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APPLICATION OF ASPHERICS FOR WEIGHT REDUCTION IN SELECTED CATADIOPTRIC LENSES

Richard A. Buchroeder

Arizona University

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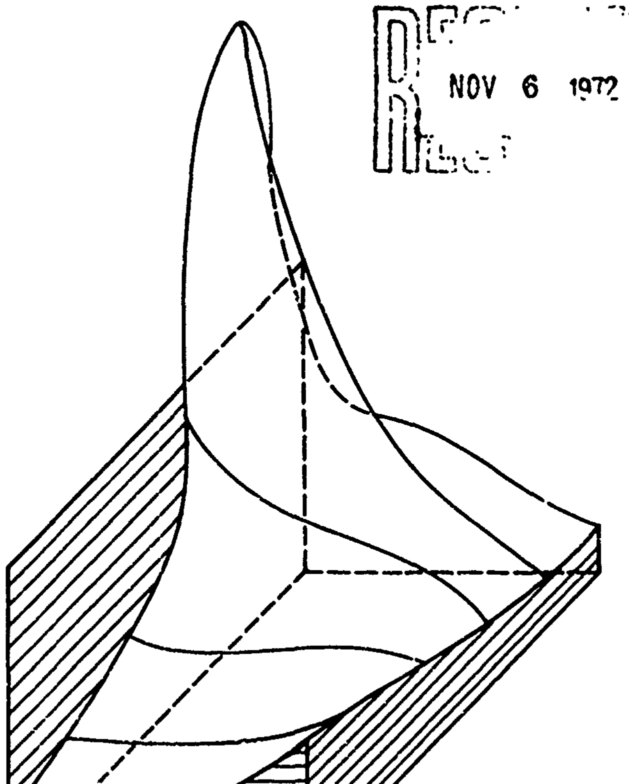

Application of Aspherics for Weight Reduction
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Richard A. Buchroeder

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APPLICATION OF ASPHERICS FOR WEIGHT REDUCTION IN SELECTED CATADIOPTRIC LENSES

Richard A. Buchroeder

Optical Sciences Center, University of Arizona, Tucson, Arizona 85721
Technical Report 69, July 1971

I

ABSTRACT

The history of modern wide-field, high-speed catadioptric lenses is reviewed. One system comprising only spherical curves and representative of the current art for low-light-level systems is evaluated and used as a baseline design in a weight-reduction study.

Five aspheric designs are computed and evaluated. It is found that the use of aspherics will permit weight reduction only in certain instances, i.e., if one element of an all-spherical design can be eliminated or if a fundamentally different configuration that is possible only with aspherics is substituted for the all-spherical configuration. Of these possibilities, the elimination of an element is the best replacement for the baseline design.

The case of a highly constrained, purely refractive triplet is studied in some detail. Four designs are computed–from the all-spherical case to the most complex polynomial aspheric. It is found that, if only conic aspherics are employed, significant improvement can be obtained and the problems involved are sensibly the same as those in all-spherical designs. When complex aspherics are applied, the problem becomes surprisingly difficult, and there is some indication that a computer can deal with it better than can a human lens designer.

CONTENTS

I. INTRODUCTION

The vast majority of lenses have curves that are sections of spheres and consequently are termed "spherical." These have the practical advantage of being producible by the motions of simple machines that combine sliding and rotating movements. In the broadest sense, any lens that is not spherical could be called "aspherical" or simply "aspheric." However, designers reserve these terms to denote a deliberate optical surface that is a figure of revolution about its axis or centerline. An example is the parabolic mirror used in observatory telescopes. Some lenses have more than one axis of symmetry; eyeglasses used to correct astigmatism are a well-known example. In this report, we shall be concerned only with single-axis curves.

Some useful aspherics differ so slightly from a perfect spherical surface that they are completely imperceptible to the eye, while others are so pronounced that their distortions are not only visible but can be felt as ripples. For our purposes, even these heavy aspherics must be produced to optical precision, often to an accuracy (in depth) of only a few millionths of an inch.

It is widely known that aspherics allow optical improvement in catadioptric lenses, but little is known about their usefulness in reducing the weight of compact, Cassegrain-like designs of moderate aperture. The primary purpose of this report is to show that a substantial weight reduction over a fully optimized, all-spherical catadioptric lens can be obtained. Therefore, we have chosen a night-vision telescope for our study.

Night-vision telescopes operate under conditions of exceedingly poor illumination, sometimes only with starlight. These telescopes consist of a light-collecting objective that forms an image on the photocathode of an electronic image intensifier, whose output phosphor screen is viewed with an eyepiece.

Compared with an ordinary telescope, the night-vision telescope has a greatly superior quantum efficiency and broader spectral response of the image intensifier's photocathode. It may be twenty times more sensitive than the human retina; therefore, much more information can be obtained from any given beam of light. Secondly, even a simple intensifier increases the image brightness more than fifty times. Consequently, the night-vision telescope gives a bright image with far more information (not necessarily resolution) than any optical telescope. Also, the diameter of the exit pupil (Ramsden disk) is not related to the aperture of the objective; therefore, the power can be made very low for a bright, wide-field image. In an optical telescope, the exit pupil's diameter is always the objective aperture divided by the telescope's magnification. Consequently there is a lower limit on magnification below which no further brightening of the image can be obtained. For a given quality level, as the magnification increases, so must the aperture and focal length of the objective.

Night-vision telescopes come in a variety of sizes from very small to quite huge. For hand-carried units, 4-in. apertures present no serious restrictions on the type of objective used. Even purely refractive lenses are not prohibitively heavy or awkward. If the aperture is 12 in. or more, sheer bulk relegates it to motorized transportation or permanent installation, so again we are not preoccupied with the exact nature of the objective.

The 6-in.- to 12-in.-aperture refractive lenses are too heavy to be portable. However, lenses of proper catadioptric form can be carried by two men. Consequently, we have selected an 8-in.-aperture field instrument for our aspheric weight-reduction study.

We are interested in a comparative study using the Shenker all-spherical lens as an arbitrary standard. This catadioptric lens, designed by M. Shenker of Farrand Optical Company, comprises all-spherical optics: three large lenses, two small, and a single mirror. It is of Cassegrain form, with the secondary reflector coated on one of the natural curves of the correcting lenses. To our knowledge, this 8-in.-aperture lens at f/1.25 is one of the best available. We do not propose to achieve a fully-optimized design because it could be prohibitively expensive. We conclude that the use of aspherics will allow a significant reduction in the weight of a moderate-aperture, high-speed catadioptric lens of Cassegrain form.

A further objective has been to design a highly constrained air-spaced triplet refractor in various ways. When the degrees of freedom are limited, and the iris position is fixed, the base design has only one optimum solution. Consequently, anything beyond an optimized all-spherical solution can be attributed only to the influence of asphericity.

II. HISTORY OF CATADIOPTRIC DESIGN

The history of the catadioptric lens is difficult to trace although certainly its most spectacular introduction was when Bernard Schmidt finished a 14-in. camera in 1930. Using only a single aspheric plate and a spherical mirror, for the first time he was able to photograph wide fields perfectly free of the coma that afflicted other telescopes of that time.

Lens designers immediately grasped the principle and translated it into all-spherical designs of comparable performance but of greater size and weight. Sonnefeld designed a compact system with only three elements at f/0.6. Houghton, working on similar principles, but independently of Sonnefeld, designed all-spherical systems for use by the Royal Air Force that were intended specifically to replace the impractically difficult Schmidt.

With the conclusion of World War II, Maksutov and Bouwers announced their discovery of the nearly concentric lens, which is another practical substitute for the Schmidt. Strangely, although the Sonnefeld-Houghton systems are easier to build and are well corrected, nearly all subsequent effort was devoted to improving the Maksutov-Bouwers type of design, frequently with the addition of an aspheric plate to supplement the nearly concentric lens. Baker's Super-Schmidt may be looked upon as a synthesis of the Schmidt and concentric systems. Then, in the 1960's, Shenker introduced the Houghton system in a Cassegrain form with external image and field lenses. This is still one of the most practical and highly corrected large-aperture all-spherical lenses. Many aspheric designs are based on this concept, notably a Perkin-Elmer lens with an aperture of nearly 14 in.

Examples of the progress of catadioptric design are shown in the following drawings, which are excerpts from the patent literature. Most recently, designs using Mangin mirrors have been introduced. Generally these are improvements on earlier, lower relative aperture designs such as Mandler's.

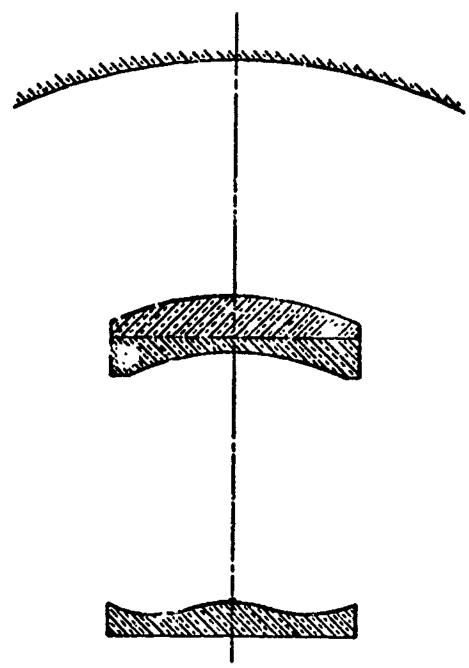
Catadioptric design is based on the same underlying principles as ordinary optical design although it is greatly complicated by the constant danger of excessive obstructions of the light path. However, the mirror is valuable because it has an effective refractive index of 2.0 and causes no dispersion of the light. Generally the obstruction problem is so great that catadioptrics are of fairly low optical sophistication by comparison with a modern lens. Most designs rely heavily on the principle of optical symmetry as a means of dealing with aberration. As with ordinary lenses, catadioptrics do not assume arbitrary configurations. A blindfolded approach to their design would be no more effective than it is with lenses.

Perusal of the U.S. patent literature provides some general feeling for the capabilities of each configuration. Frequently the principles of one design can be incorporated into those of another, and we can obtain an improved design suited to our purposes.

In the following pages, we will examine certain representative patents that have features useful in a fast, wide-field catadioptric lens.

USP 2,448,699 1948

Bouwers has been the most prolific designer in the catadioptric field and is an original inventor of high-speed designs. The accompanying figure shows a number of basic ideas synthesized into a single design. The original Schmidt camera used only an aspheric plate at the center of curvature of a spherical mirror. A concentric lens (center of curvature at that of the mirror) has field correction comparable to that at the axis, but it is uncorrected for axial color. An achromatized concentric lens corrects the axial color. By combining a Schmidt plate with such a lens, it is possible to eliminate zonal spherical aberration of the concentric lens and to offset its spherochromatism. In this patent, Bouwers claims from 10 to 300 times improvement (depending on the field of view) over an ordinary Schmidt at f/1.5. A substantial but lesser gain is still obtained at f/0.65.



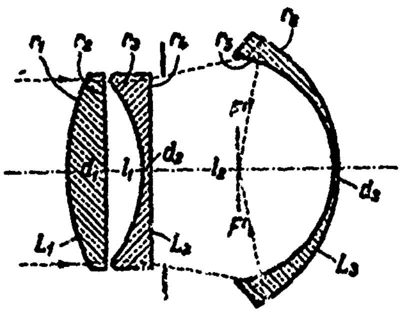
A. Bouwers, Patent 2,448,699 "Schmidt type image former with negative meniscus lens spherical aberration corrector." Filed December 18, 1945, dated September 7, 1948.

The advantage of the concentric camera (or nearly concentric in the case of the achromatic Bouwers, or Maksutov, telescope) is that all correction is carried on a single lens, which is usually spherical. Once made, it is relatively insensitive to failure. However, it is not effective unless assisted by aspherics at speeds in excess of f/2 and therefore is not well suited to Cassegrain-like arrangements. For some designers, it is an inefficient application of glass to achieve the desired end.

The lens' mechanical strength makes it a fine window that will survive much abuse. The advantages of the Schmidt plate are many: its light weight, the fact that temperature changes do not affect focus position (except for aberration), and its tremendous effectiveness over small fields of view.

USP 2,141,884 1938

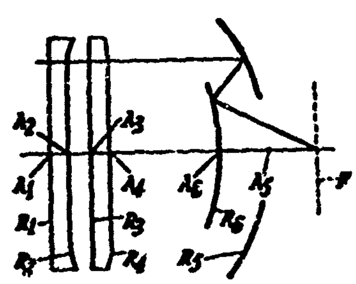
Sonnefeld, while undoubtedly impressed by the invention of his countryman, Schmidt, was not content merely to translate the latter's instrument into an all-spherical equivalent. Here, both crown and flint glass are combined with a permanently protected back-surface (Mangin) reflector to achieve a speed of f/0.6 with a field of ~10°. The principles intrinsic to this remarkable design, which are more subtle than those of the Schmidt, recur often in later art. This is perhaps the most ingenious and farsighted of all catadioptric patents. Of particular importance is the use of the Mangin mirror.



