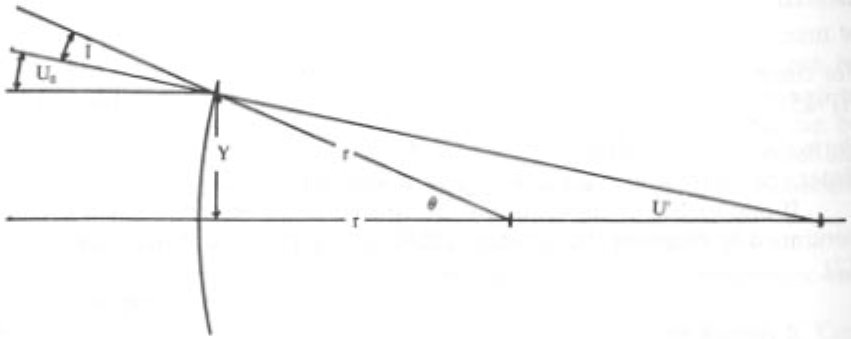
If incremental steps are automatically programmed, the figure can be obtained and checked by RCL 0.

After the program and storage has been entered, hit the f Clear Program buttons and then R/S. After the first calculation on the automatic sequence, just continue to hit the R/S key. The "3" at the top of the automatic program should be the maximum radius of the outside zone to be measured (I used 3 just for an example) and when the program has reached the outside zone radius it will not continue to calculate and the same figure will keep appearing in the registers, this is the sign to quit.

Ray Trace Program

HP-25 by W. R. Deazley, June 1976

Program with start and continue through any number of surfaces.



Key entry	*X*	*Y*	*Z*	*T*	*Comments*	*Registers*
RCL 0	Y					R_0 Y or L
RCL 1	r	Y				R_1 r
÷	Y/r					R_2 U_o or U
g arc sin	θ					R_3 N
RCL 2	U_o	θ				R_4 N'
−	θ−U_o					R_5 sin I
f sin x	sin I					R_6 sin I' or L'
STO 5	sin I					R_7 d
RCL 3	N	sin I				
RCL 4	N'	N	sin I			
÷	N/N'	sin I				
X	sin I'					
STO 6	sin I'					
g $\sin^{-1}$	I'					
RCL 5	sin I	I'				
g $\sin^{-1}$	I	I'				
−	I'−I					
RCL 2	U	I'−I				
⇄	I'−I	U				
−	U+I−I'					
STO 2	U'					
f sin x	sin U'					
STO÷6	sin U'				sinI'/sinU' in 6	
RCL 1	r	sin U'				
STO X 6	r	sin U'			r sinI'/sinU' in 6	
STO + 6	r	sin U'			r + r sinI'/sinU' = L'	
RCL 6	L'	r	sin U'			
STO 0	L'	r	sin U'			
RCL 4	N'	L'	r	sin U'		
STO 3	N'=N^{new}	L'	r	sin U'		
↓	L'	r	sin U'	N^{new}		
RCL 2	U'	L'	r	sin U'		
⇄	L'	U'	r	sin U'		
R/S	L'				read L' after last surface	

Programs for hand-held calculators.

The following programs are of use in the telescope maker's workshop. They are written for the SR-52 calculator made by Texas Instruments Inc. but can be adapted without much difficulty to any of the other calculators made by T.I. with the addition of a pencil and paper. Conversion to the Hewlett-Packard series (and other calculators) might be rather more difficult.

All formulae used in the programs have been taken from Machinery's Handbook, 14th edition.

Program.

For finding the volume and weight of metals in rectangular blocks and sheets. by Allan Mackintosh.

SR-52

Key	Code	Comments	Key	Code	Comments	Registers
LBL A'	16		LBL C	13		01 length
RCL 01	01		RCL 04	04		02 width
X	65		X	65		03 thickness
RCL 02	02		.	93		in inches
X	65		3	03		
RCL 03	03		2	02		Labels.
)	54	vol. cu. ins.	1	01		
STO 04	04		)	54	wt. copper	A, B, C, D, E, A'
rtn	56		rtn	56		
LBL A	11		LBL D	14		
RCL 04	04		RCL 04	04		
X	65		X	65		
.	93		.	93		
0	00		4	04		
9	09		0	00		
7	07		9	09		
5	05		6	06		
)	54	wt. aluminum	)	54	wt. lead	
rtn	56		rtn	56		
LBL B	12		LBL E	15		
RCL 04	04		RCL 04	04		
X	65		X	65		
.	93		.	93		
3	03		2	02		
0	00		8	08		
4	04		1	01		
8	08		7	07		
)	54	wt. brass	)	54	wt. steel	
rtn	56		rtn	56		

Procedure.