A. Sonnefeld, Patent 2,141,884 "Photographic objective." Filed November 5, 1937, dated December 27, 1938.

USP 2,336,379 1943

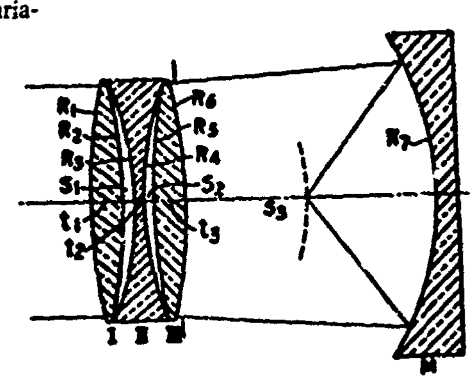
By compromising field correction, a Cassegrain form of the Schmidt is obtained. Since the final speed is lower than the mirror's speed, Warmisham achromatized the aspheric plate to keep color within reason. The advantage of such a design is that it is the lightest possible one offering a significant focal length. Mechanically, the plates need only be thick enough to survive the environment, and the mirror may be reduced to a very thin condition. Such designs are limited principally by oblique aberrations, which are partially corrected with small lenses near the focus. In our study we investigated several variations that gave encouraging results.



A. Warmisham, Patent 2,336,379 "Optical systems." Filed May 22, 1941, dated December 7, 1943.

USP 2,350,112 1944

This design was invented without prior knowledge of the Sonnefeld work. Because England was faced with a shortage of skilled labor, Mr. Houghton deliberately sought a means of replacing the Schmidt plate with more easily made spherical lenses. This example is for a speed of f/0.6. For a speed of f/2, another design requires only two lenses. Mr. Houghton has recently developed an



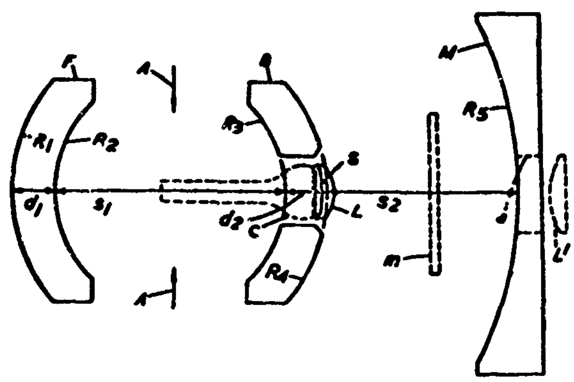
J. L. Houghton, Patent 2,350,112 "Lens system." Filed March 2, 1942, dated May 30, 1944.

analytical treatment of compound (i.e., with a secondary reflector) multilens designs (private communication 1971).

Applying aspherics to the outer lenses of the triplet corrector allows almost perfect elimination of oblique as well as axial aberration. In fact, using only spherical curves, an improvement over the true Schmidt can be obtained. The use of a three-element corrector is a fundamental advance in the art of catadioptric design that we utilize in modern optical designs.

USP 2,509,554 1950

Maksutov and Bouwers made it clear that any number of concentric lenses surrounding the aperture stop could be used because each element allows further improvement in correction. This figure shows how a detector could be used with a folding flat if the prime focus were unsuitable. The famous Baker Super-Schmidt resembles this design but with an aspheric doublet at the stop position for reasons like those discussed in the Bouwers design. The present design is monochromatic because no means for correcting color are shown. Wynne also gives examples with split elements and various bendings and power distributions for better correction.

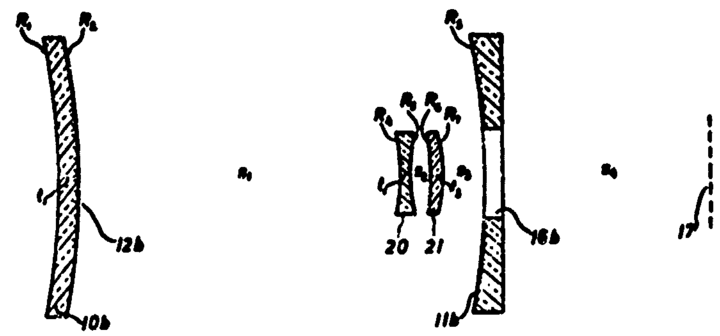


C. G. Wynne, Patent 2,509,554 "Catadioptric system with correcting lens means." Filed April 21, 1947, dated May 30, 1950.

USP 2,701,983 1955

The Maksutov-Bouwers Cassegrain can be supplemented with field elements to deal with oblique aberrations. The use of a reflecting secondary coating on the lens is a simplification attributed to John Gregory, for whom the Gregory-Maksutov telescope is named.

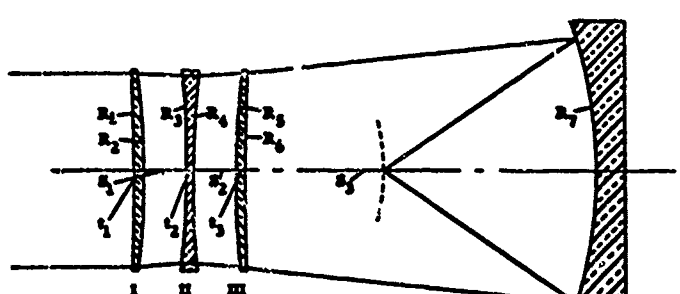
The most important feature of the design is the use of field lenses. The increasing use of such elements is noted in more modern designs. They allow more freedom in choice of mirrors because lenses can be used to flatten the field. They also provide additional control of astigmatism. Usually at least two such lenses are required if lateral color is to be corrected.



F. G. Back et al., Patent 2,701,983 "Catadioptric telephoto systems." Filed November 25, 1953, dated February 15, 1955.

USP 3,022,708 1962

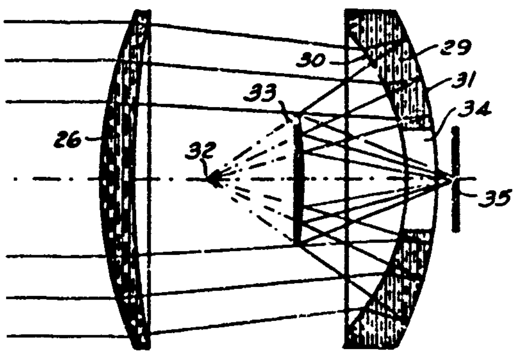
This is the design for the Baker-Nunn satellite tracking camera. It has a speed of f/1 with an aperture of about 24 in. All four inside curves have aspheric figures. The salient feature here is the use of *three* significantly spaced correcting lenses that, as in the Houghton design, allow correction of oblique aberration. This design is accomplished with the aspheric figures whereas Houghton uses the bendings of his spherical lenses. We suggest a Cassegrain version of this design for future research if higher correction is required.



J. G. Baker, Patent 3,022,708 "Correcting optical system." Filed December 16, 1957, dated February 27, 1962.

USP 3,326,621 1967

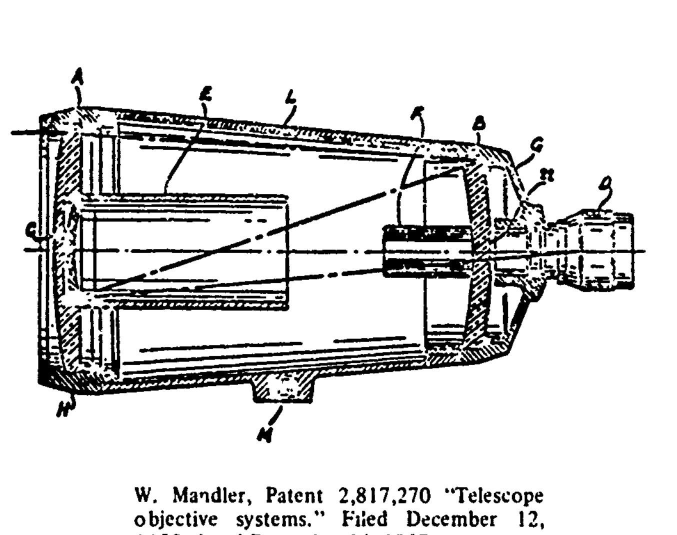
The use of a Mangin mirror has already been mentioned in Sonnefeld's design. An early application of such an element is in Schupmann's 1899 patent (USP 620,978). Nygorden and Mandler (see below) both make use of the color-corrective effectiveness of the Mangin. The theoretical advantage of this configuration is a very small camera diameter without vignetting and without the usual color of a lens. This is obtained because the light converges to the primary, and only one type of glass is used. In principle, this is one of the most desirable of all possible configurations for our purposes. However, some years ago we studied such an approach and found that the positive objective lens was doing so much "work" that the over-all correction was poor. To a certain extent, the use of field lenses and an aspheric should improve the situation.



P. J. Berggren de Nygorden, Patent 3,326,621 "Catadioptric imaging systems." Filed January 19, 1961, dated June 20, 1967

USP 2,817, 270 1957

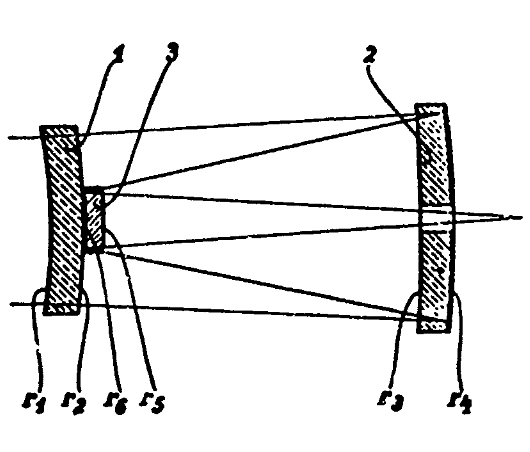
This design is suitable only for visual use because of an intrinsically large obscuration due to the baffling problem. It has the advantage of an erect image when used with an eyepiece. One might use relay optics rather than relying solely on large lenses or field elements. Unfortunately, we saw no way to incorporate such principles into our effort because of the excessively large field of view. For very large designs, relay optics offer substantial weight reduction when a large aperture is the principal concern.



W. Mandler, Patent 2,817,270 "Telescope objective systems." Filed December 12, 1955, dated December 24, 1957.

USP 2,730,013 1956

This design is of considerable interest. Both reflectors are Mangin mirrors. They scatter less light than a first-surface mirror and of course are permanently protected. While the use of a diverging front lens suggests that such a design would be comparatively long, the positive-lens-shaped primary mirror offsets most of this disadvantage. A diverging objective such as this is very effective for the correction of spherical aberration; the first-order layout favors the correction of oblique aberrations. It is, in that sense, a "natural design." This particular design, with an aperture of 4 in. at f/8, is diffraction-limited on a 35-mm format; the lens may be opened to f/5.6 without losing its usefulness for a 35-mm camera. Indeed, lenses of this type are being marketed at very low cost by the Japanese (Vemar is one), which attests to its ease of fabrication and reliability.



W. Mandler, Patent 2,730,013 "Reflecting lens objective." Filed August 30, 1951, dated January 10, 1956.

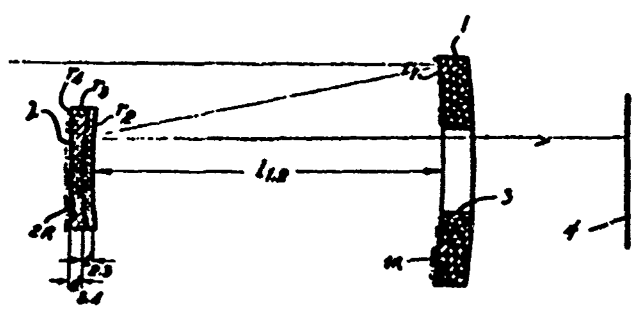
Baffling is easily achieved thanks to the divergent front lens, which allows the obscuration to be less than that in zero-power corrector groups. Its drawbacks are that good-quality glass is required, light weighting cannot be carried too far, and a Mangin mirror is affected more by temperature changes than an ordinary mirror. Balancing this is a very high degree of correction obtained with a small number of elements; whether this is enough to justify its use remains to be decided.

USP 2,761,354 1956

Acht may have been the first to suggest the use of a complex Mangin secondary mirror to correct a large, simple primary mirror (USP 1,967,214 1934), but Steglich seems to be the first to patent a usable design. P. P. Argunov modified the secondary (Russian Author's Certificate No. 158697) in 1962 for an f/8 system with an air-spaced Mangin. Several designs with apertures to 16.7 in. have been successfully built.

Using only a doublet secondary and a first-surface mirror, it is not possible to obtain a wide field. There are not enough degrees of freedom to eliminate the basic aberrations. If an aspheric plate were added, we would have enough freedom to eliminate basic image defects. To a lesser efficiency, the use of field lenses would work, but secondary spectrum is still a serious defect. To overcome this, Wilkinson used an achromatic secondary Mangin to collimate the light, then with a suitable achromatic positive lens placed near the primary mirror, formed a flat image that can now be well corrected. If the powers of the two achromats are properly chosen, color is self-cancelling This is identical in concept to the Schupmann telescope, which uses balanced positive and negative singlets to the same end. One of the major problems with Wilkinson's lens is that the collimated light condition causes a very large obscuration if the field is significant. Designs using a field lens that minimizes vignetting are described by Buchroeder (USP 3,529,888).

The advantages of these designs are low cost, simplicity, light weight, and a small tube diameter. It seems logical to utilize some of the features of a complex secondary corrector and those of a Schmidt to minimize the size and weight, and possibly to reduce the difficulty caused by normally strong asphericity.

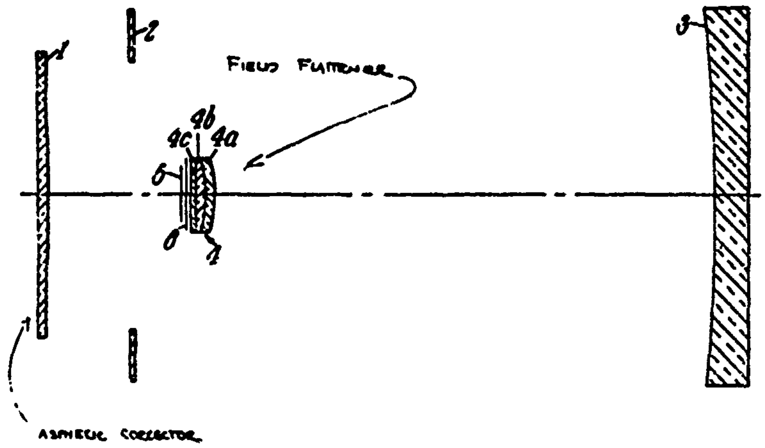


K. Steglich, Patent 2,761,354 "Cassegrain mirror lens objective." Filed April 19, 1954, dated September 4, 1956.

BP 1,068,028 1967

It was not possible to find an example in the U.S. literature, but in Britain we find a Schmidt design that is more compact. Here, we have a spherical mirror and field lenses. Baker and Wynne studied the case with a parabolic mirror, hoping to convert ordinary telescopes. Rosin advocated hyperboloidal primaries for smaller designs because these could be more highly corrected.

Prime focus placement of the detector allows a minimum sized obscuration, wider field, and always a higher degree of optical correction. The Cassegrain designs are difficult to baffle and are used solely for external positioning of the detector.



Eric Braithwaite, British Patent 1,068,028.
Filed August 31, 1964, dated May 10, 1967.

USP 3,119,892 1964

Shenker's modern catadioptric is related to the Sonnefeld-Houghton systems but with the additional advantage of compactness made possible through the efficient use of complex, full-aperture correcting lenses. In the Cassegrain form, it is shorter than its equivalent focal length, which is highly desirable in a lightweight lens. Both lenses are made of the same type of glass, which eliminates secondary spectrum, but superior monochromatic correction can be achieved by mixing glass types. In some cases, as we found, the secondary color of a two-glass design is substantially less than the spherochromatism of a single-glass design.

Our best designs in this study were of aspheric form, using both crown and flint glass, and closely resembling in appearance the Shenker designs. Our aspheric depth was on the order of 1/8 in. showing clearly that no mere "touch-up" of a spherical design was obtained. If we separate the aspheric deformation from the spherical vertex curvature, we have Schmidt correctors superimposed on a spherical design. The nodes of the spherical lenses do not coincide with the asphericities, and consequently we have the effect of a correcting system composed of more than two elements. The importance of this was mentioned in discussing the Houghton and Baker designs.

FIG. 1

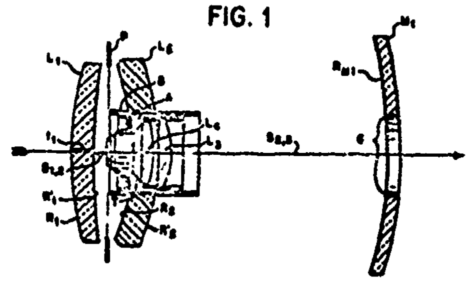
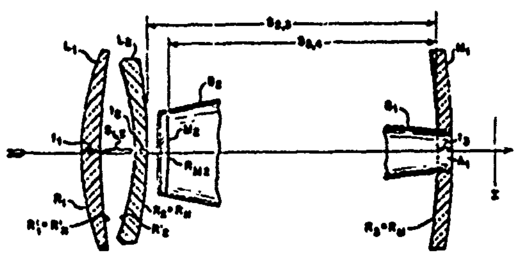


FIG. 2

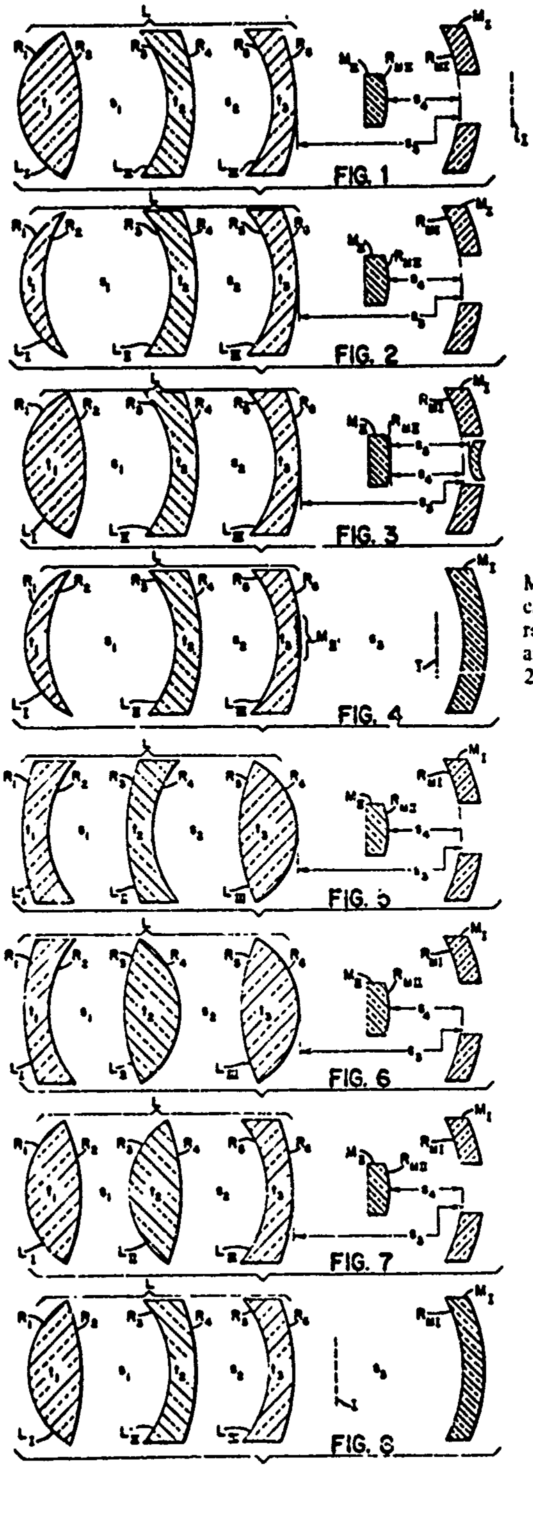


M. Shenker, Patent 3,119,892 "Catadioptric system." Filed July 1, 1960, dated January 28. 1964.

USP 3,252,373 1966

When three lens correctors are employed, a general study can proliferate into a massive collection of optical types. Shenker delivered a paper at the 1961 October Optical Society of America meeting in which he compared the correction with three lenses versus two. The advantage seemed partly due to "splitting" elements so that better zonal correction could be achieved. But the use of three significantly spaced elements adds an important dimension to the ability to correct oblique aberrations.

When we added general asphericity to a representative spherical design of this class, so great was the optical improvement that we immediately decided to go to a two-element corrector. At that point, the importance of having three correcting elements was not fully appreciated. As it turned out, we were quite successful with only two lenses; it may be, however, that it was a heavyhanded solution with needlessly deep asphericity. Possibly, if only three weak aspheric lenses were used, the curves would have been less extreme and the asphericity much milder, perhaps out of proportion to any effects due to splitting.



M. Shenker, Patent 3,252,373 "High speed catadioptric objective in which three corrector elements define two power balanced air lenses." Filed May 26, 1961, dated May 24, 1966.

Could anything be done with three widely spaced Schmidt plates? Intuitively, the value of using *some* power in the lenses is that it allows at least correction of spherochromatism. Whether it is absolutely essential to over-all monochromatic correction is not clear at this time. Very definitely, when a higher degree of correction is required for a lightweight design, the use of a three-element correcting group, with asphericity, is indicated.

IV. LENS DESIGN PROGRAMS

While certain calculations in the design of a lens can be made on a desk calculator, or even with a slide rule, nearly all modern lenses are designed with sophisticated computer programs by a process of successive iteration. Two separate design programs were used in this study. All computing was done on the University of Arizona CDC 6400 computer on whose disk and tape files we have stored ACCOS-IV and GREY.

ACCOS-IV

This commercially available program may be purchased as a basic package from Scientific Calculations, Inc. (Rochester, N.Y.). Our version has been modified extensively over the years to suit a diversity of needs here at the University. A new program, ACCOS-V, should eventually replace ACCOS-IV, but it was not available at the time of the study.

Originally we intended to perform the design study using only ACCOS because it is easy to use and the designers are very experienced with it. Unfortunately, while it works quite well on "gentle" optical designs, it proved less than satisfactory for the extremely fast Cassegrain designs we required. We encountered a great deal of difficulty in making a rough design converge to a good one because successive iterations changed too fast for its assumption of linearity to apply. By the time damping could be applied, the basic design had diverged to a much worse one. The method of strictly damped least squares in the optimization mode was not only ineffective in this program but was excessively expensive since convergence (once obtained) was too slow. It became clear after a very short time that if we persisted in using ACCOS, we would soon deplete our computing fund.

While this program was abandoned as a design tool, its evaluation routines were used exclusively. It has one of the most complete and easy to use evaluation packages known to us. Because it can be linked directly to a computer plotter, it greatly aided in presenting lens drawings and aberration plots.

GREY

We obtained a copy of this program through a special agreement with David Grey Associates (Waltham, Mass.). It is now available to the public on the CDC

Cybernet system. Its users are few and seem to consist mainly of professional lens designers faced with desperately difficult design problems. Originally the program was not intended to be made commercially available, but Mr. Grey was prevailed upon by a number of people to share his private program. Since it is basically a personal program undergoing constant revision, little attention has ever been given to making its use convenient. Its input is very brief, its output very concise. Neither, unfortunately, is self-evident nor fully documented.

The GREY program, once successfully entered (therein lies the challenge!), virtually makes the designer superfluous. It is almost human (if not superhuman) in the way it appraises the progress of its work, makes compensations, and ultimately proceeds to the sort of design that was requested from it. While the ACCOS program required interminable nursing to get anywhere at all with these designs, GREY was able to accept even the most primitive starting points and come up with quite usable, if not optimized, designs. Indeed, the problem when using GREY is not designing a lens; it is getting the program to run! If it were not for its exasperating peculiarities, it no doubt would be the most popular lens design program available. It can be said quite truthfully that without the GREY program, it would have been impossible to obtain the number of aspheric designs that are the basis of this report.

As already mentioned, evaluations were performed using the ACCOS routines. GREY is not linked to our plotter here, and its automatic line-plots are not conveniently transposed to pictorial form for a report.

V. OPTICAL TOLERANCES

The primary purpose of establishing a set of tolerances for a lens is to enable it to be produced as quickly and cheaply as possible, consistent with its optical performance requirements and delivery schedules. Obviously, the better a lens is made, the better it will perform. It is equally obvious that there are practical limits in the fabrication process, and a perfect lens has not yet been built. It is the lens designer's job to see that the relative importance of each parameter is made known to production engineers, and to assist in making any necessary adjustments to the elements.