Enter length, width and thickness in appropriate registers (in ins.)
Hit A' for volume in cu. ins.

" A " wt. aluminum in lbs.
" B " " brass " "
" C " " copper " "
" D " " lead " "
" E " " steel " "
the current price can then be entered from the keyboard.

Program.

For finding the volume and weight of metals (rounds) rod.

SR-52 by Allan Mackintosh.

Key	Code	Comments	Key	Code	Comments	Registers
LBL A'	16		LBL C	13		01 length
RCL 02	02		RCL 03	03		02 dia.
x^2	40		X	65		in inches
X	65		.	93		
RCL 01	01		3	03		Labels
X	65		2	02		
π	59		1	01		A, B, C, D, E, A'
÷	55		)	54	wt. copper	
4	04		rtn	56		
)	54	vol. cu. ins.	LBL D	14		
STO 03	03		RCL 03	03		
rtn	56		X	65		
LBL A	11		.	93		
RCL 03	03		4	04		
X	65		0	00		
.	93		9	09		
0	00		6	06		
9	09		)	54	wt. lead	
7	07		rtn	56		
5	05		LBL E	15		
)	54	wt. aluminum	RCL 03	03		
rtn	56		X	65		
LBL B	12		.	93		
RCL 03	03		2	02		
X	65		8	08		
.	93		1	01		
3	03		7	07		
0	00		)	54	wt. steel	
4	04		rtn	56		
8	08					
)	54	wt. brass				
rtn	56					

Procedure.

Enter length and diameter in appropriate registers (in inches)
Hit A' for volume in cubic inches

" A " weight of aluminum (in lbs.)
" B " " " brass " "
" C " " " copper " "
" D " " " lead " "
" E " " " steel " "
the current price can then be entered from the keyboard.

Program.

For computing columes and areas of spheres, spherical sectors and spherical segments.

SR-52

by Allan Mackintosh.

Sphere	Spherical Sector	Spherical Segment
Formulas $V = 4/3\ \pi r^3$	$V = 2/3\ \pi r^2 h$	$V = \pi h^2(r - h/3)$
$A = 4\ \pi r^2$	$C = 2\quad h(2r - h)$	$A = 2\ \pi rh$
	$A = \pi r(2h + .5C)$	

Key	Code	Comments	Key	Code	Comments	Key	Code	Comments
LBL A	11		=	95	vol. sph.	rtn	56	
RCL 01	01		rtn	56	sector	LBL A'	16	
y^x	45		LBL D	14		RCL 02	02	
3	03		RCL 01	01		x^2	40	
X	65		X	65		X	65	
π	59		2	02		π	59	
X	65		)	54		)	54	
4	04		–	75		X	65	
÷	55		RCL 02	02		(	53	
3	03		)	54		RCL 01	01	
)	54	vol. sphere	x	40		–	75	
rtn	56		X	65		(	53	
LBL B	12		2	02		RCL 02	02	
RCL 01	01		)	54	"C"	÷	55	
x^2	40		STO 03	03		3	03	
X	65		rtn	56		)	54	
π	59		LBL E	15		)	54	vol.
X	65		π	59		=	95	sph.
4	04		X	65		rtn	56	segment
)	54	sph. surf.	RCL 01	01		LBL B'	17	
rtn	56	area	X	65		2	02	
LBL C	13		(	53		X	65	
RCL 01	01		2	02		π	59	
x^2	40		X	65		X	65	
X	65		RCL 02	02		RCL 01	01	
RCL 02	02		+	85		X	65	
X	65		.	93		RCL 02	02	surf. area
π	59		5	05		=	95	sph. segment

Key	Code	Comments	Key	Code	Comments	Key	Code
X	65		X	65		rtn	56
2	02		RCL 03	03			
÷	55		)	54	surf. area		
3	03		=	95	sph. sector		

Registers.

01	r
02	h

Labels.

A, B, C, D, E, A', B'

Procedure.
Enter r and h in the appropriate registers.
Hit A for spherical volume
" B " spherical surface area
" C " volume of spherical sector
" D " dimension "C"
" E " spherical sector surface area
" A' " volume of spherical segment
" B' " surface area of spherical segment

Program.

For finding area and perimeter (close approximation) of an ellipse and the volume of an ellipsoid.