One method of tolerancing an optical design is as follows. Alter each parameter by a small amount, perhaps by an anticipated amount of fabrication error. Now, either by aberration theory or with exact rays, determine the effect on the image. Reset the lens and alter another parameter, repeating the process for all potentially variable parameters. We catalog this information, and finally, on the assumption that the tolerable errors should be distributed uniformly, we can divide the total tolerable error by some number (usually the square root of the number of potential variables), and this is the allowable error for each parameter. While simple in concept, this suffers from the reality that errors are rarely distributed at random. In general, for example, the conventional production of lenses results in concave surfaces being too strong, convex being too weak, and lenses being too thick. Thus, there is a systematic error rather than a random one. Furthermore, some errors such as centration in aspherics are more difficult to control than others, so a nonuniform distribution of tolerable errors is allowed.

Consider a singlet some place in a complex optical system, with arbitrary marginal and principal rays traversing it. One can compute the Seidel aberrations from these, and it will be found that, in general, if the marginal ray strikes farther from the axis than the principal ray, then the aperture-sensitive errors will dominate the field-sensitive ones. The opposite is true, generally, if the role of the rays is reversed. It occurs that for nondecentered errors, which are directly related to the nominal ray paths, a change in parameter will usually affect the aberration that has the highest surface contributions. Exceptions to this rule are aplanatic surfaces including those where one ray passes precisely through its vertex. Thus, by a cursory study of the paraxial ray path we can predict the nature of aberration caused by parametric error. The relative ray heights further give an immediate indication of the required regularity on each surface.

Tilting a lens is similar to decentering it. The "wedge" in a spherical lens is directly related to its decentration and focal length. The case of a conic is more complex, as is that of a general aspheric. The effect in the case of either decentration or tilt is to offset the optical axis and redirect it through subsequent elements. Optically, the decentered lens causes the former axis of the optical system to show field aberrations, nonsymmetric with respect to the former center of the field. Subsequent lenses, since their ray paths have been altered, will likewise exhibit altered aberrations.

The study of tilt and decentration in an optical system is not well defined, and the lens designer must have the greatest possible accuracy in these errors simply because they are the most complex with which to deal. Generally, errors of decentration can be partially compensated by rotating elements in their cells until the combined effects of several imperfect lenses give an optimized image. It is believed that this has never been fully programmed into a computer, but it is a standard practice in the assembly of complex lenses.

The effect of tilting conic or aspheric mirrors on their vertices is not difficult to compute. The single surface and lack of transfer equations make it a simple matter to redefine the axis and compute asymmetric parabasal aberrations about the new axis. The Schiefspiegler telescope takes advantage of this theory in order to achieve an off-axis telescope that is corrected by balancing the parabasal aberrations of several tilted elements. No complete theory yet exists, however, to treat the "field" of a system in which this is done.

We are now in a position to discuss, but not prescribe, tolerances on our lightweight lens study designs.

VI. CATADIOPTRIC DESIGNS

The optical specifications for five different aspheric catadioptrics are presented on the following pages. All optical surfaces are described by

$$z = \frac{y^2}{R\{1 + [1 - (\kappa+1)(y^2/R^2)]^{1/2}\}} + Dy^4 + Ey^6 + Fy^8 + Gy^{10},$$

where z is the sag or coordinate of the surface along the optical axis with respect to the surface's vertex (where the surface crosses the axis); R is the vertex radius of curvature (infinite for a plane); κ is a number that describes a conic surface, being zero for a sphere, −1 for a paraboloid, and with other values to describe any conic of revolution; and D through G are the polynomial aspheric coefficients that are used to define a complex optical surface like the Schmidt lens.

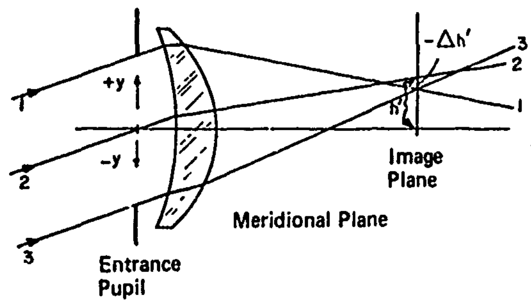
In scaling a lens design up or down, attention must be given to scaling the polynomial coefficients. The scaling factors are not linear but vary according to the exponent of y for that term.

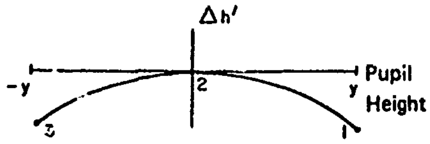
In this report, all design dimensions are in millimeters. Unless otherwise specified, the κ and polynomial coefficient values are assumed to be zero.

The five aspheric catadioptrics are to be compared with the baseline lens designed by M. Shenker of Farrand Optical Company. This lens is a production item and is one of the best commercially available lenses of this size and speed. Each design is described with rayfan aberration plots. Obscuration and vignetting, which obscure part of the fans, are not shown. All designs have approximately a 50% (diameter) obscuration, and, ideally, none should vignette.

Despite the attractiveness of spot diagrams, MTF curves, and related means of describing a finished lens, only transverse ray intercept plots are used to any extent in designing and appraising the progress of a lens. This method has several advantages: we can see where the rays are coming from, pupil aberrations are noted by slope errors, and the shape and slope of the plot tell the nature of the aberration as well as its magnitude. The effect of vignetting is easily understood in terms of these plots.

The following drawing shows what a transverse ray intercept aberration plot is. We would actually be interested in rays passing through every point of the entrance pupil, but, generally, sufficient information is gained by tracing fans of rays in two mutually perpendicular planes. The one shown is the "meridional" (or tangential) plane, while the one perpendicular to it is known as the "sagittal" plane. Generally, rays in the sagittal plane are well behaved. The rays in the tangential plane need show no symmetry and can be very complex in an aspheric lens. We can assume that the rays in some intermediate plane will be no worse than those in the two planes traced. (Occasionally, this is a poor assumption.)





Transverse Aberration Plots

Transverse Ray Intercept

The ray passing through the center of the pupil, if it reaches the extreme field of view, is known as the "principal" (or chief) ray. Any other central ray can be considered a fractional principal ray. Its intercept height is on the image plane, which we take as the paraxial focal plane. The intercepts of the other rays, with respect to this intercept, are then plotted versus the height of the ray on the entrance pupil. The abscissae are pupil heights, y, while the ordinates are $\Delta h'$ or h'. We can also plot the slopes of the emerging rays versus $\Delta h'$, which strictly speaking, is the best way. If we plot pupil height versus $\Delta h'$, the pupil information is concealed.

Similarly, sagittal fans can be traced and their intercepts plotted. With the slope plotted against the intercept, these are termed ($Z'-\tan V'$) curves. It is only necessary to trace half a fan because it shows an inverted mirror symmetry.

Some designers prefer to plot the sagittal data separately from the tangential. Consequently the two are not confused, especially when a computer is used to plot. However, it is hard to compare the two curves because their relative rotation is an important factor in determining their optimization. In this report, we have superimposed the two curves; the tangential curves are drawn solid, and the sagittal curves have dashed lines.

Interpretation of the intercept plots is not easy, but basically there are three phenomena to be aware of. First, assuming there is no significant rotation of the tangential with respect to the sagittal fans, then any general rotation is due to field curvature. In our study, we are concerned with a flat field, so we must penalize any rotation that is not common to all fields.

Second, there are what might be termed symmetrical and nonsymmetrical aberrations. The first, spherical aberration and astigmatism, can be mitigated by selective refocusing. The others, distortion and coma, are not improved by refocusing.

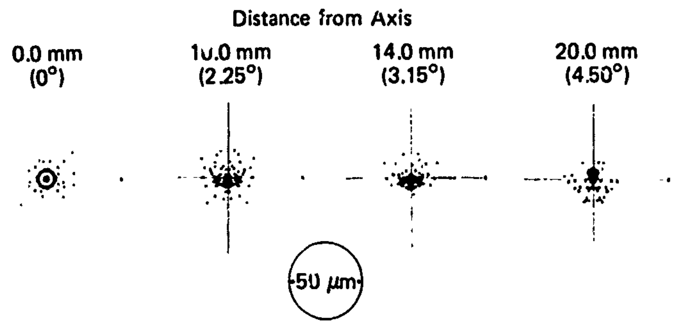
Ultimately, we want a minimum ray deviation from a common focal position. In this design study, we have tried to obtain the same degree of correction at the edge of the field as near the axis; more realistically, we would emphasize the axial region since image intensifiers have their best resolution there.

We have included spot diagrams on the following page for only the all-spherical baseline design and the first of the Schmidt-Cassegrain designs. These describe, in a qualitative way, the nature of all the designs. For versions that use large, full-aperture correcting lenses, the limiting defects are zonal ripples in the aberration fans. These can usually be further reduced in the aspheric designs although they are an intrinsic defect of an all-spherical design. In those designs that use a zero-power, aspheric plate, the limiting defect is always flare, which is due to the intrinsic oblique spherical aberration of these designs. This may be corrected by introducing compensating axial spherical aberration in order to obtain a uniform "resolution" over the entire field. For smaller fields of view, of course, this flare can be eliminated entirely.

We have not plotted the chromatic behavior of the designs because they are all corrected for axial and lateral color; an appraisal of the lenses strictly on the basis of the monochromatic fans is sufficient for comparison. The distortion of all designs is under 1% and considered negligible for the purpose to which the lens will be applied. All designs are for a flat, 40-mm-diameter image plane (corresponding to 9° full field).

In summary, our best corrected designs use lens correctors that are heavily aspheric. The location of the entrance pupil is determined only by vignetting and obscuration, and it has only a weak effect on the degree of optical correction obtainable. The Schmidt-Cassegrain designs are not capable of replacing the all-spherical design because the oblique spherical aberration is uncorrectable. However, by using a flat secondary or possibly a concave secondary, the oblique spherical aberration falls within acceptable limits. Such a design should be capable of replacing the all-spherical design if the image tube is placed inside the lens barrel.

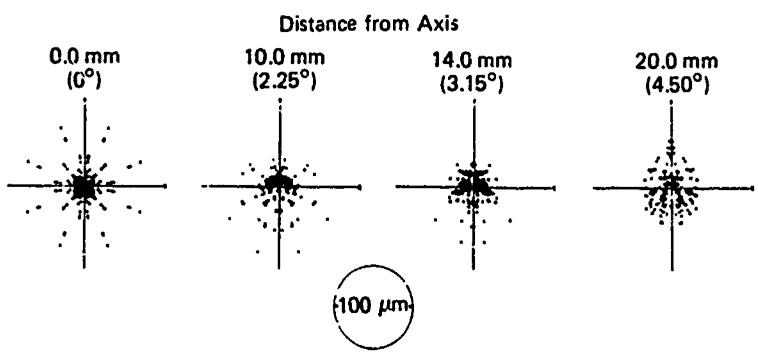
Design 1
All-Spherical Baseline Catadioptric Lens



Designed by: M. Shenker
Farrand Optical Company

8-Inch Aperture
f/1.25
9° Total Field

Design 2
Achromatic Schmidt-Cassegrain Catadioptric Lens

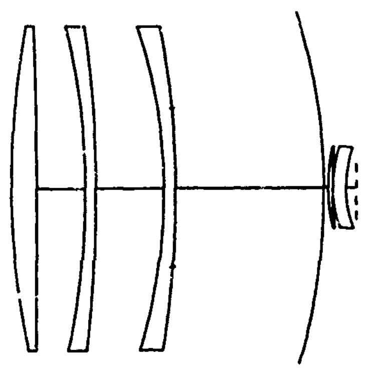


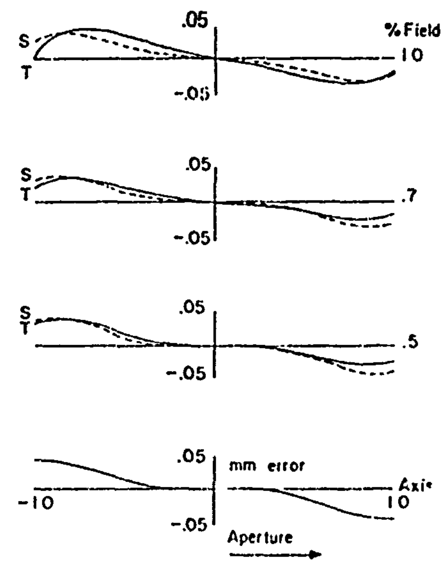
Designed by: R. Buchroeder
Optical Sciences Center

8-Inch Aperture
f/1.25
9° Total Field

Comparison of Optical Correction Obtained
in a Lens Corrector (Spherical or Aspheric)
and in a Schmidt Plate

Design 1
10-Inch f/1.25 All-Spherical Baseline Design
Farrand Optical Company





EFL = 254.000
Format: 40 mm diameter
Entrance pupil: variable, determined by clear apertures, evaluations with first surface as the stop

This 8-in. aperture, f/1.25 catadioptric lens was designed by Martin Shenker and is of the type protected by U.S. Patent 3,252,373 (1966). The logic of this configuration is described earlier.

Basically, this is a low-flare, low-resolution lens intended for use with an image intensifier that might have an optimum resolution of 25 lp/mm.

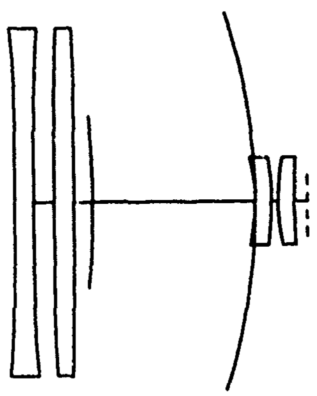
An appraisal of the ray fans for this design suggested that the defining rays for GREY must be located near the pupil margins. Improvement was likely to come by reducing the zonal errors. We reran the baseline design using the optimization routine. The result was that no significant change was obtained, which confirmed the fact that we had duplicated the conditions used in its design the first time.

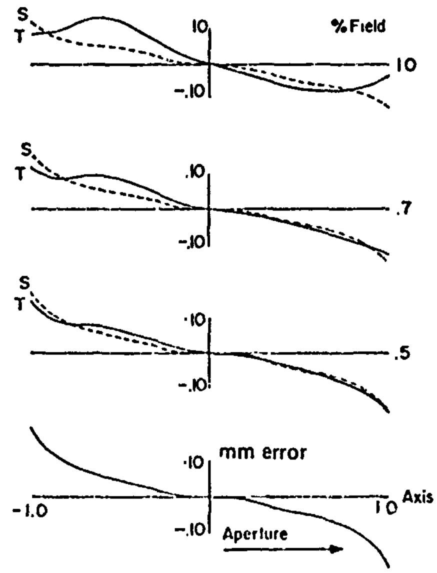
We next added the freedom of aspheric surfaces to the lenses of the baseline design. The degree of improvement was enormous; a cursory examination of the rayfan plots showed that the spot size would diminish by approximately a factor of three. Relating this to contrast was not done as easily, but it was obvious that the improvement was more than enough.

The lenses in this design are so thin already that no gain in weight reduction would be obtained by making them any thinner. Consequently, we decided that the best way to make progress would be to eliminate at least one element, apply aspherics and try again.

First, we eliminated a lens and after reintroducing power to balance out the pair of lenses, let the design optimize. It became clear that with only one type of glass, such a design could not equal the original all-spherical design using three lenses. We postponed further effort with full-aperture lenses until we had studied the zero-power Schmidt-Cassegrain designs discussed next.

Design 2
10-Inch f/1.25 Glass Achromatic
Schmidt-Cassegrain





EFL = 251 057
Format: 40 mm diameter
Entrance pupil at first surface
Color correction: d-F-C

SPECIFICATIONS

Surface	Radii	Thickness or Airspace	Kappa	Index & Abbe number
1	plano	12.0		1.517/64.5
2	plano	12.0		AIR
3	plano	12.0		1.617/36.6
4	plano	110.0		AIR
5	-368.9 CONCAVE	-98.7	1.426553	REFLECTOR
6	-572.1 CONVEX	98.7	15.56941	REFLECTOR
7	-112.8025	10.0		1.517/64.5
8	-162.9677	4.0		AIR
9	125.0484	10.0		1.617/36.6
10	576.0386	<u>7.7331 to Image</u>		

POLYNOMIAL COEFFICIENTS

Surface	D	E	F	G
1	-2.37925E-8	-5.53299E-13	-1.07294E-18	2.50901E-22
2	1.64419E-8	3.81585E 13	-1.07488E-19	-1.58012E 22
3	9.19540E-9	1.62680E-13	7.49579E-18	-1.06951E-22
4	-1.13366E-8	-1.61697E-13	-1.45751E-18	6.42617E-22

Design 2

The advantage of this configuration is that the weight of the correcting plates can be reduced virtually to nothing because their thickness is not needed for correction. It was predicted and verified that oblique spherical aberration would be a limiting defect.

Under the requirement that the field be uniformly corrected, it is impossible to compete with the baseline design. However, if the optical degradation (correction) at the edge of the field is doubled, the axial region becomes essentially perfect, with the degree of correction falling off parabolically.

The secondary dispersion of the achromatic pair is slight and more than competitive with the spherochromatism of the baseline design. Because the plates are close together, the problems of lateral color are eliminated. It would be of interest to space the plates more widely (in an effort to cope with oblique spherical aberration) and require the field elements to correct the lateral color.

The curvatures of the primary and secondary mirrors in this design are the same as those of the all-spherical baseline design. We doubt that altering this configuration would substantially affect the degree of correction obtained.

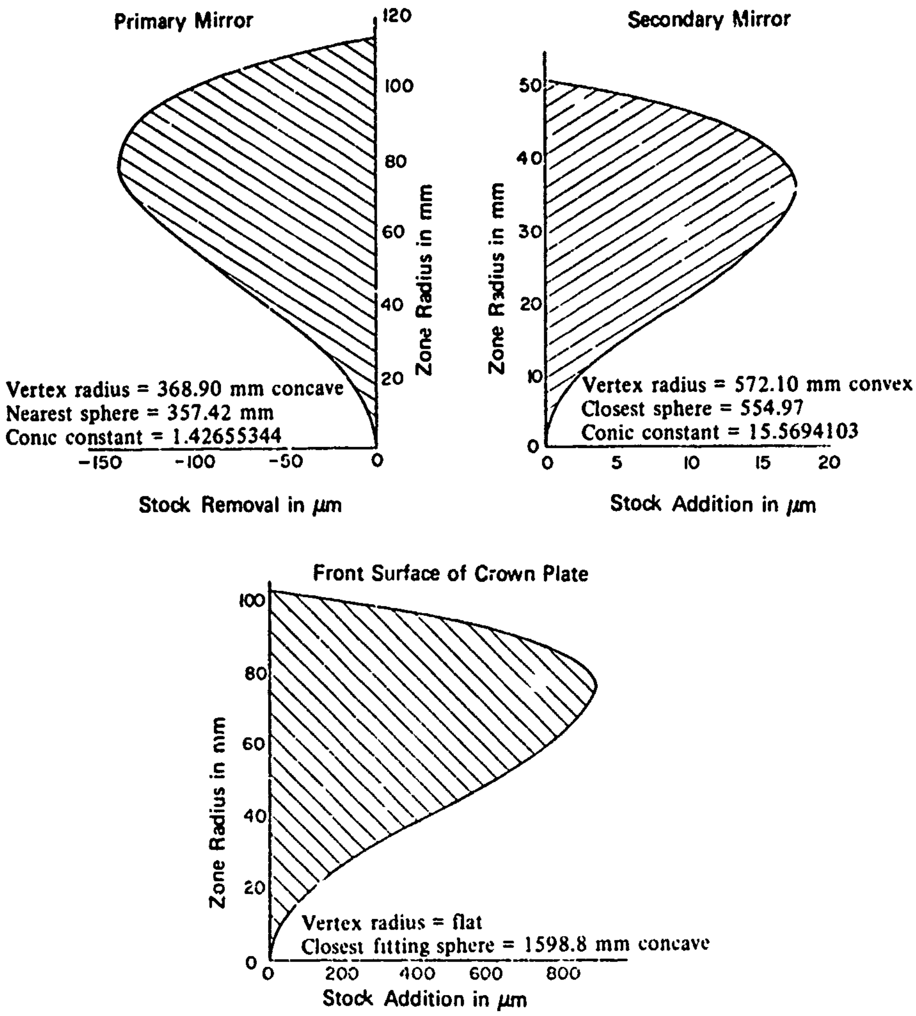
Greater emphasis could be placed on the field group lenses to increase the power of the system and thereby reduce the depth of asphericity on the corrector plates. While this would complicate the correction of aberration and introduce a problem with secondary color, it could conceivably reduce the oblique spherical aberration attributable to the aspheric plates.

Tolerances

The stop is at the first surface, which is an aspheric plate. Tilting this plate has the effect of introducing "astigmatic" axial aberration. Because the plate is nearly flat, upper and lower meridians will have similar effects on the axial image, which can then be expected to show oblique spherical aberration. The effect of decentering the plate will be to introduce axial coma of the "ordinary" sort. Tilting the flint plate will introduce more complex aberration because the principal ray intercepts above the vertex. Since the field of view is small, decentration and tilting of this lens will produce effects very similar to those of the first plate. If either plate is tilted or decentered, lateral color on axis will occur. The thickness and spacing of the plates are of minor importance.

The effect of nonconcentric figuring on the plates will again cause astigmatic effects on axis. If the figuring is elliptically distorted, then it will resemble the effect of tilting the plate. In prescribing the figuring, it is desirable to quote the wedge of the plate plus the local deviations at each zonal radius. It is perhaps best to test the plate by transmission rather than studying the opposite sides separately.

The primary mirror is an oblate spheroid but with a geometrically mild figuring (nearly the opposite of a paraboloid of the same relative aperture). If decentered, it will introduce axial coma. Tilting the mirror will also cause axial coma but in a different amount. Its separation from the aspheric plates is not critical since the combination of plates is afocal. Figuring on the primary mirror will affect field aberration; it should be only a conic and not nulled with an arbitrary polynomial figure during fabrication. Its surface figure, in general, must be four times as accurate as the figuring on the aspheric plates. This is characteristic of any mirror relative to a refracting surface.

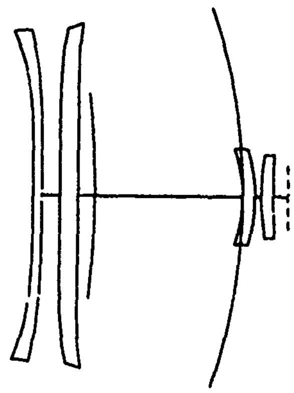


10-Inch f/1.25 Achromatic Schmidt

Separation to the secondary, which is also an oblate spheroidal mirror, determines the position to final focus, which is sensitively dependent on this spacing. Here, the principal ray strikes very high, and astigmatism may become as much a problem as coma if the mirror is tilted or decentered. Figuring on it is as critical as on the primary if field correction is to be maintained.

Two field lenses are used. These experience only a small marginal intercept; therefore, figuring is less critical than in preceding elements. They are spherical so they may be tested by conventional methods. If decentered or tilted, they will cause the image to tilt, cause some keystone distortion, and introduce a small amount of axial astigmatism. Their radius and thickness tolerances are not critical.

Design 3
10-Inch f/1.25 Plastic Achromatic Schmidt-Cassegrain



EFL = 260.775
Format: 40 mm diameter
Entrance pupil at first surface
Color correction: d-F-C

SPECIFICATIONS

Surface	Radii	Thickness or Airspace	Kappa	Index & Abbe number
1	plano			
		6.0		1.489/57.4
2	plano			
		12.0		AIR
3	plano			
		12.0		1.590/30.8
4	plano			
		110.0		AIR
5	-368.9 concave		1.258248	
		-98.7		REFLECTOR
6	-572.1 convex		13.62809	
		98.7		REFLECTOR
7	-91.02033			
		8.0		1.489/57.4
8	-105.9075			
		4.0		AIR
9	136.8270			
		8.0		1.590/30.8
10	371.9514			
		9.9677 to image		

POLYNOMIAL COEFFICIENTS

Surface	D	E	F	G
1	-1.29519E-7	4.60259E-12	-6.25840E-16	3.47785E-20
2	-9.16213E-8	7.52516E-12	-9.00870E-16	4.14632E-20
3	-1.01060E-9	4.56329E-12	-1.14733E-16	4.53378E-22
4	-1.88492E-8	2.24336E-12	1.92059E-16	-9.42020E-21

Design 3

The advantage of plastic is its light weight. However, because plastics offer a smaller difference in Abbe number (relative dispersion number), they are also somewhat less corrected than a similar design using optical glass. To study plastics we replaced the glass elements of the previous Schmidt-Cassegrain with methyl methacrylate crown and polystyrene flint. The GREY program reoptimized to a new solution without difficulty.

The optical correction is nearly the same as that in the glass design, but not superior. Consequently, we have not included it in this report.

The shape of the corrector plates is interesting. We do not know whether this was a coincidental solution, or if it has some deeper significance.