SR-52

by Allan Mackintosh.

Formulas

Ellipse: Area = πab , Perimeter = $\pi \quad 2(a^2 + b^2 - \frac{(a-b)^2}{2.2}$

Ellipsoid: Volume = $4/3\ \pi abc$

Key	Code	Comments	Key	Code	Comments
LBL A	11		RCL 02	02	
RCL 01	01		)	54	
X	65		x^2	40	
RCL 02	02		÷	55	
X	65		2	02	
π	59		.	93	
=	95	area, ellipse	2	02	
STO 04	04		)	54	
rtn	56		=	95	
LBL B	12		x	30	
(	53		)	54	
2	02		X	65	
X	65		π	59	
(	53		=	95	perimeter, close approximation
RCL 01	01		rtn	56	
x^2	40		LBL C	13	
+	85		RCL 04	04	

Registers

01	a
02	b
03	c

Labels.

A, B, C

RCL 02	02	X	65	
x^2	40	RCL 03	03	
)	54	X	65	
=	95	4	04	
−	75	÷	55	
(	53	3	03	
(	53	=	95	vol., ellipsoid
RCL 01	01	rtn	56	
−	75			

Procedure.
Enter a, b and c in appropriate registers
Hit A for area of ellipse
" B " perimeter (close approximation) of ellipse
" C " volume of ellipsoid

Program.

For finding the area of a parabola and
the volume and surface area of a paraboloid.

SR-52

by Allan Mackintosh.

Formulas:

Parabola, Area = 2/3rh

Paraboloid, Volume $= \frac{\pi}{2} r^2 h$

Surface area $= \frac{2\pi}{3p} \left[\frac{d^2}{4} + p^2 \quad 3 \; - \; p^3 \right]$

where $p = d^2 / 8h$

Key	Code	Comments	Key	Code	Comments	Registers
LBL A	11		(	53		01 r
2	02		(	53		02 d
X	65		(	53		03 h
RCL 01	01		(	53		
X	65		RCL 02	02		Labels.
RCL 03	03		x^2	40		
÷	55		÷	55		A, B, C
3	03		4	04		
=	95	area,	)	54	$d^2 / 4$	
rtn	56	parabola	+	85		
LBL B	12		RCL 04	04		
RCL 01	01		x^2	40		
x^2	40		)	54	$(d^2 / 4 + p^2)$	
X	65		y^x	45		

RCL 03	03		3	03	
X	65		)	54	$(d^2 / 4 + p^2)^3$
π	59		x	30	$(d^2 / 4 + p^2)^3$
X	65		−	75	
.	93		RCL 04	04	
5	05		y^x	45	
=	95	volume	3	03	
rtn	56	paraboloid	)	54	[$(d^2 / 4 + p^2)^3 - p^3$]
LBL C	13		X	65	
RCL 02	02		2	02	
x^2	40		X	65	
÷	55		π	59	
8	08		÷	55	
÷	55		3	03	
RCL 03	03		÷	55	
=	95	p	RCL 04	04	
STO 04	04		=	95	surface area, paraboloid
			rtn	56	

Procedure.
Enter r, d and h in appropriate registers
Hit A for area, parabola
" B " volume, paraboloid
" C " surface area, paraboloid

Program.

For finding the area of an hyperbola.

SR-52

by Allan Mackintosh.

Key	Code	Comments
LBL A	11	
RCL 01	01	
X	65	
RCL 02	02	
÷	55	
2	02	
)	54	xy/2
STO 05	05	
(	53	
RCL 01	01	
÷	55	
RCL 03	03	
)	54	x/a
+	85	
(	53	
RCL 02	02	

Formula.

Area $= \frac{xy}{2} - \frac{ab}{2} \log_e \left(\frac{x}{a} + \frac{y}{b}\right)$

÷	55	
RCL 04	04	
)	54	y/b
=	95	(x/a + y/b)
ln x	23	$\log_e (x/a + y/b)$
X	65	
RCL 03	03	
X	65	
RCL 04	04	
÷	55	
2	02	
=	95	$(ab/2) \log_e (x/a + y/b)$
STO 06	06	
RCL 05	05	
−	75	
RCL 06	06	
=	95	area, hyperbola
rtn	56	

Registers.

01 x
02 y
03 a
04 b

Labels.

A

Procedure.

Enter x, y, a and b in appropriate registers
Hit A for area.

INDEX

—T—

—U—

—V—

—W—

—X—

—Y—

—Z—