Tolerances

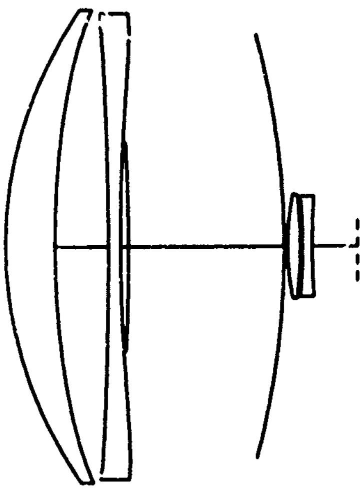
All that has been said of the glass design can be applied to this plastic design. The heavier aspherics may or may not be a problem to fabricate. Because the processes applicable to working plastic will differ from those of glass, especially in a molding or replicating process, it is possible that the plastic elements can be produced faster and more cheaply than their glass counterparts.

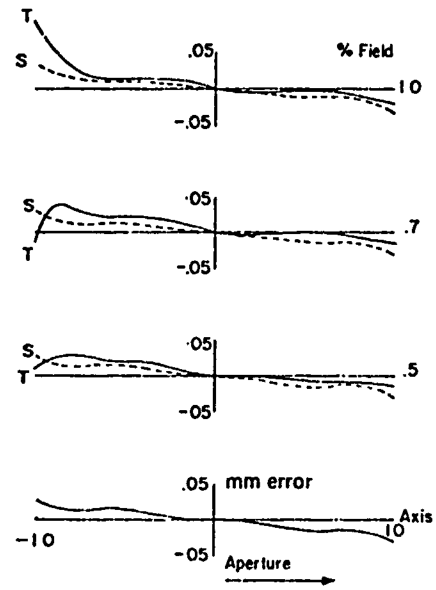
The field lenses here are slightly more aberrated than those in the glass Schmidt. This is perhaps attributable to the lower difference in dispersion between the two plastics compared with that of the glasses. This is not a particularly important point because the difficulties of fabrication are very much alike.

Problems intrinsic to plastic will probably make the athermalization of this unit mandatory for the maintenance of optical correction and focus. Problems that can be ignored in glass become prominent in plastic since its coefficient of expansion is some fifty times that of glass.

A hybrid of glass and plastic may be of value here. We have not studied this possibility since it is fairly easy to extrapolate from our all-glass and all-plastic designs. Grey pointed out in 1948 that athermalization is frequently made easier if at least one piece of glass is incorporated in an otherwise all-plastic design.

Design 4
10-Inch f/1.25 Large Two-Lens Aspheric Catadioptric





EFL = 262.974
Format: 40 mm diameter
Entrance pupil 481 mm
inside first surface
(stop on the secondary mirror)
Color correction: d-F-C

SPECIFICATIONS

Surface	Radii	Thickness or Airspace	Kappa	Index & Abbe number
1	232.312		0.233002	
		30.0		1.517/64.5
2	555.777		7.290323	
		32.2		AIR
3	-2081.74		-110.1526	
		7.3		1.617/36.6
4	1055.84		0.705135	
		98.7		AIR
5	-472.23 Concave		-.5084125	
		-94.0		REFLECTOR
6	-1139.28 Convex		90.26734	
		96.0		REFLECTOR
7	144.241			
		8.0		1.517/64.5
8	-220.180			
		1.0		AIR
9	-350.252			
		6.0		1.617/36.6
10	481.393			
		27.5142 to Image		

POLYNOMIAL COEFFICIENTS

Surface	D	E	F	G
1	-4.88421E-9	-1 39966F-14	-2.67287E-18	-2.31359E-22
2	-6.28203E 10	2.41096E-13	8.86989E-19	1.85455E-23
3	1.29347E-10	8.54184E-16	4.59887E-19	-4.91552E-22
4	-1.47967E-9	-1.16150E-13	-2.02789E-17	-6.23801E-23

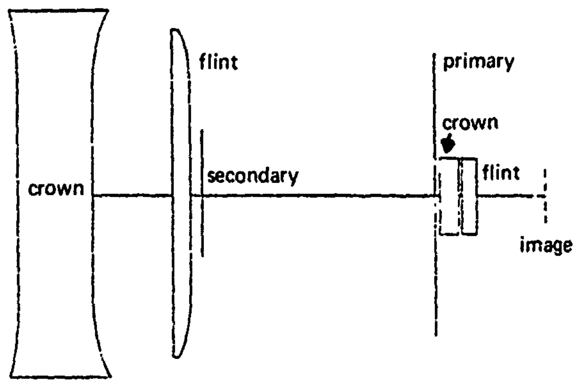
Design 4

Full-aperture corrector groups comprising two or more lenses whose net power is approximately zero are very effective in dealing with oblique aberration. This was apparent from consideration of the baseline design. The drawback to this type of corrector is simply that it is heavy and cannot be made as large as the Schmidt plate.

One of the three elements from the Shenker baseline design was removed, the power of the corrector was restored to zero by transferring power to another lens, and the design was resubmitted to GREY. The solution proved to be quite inferior to the original, and aspherics could not improve its limiting defect of spherochromatism. The two lenses became very highly curved and highly aspheric; the weight of such lenses would have been only a slight improvement over the three milder lenses used in the Shenker design.

It occurred to us that the negative element was, to a very large extent, working to balance out the color from the more highly aspheric positive lens, and that if this were the case, then it should be made of flint rather than crown. It was known that this would introduce some secondary spectrum, but as long as the net power of the corrector group was not too great, this should be acceptable. We altered the lens to include flint, reoptimized, and the results are in this report. Its performance over the spectral region of interest is superior to that of the Shenker design. The front elements are large because the aperture stop was located near the secondary reflector; to avoid vignetting, the lenses must be large. Perhaps the best place for the aperture stop is closer to the primary mirror if vignetting is to be a minimum.

The general shape of the aspheric curves of these two lenses is reminiscent of that of the achromatic Schmidt-Cassegrain. We can subtract the aspheric component of each element from its vertex curvature and have the computer plot this. Such a plot, with the aspherics exaggerated slightly as shown below, follows the lens description. The deformations on the mirrors are almost too slight to be visible, while those on



Deformations only of large two-lens aspheric catadioptric with 8-in. aperture, f/1.25, 40-mm flat field (9°). The lengths shown are actual size, the aspherics are double true size, and the diameters are half size.

the plates clearly resemble the aspherics on our Schmidt designs. We might conclude from this that we have superimposed a Schmidt corrector on a two-lens spherical corrector. Since the aspheric components are not superimposed on the nodal points of each lens, we have, in fact, achieved an aspheric two-lens "equivalent" of an all-spherical three-lens corrector.

Tolerances

In this design the aperture stop is located near the secondary mirror; thus errors of the large lens will have a greater effect in upsetting field as well as axial correction. Asphericity is nearly as severe as that in the achromatic Schmidt. Indeed, when the deviations from the vertex curvatures of the large lenses are plotted, the deformations very much resemble those of the achromatic Schmidt.

If the two aspheric lenses have inaccurate thickness, spacing, or index of refraction, then spherical aberration and axial color are immediately and predominately affected. Because they are compensating for the coma of the primary plus secondary mirror (note that the field lenses are not bent in a manner to greatly affect coma but rather to approach the typical aplanatic-type bending for a field flattener), tilts and decentrations will have a greater effect on coma than is the case in the Schmidt-Cassegrain. Shearing of the aspherics will result in axial coma if the lenses are decentered and in astigmatic errors if they are "wedged." If they are not perfectly concentric, they again have the same effect as caused by tilting a perfect Schmidt plate.

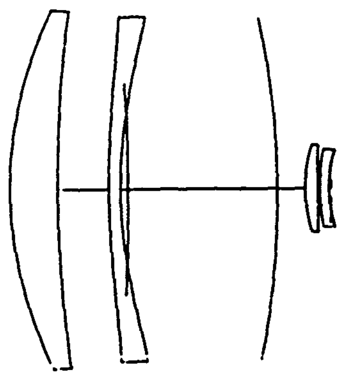
The production of these lenses to the requisite accuracy is presently beyond the state of the art, but we expect that our new techniques will allow their fabrication.

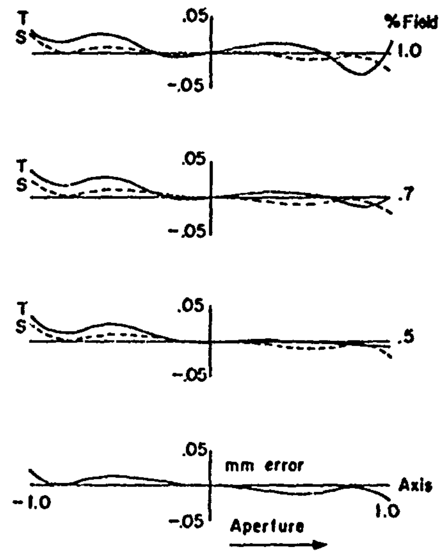
The two mirrors have many of the same problems as the mirrors in the achromatic Schmidt-Cassegrain; therefore, they will not be discussed further.

The field group of all-spherical lenses of common glass poses a negligible problem because they are strictly conventional simple lenses. They have a minor amount of surface contributions; thus they are relatively insensitive to fabrication errors.

Spacings are critical to maintain focus, which at f/1.25 is measured in micrometers. Because we use two different glass types, both focus and aberration correction will vary more than in a one-glass design as temperature changes. It is suggested that this type of design should be athermalized by a suitable choice of spacer materials. This problem was treated in part by Grey (J. Opt. Soc. Am. 38(6):542, 1948) and does not seem to be a major, although unusual, one.

Design 5
10-Inch f/1.25 Compact Two-Lens Aspheric Catadioptric





EFL = 262.975
Format: 40 mm diameter
Entrance pupil at first surface
Color correction: d-F-C

SPECIFICATIONS

Surface	Radii	Thickness or Airspace	Kappa	Index & Abbe number
1	217 549		-.157691	
		30.0		1.517/64.5
2	764.877		1.88594	
		32.2		AIR
3	471.508		2.73483	
		7.3		1.617/36.6
4	243.816		0.28281	
		98.7		AIR
5	-472.23 Concave		-.37891	
		-94.0		REFLECTOR
6	-1306.4 Convex		141.535	
		111.308		REFLECTOR
7	83.8457			
		8.0		1.517/64.5
8	-3793.70			
		1.0		AIR
9	116.218			
		6.0		1.617/36.6
10	73.7184			
		1.2716 to Image		

POLYNOMIAL COEFFICIENTS

Surface	D	E	F	G
1	-1.03970E-8	4.12961E-14	-8.58354E-19	4.11964E-23
2	5.32522E-10	1.75512E-13	2.89774E-18	-1.86086E-22
3	-4.38305E-8	1.65339E-13	3.70130E-19	4.90174E-22
4	-5.66154E-8	-1.3[illegible]007E-13	-1.47361E-17	1.55162E-21

Design 5

The only apparent drawback of Design 4 is the large size and weight of its corrector lenses. If the aperture stop is at the first surface rather than at the secondary mirror, then the size of these lenses is decreased while the diameter of the secondary must increase if it is not to vignette. Somewhere between these two extremes there is minimum light loss as a tradeoff between obscuration and vignetting.

Design 5 gave nearly as good an optical correction as in the "easier" design with the larger correctors. Any intermediate position of the aperture stop would give a design whose correction should be intermediate in quality between the two designs we obtained.

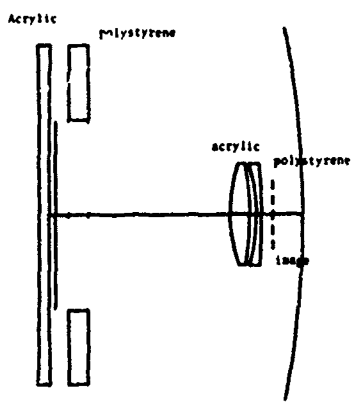
It proved more difficult to design this (5) than the preceding version (4). The computer program showed a great deal of ambivalence in regard to the proper "bending" for the negative correcting lens. Consequently we had to avoid boundary violations or undue lengthening of the lens, which would result in excessive vignetting. We inadvertently neglected to watch the distance from the last field element to the focal plane, and, as may be noted, that image plane lies partly inside the small lens! This could easily have been corrected without affecting the nature of the design, but it was not included in the optimization process because we had never previously encountered difficulty. We stopped at the point shown because the cost of designing this one version was growing out of all proportion to the lens's worth.

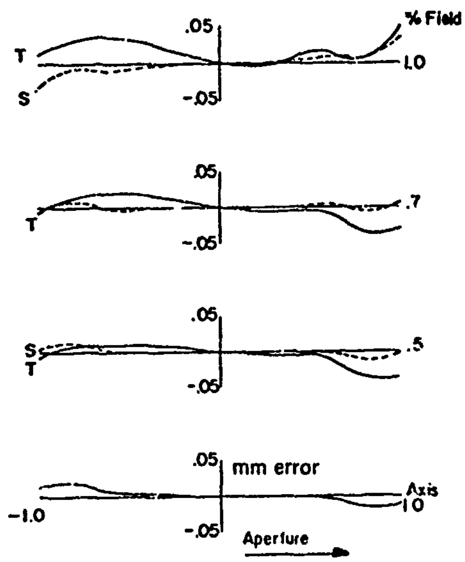
The corrector bears a resemblance to a split-concentric lens, such as those of Bouwers. This may be a useful observation in prescribing the form similar lenses should assume.

Tolerances

The compact catadioptric is a variation of the previous design in which the stop was placed at the first surface. It still has most of the sensitivity of the preceding designs; thickness of the lenses and their centration are important. It, too, must be considered at various temperatures, or athermalized. It has the advantage of somewhat milder asphericity on the lenses; we do not know whether this is characteristic of this configuration or merely coincidental. The advantage of a mild aspheric is that it often can be produced by simpler methods.

Design 6
10-Inch f/1.25 Plastic Achromatic Schmidt-Cassegrain With Flat Secondary Mirror





EFL = 247.818
Format: 40 mm diameter
Entrance pupil at first surface
Color correction: d-F-C

SPECIFICATIONS

Surface	Radii	Thickness or Airspace	Kappa	Index & Abbe number
1	plano	6.0		1.489/57.4
2	plano	12.0		AIR
3	plano	12.0		1.590/30.8
4	plano	130.0		AIR
5	-559.0 concave	-150.0	1.240471	REFLECTOR
6	PLANO	105.8626		REFLECTOR
7	90.73737	12.0		1.489/57.4
8	-155.4774	4.0		AIR
9	-102.3013	3.0		1.590/30.8
10	-395.7847	6.8737 to Image		

POLYNOMIAL COEFFICIENTS

Surface	D	E	F	G
1	-6.55567E-9	-1.73699E-13	1.68383E-18	3.85373E-22
2	6.27397E-9	1.79041E-13	1.13655E-18	3.91638E-23
3	2.30871E-9	9.06285E-14	6.79860E-18	-7.57109E-23
4	-2.95862E-9	-9.05546E-14	-2.89952E-18	6.82918E-22

Design 6

The Cassegrain form of the catadioptric is virtually indispensable when the final image must be external to the lens barrel. Unfortunately, the only optical advantage is that this configuration helps to obtain a flat field of view; in all other optical respects it is an unfavorable form of high-speed catadioptric lens. First, it destroys the symmetry of the ordinary Schmidt, thereby requiring more elements to achieve the same degree of aberration correction. Second, because the primary mirror is appreciably faster than the final speed of the system, and because the spherical aberration to be corrected by the plate is at least the cube of the speed of the primary mirror, the aspheric plates are much more deformed, and consequently the residual aberrations are higher. The Cassegrain form is difficult to make to the necessary accuracy. A considerably improved design is achieved if we abandon the external image plane and allow the image to fall inside the lens barrel.

By comparing the computer drawing of this design with that of the achromatic Schmidt-Cassegrain, it is obvious that the depth of asphericity has been reduced by an order of magnitude. The aberration plots show clearly that this design offers a superior degree of correction. Because our secondary mirror is flat and undeformed, it has no effect on the aberration and can be located without precision. It can also be inclined at 45° to place the image anywhere along the side of the lens barrel. An array of detectors can then be employed with a single objective. Furthermore, a complicated baffling system is eliminated because this "Newtonian" form of the Schmidt design is virtually free of stray light.

Tolerances

One way to reduce surface contributions, and consequently to reduce sensitivity to fabrication errors, is to use noncontradictory power elements. The "long Schmidt" does just that. The secondary is plane although it would be better to use a concave mirror if length were allowed to be longer and the image were placed still further inside the tube. It is apparent from the scale plot that asphericity is down from that of the Schmidt-Cassegrain types previously discussed. Thus, all difficulties with those designs are diminished in this flat secondary design. It is noted that the optical correction here is superior to that of the Schmidt-Cassegrain designs by perhaps a factor of 2; this reflects the lower surface contributions that eliminate much of the zonal aberration. Since only one design was attempted with this first-order concept, we are reluctant to predict its ultimate potential, but we do feel that it will be less expensively and more reliably fabricated than its more sensitive counterparts.

VII. AIR-SPACED TRIPLETS

The problem with lens designing, even without aspherics, is to obtain the best possible configuration with a given number of elements. In complex designs, it is necessary to use more than the theoretical minimum of three. Then, because there are redundant degrees of freedom, more than one reasonably well-corrected design will be found, and the designer must decide whether he has discovered a local minimum (the computer cannot tell and will refuse to budge unless forced to leave) or if he indeed has the best available design. This judgment is based on knowledge of prior art, experience, and intuition. Once we add aspherics, the problem becomes hopelessly complex. Consequently, a study of the effect of a multiplicity of aspherics in a complex lens will prove almost nothing except that aspheric lenses can be better corrected than spherical lenses. For meaningful study, we decided to examine the case of the air-spaced triplet.

The first air-spaced triplet was designed by H. Dennis Taylor (U.S. Patent 540,122 dated 1895). No other lens has had such an impact on the course of lens design.

The air-spaced triplet is the most fundamental of fully corrected photographic objectives. Indeed, perhaps all other basic lenses that use "natural" means of correction can be reduced in principle to the form of a triplet. For example, the popular Biotar, which consists of two singlets and two cemented doublets centered about a stop, is recognized as equivalent to an air-spaced triplet because the positive air gap in the middle is equivalent to a negative singlet.

In our study we eliminated redundant degrees of freedom by holding the glass type, lens thickness, and iris position constant. One optimized design is obtained by using only spherical curves. Consequently, it is possible to discriminate between such a spherical design and a similar one allowing aspheric curves.

Our designs are presented on the following pages. The nature of correction using conics is more or less understandable because, being monotonic, a conic has many of the limitations of a spherical surface.

When general (polynomial) deformations are allowed, the results are not as simple to interpret. Of particular interest is our complex polynomial design. An ordinary, all-spherical lens such as our baseline design gives the best over-all image when its astigmatism is zero at about 70° full field and its spherical aberration is somewhat undercorrected.

In contrast, the spherical aberration of the highly controlled polynomial aspheric design is heavily overcorrect. The GREY program elected to keep its astigmatism undercorrected and reasonably constant even to the edge of the field. Such behavior was most unexpected and not at all like that usually obtained in purely spherical designs.

A further feature of general aspherics is illustrated in this design: they are capable of giving more than one inflection in the ray fans. Indeed, it is difficult to pull one part of the fan down without having it bulge out somewhere else. Herein lies the difficulty of aspheric lens design: the designer must control a very large number of zones, be careful about interpolation, and exercise considerable judgment as to what is a good design. For example, the computer can judge quality only in terms of what it is given to control. Using the computer's merit function, in a case like this, is highly misleading.

The first three designs (7-9) were accomplished on GREY using the same set of controlled rays. In each case, the fields were weighted equally; therefore we would expect them to have about the same quality. The limiting control rays were at about 80% of the pupil radius; additional flare was not objectively controlled. This is typical in the design of spherical lenses because they behave in a predictable manner. It is apparent that the conic lens is a definite improvement over the all-spherical design; it has a tighter core and less separation of the meridional and sagittal fans. In every respect, it is well behaved, and targets appropriate to a spherical lens are applicable to it.

Now note the first polynomial aspheric design, which also used the same targets. Because rays beyond the 80% zone were uncontrolled, we have considerable flare. In terms of what was requested, however, its core is much superior; indeed, note that now the Petzval curvature is practically zero. This is not practical in an all-spherical lens. When general deformations like these are allowed, we must use more rays.

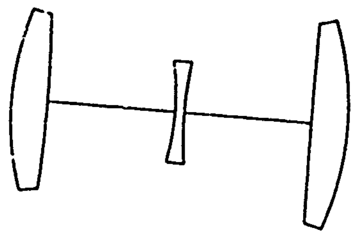
In an effort to control the flare, additional rays were added at the margin. We had no idea this would cause such a perturbation of the ray fans. The nature of the solution is as different from the previous design as it is from the all-spherical design. At this point, the cost of computation on the lens was growing in an alarming fashion, at least as rapidly as the number of additional rays that are required to be controlled. We were sufficiently impressed with the peculiarities possible with general aspherics that it seemed sufficient to quit here.

Some concluding remarks are in order with regard to the triplets. In general, one expects, finds, and demands that the position of "best focus" nearly coincides with the paraxial focus. This is observed in the first three triplets. In the last, however, the extreme rotation of the transverse ray intercept fans is reminiscent of what happens in a Schmidt camera. There, the axial fan is perfectly straight, but its rotation depends on the null zone of the correcting plate. The same thing seems to be happening here. We must then revise our thinking in order not to be alarmed by this unusual occurrence in a refractive lens.

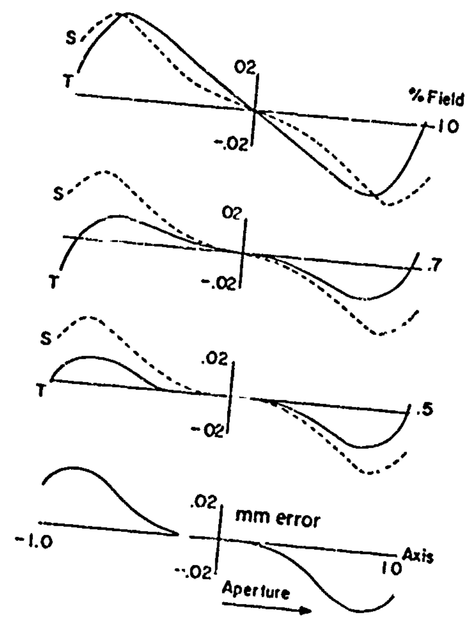
This result would not have come to light had the GREY program not been used. Not only did the lens designer not expect it, but it would have been far more difficult to achieve with a program like ACCOS, where the designer is forced to make some presumption about where the best focus should lie. Perhaps it was a coincidence, but then perhaps it is something intrinsic to the nature of aspheric optimization. We do not know.

Even in so simple a lens as the triplet, we find that we cannot make any generalization except that an aspheric lens can be more highly corrected than a spherical lens. Obviously, if the same quality as a baseline spherical design is acceptable, then the size of the aspheric design can be reduced. In a more complex lens form, it should be possible to eliminate one or more elements due to the powerful degrees of freedom made available with the aspheric deformations. The matter of color correction is even more difficult to generalize upon. The paraxial color of any lens is invariant unless the use of special glass types is possible. However, we should be able to exercise additional control over spherochromatism.

Design 7
24-Inch f/6 All-Spherical Triplet



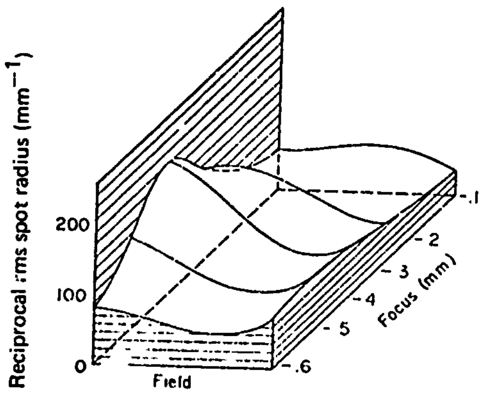
EFL = 610.062
BFL = 495.503
Format: 4 X 5 in.
Entrance pupil 164.377 mm
inside first surface
Color correction: d-F-C



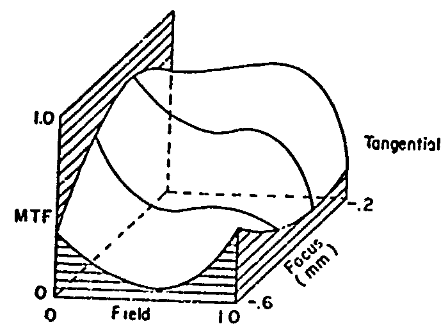
SPECIFICATIONS

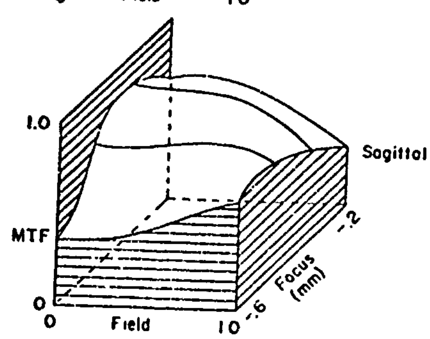
Surface	Radii	Thickness or Airspace	Schott Glass type
1	200.311		
2	-4003.91	25.4	SK4(613586)
		88.7046	AIR
3	-231.749		
4	163.147	6.35	SF5(673322)
		89.1282	AIR
5	824.699		
6	-195.662	25.4	SK4(613586)
		495.503 to Image	

GENERAL QUALITATIVE RESOLUTION

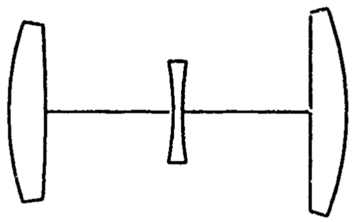


RESPONSE AT 25 CYCLES/mm

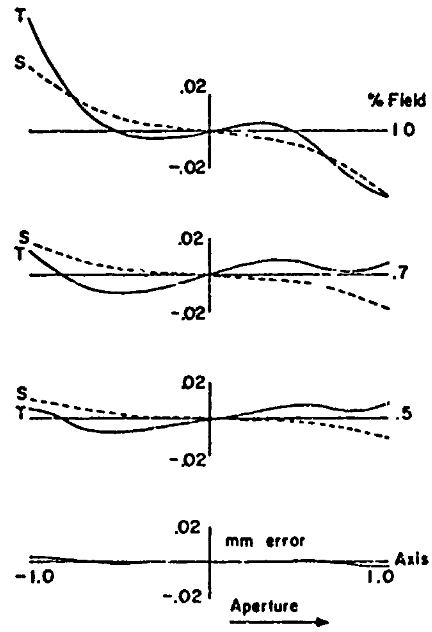




Design 8
24-Inch f/6 Conic-Surface Triplet



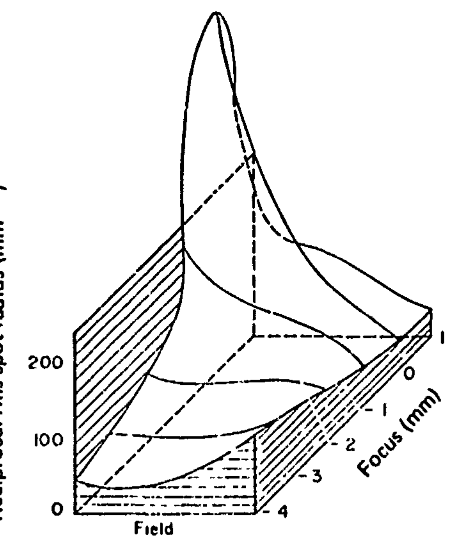
EFL = 610.062
BFL = 495.503
Format: 4 X 5 in.
Entrance pupil 164.377 mm
  inside first surface
Color correction: d-F-C



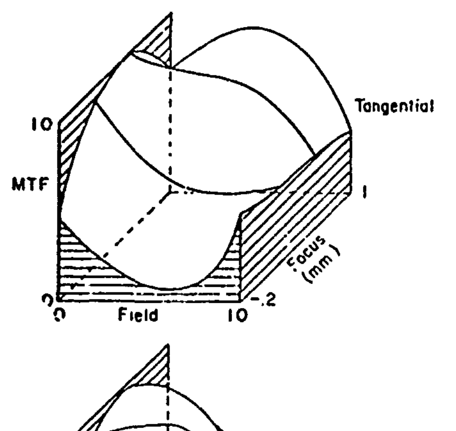
SPECIFICATIONS

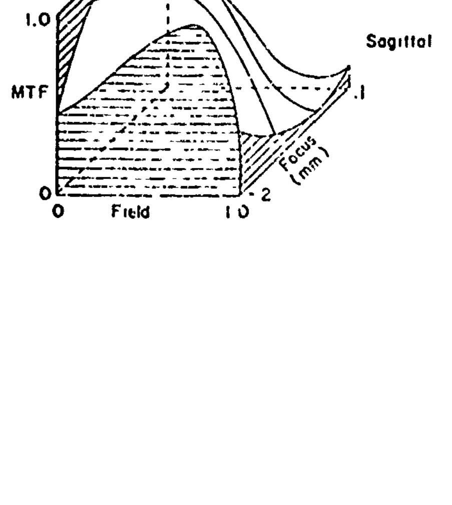
Surface	Radii	Thickness or Airspace	Kappa	Schott Glass Type
1	199.915	25.4	0.1570602	SK4(613586)
2	-15683.6		-3374.082	
		89.4638		AIR
3	-224.531	6.35	-2.571404	SF5(673322)
4	179.342		1.670176	
		89.3111		AIR
5	932.896	25.4	-88.30321	SK4(613586)
6	-195.436		0.5839694	
		495.503 to Image		

GENERAL QUALITATIVE RESOLUTION

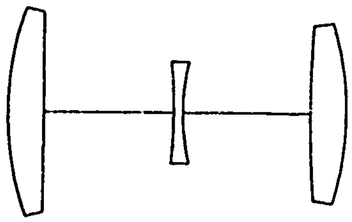


RESPONSE AT 25 CYCLES/mm

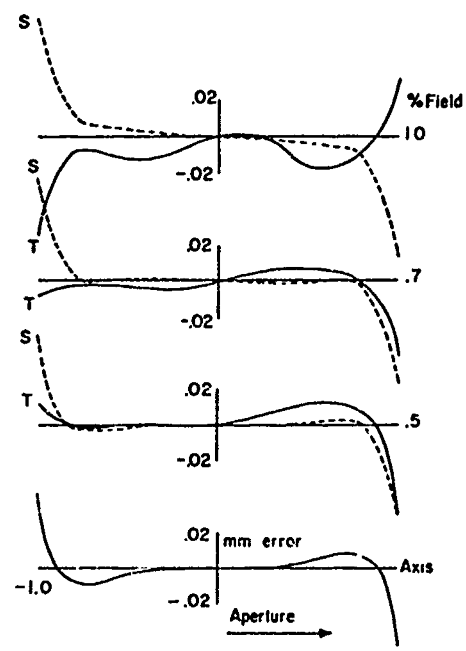




Design 9
24-Inch f/6 Simple Polynomial Aspheric Triplet



EFL = 610.062
BFL = 495.503
Format: 4 X 5 in.
Entrance pupil 166.607 mm
inside first surface
Color correction: d-F-C



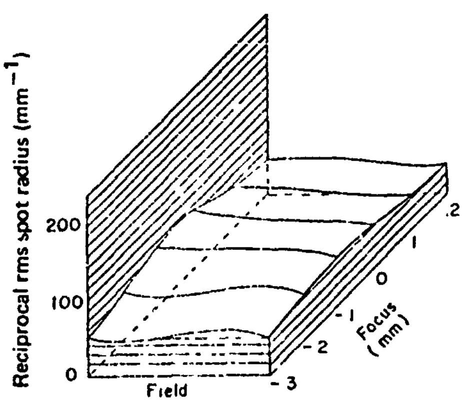
SPECIFICATIONS

Surface	Radii	Thickness or Airspace	Schott Glass Type
1	216.802	25.4	SK4(613586)
2	-2111.18		
		91.0678	AIR
3	-369.198	6.35	SF5(673322)
4	133.253		
		89.3680	AIR
5	816.008	25.4	SK4(613586)
6	-197.243		
		495.503 to Image	

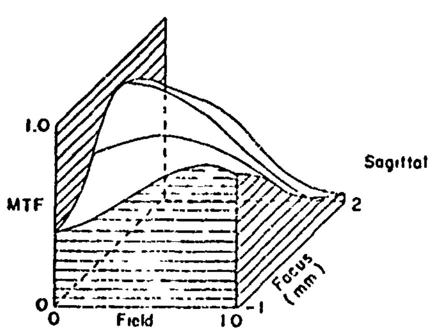
POLYNOMIAL COEFFICIENTS

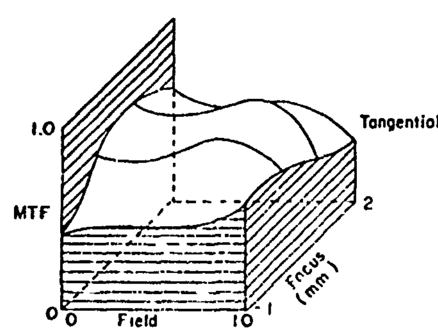
Surface	D	E	F	G
1	2.76030E-8	8.13646E-13	-9.10125E-19	1.36067E-21
2	4.66558E-8	-1.48710E-12	6.18185E-18	2.06376E-21
3	-1.82444E-7	-1.47499E-12	4.98883E-16	1.69087E-20
4	-2.30643E-7	7.81552E-13	-8.14677E-16	3.57183E-21
5	1.32256E-8	-2.13813E-12	-5.14603E-17	7.09292E-22
6	9.44314E-9	-1.21301E-12	-1.08211E-17	-4.65663E-21

GENERAL QUALITATIVE RESOLUTION

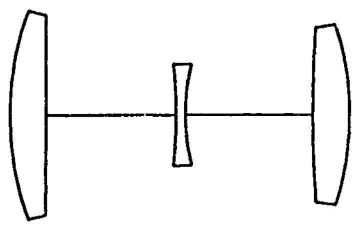


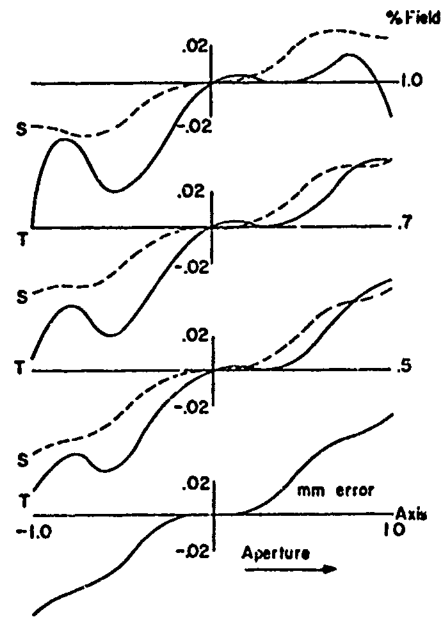
RESPONSE AT 25 CYCLES/mm





Design 10
24-Inch f/6 Complex Polynomial Aspheric Triplet





EFL = 610.076
BFL = 495.523
Format: 4 X 5 in.
Entrance pupil 164.884 mm
inside first surface
Color correction: d-F-C

SPECIFICATIONS

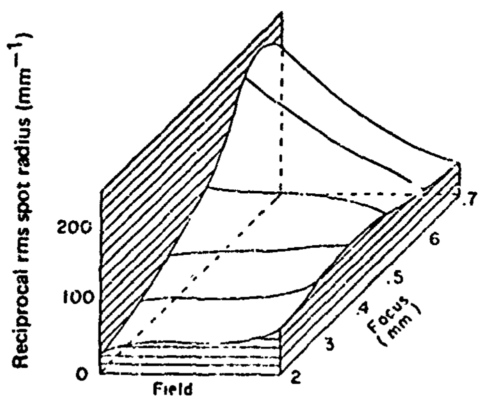
Surface	Radii	Thickness or Airspace	Kappa	Schott Glass Type
1	198.415	25.4	-1.086262	SK4(613586)
2	-15282.0		10254.00	
		89.3938		AIR
3	-282.522	6.35	14.62265	SF5(673322)
4	148.964		-2.425402	
		88.6852		AIR
5	892.659	25.4	-0.769292	SK4(613586)
6	-193.386		-.011084	

495.523 to Image

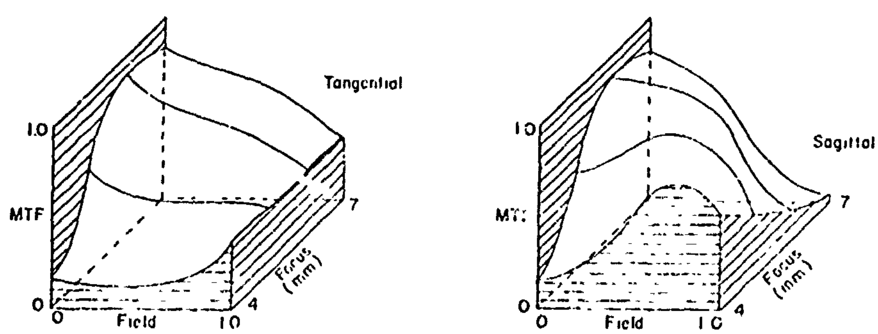
POLYNOMIAL COEFFICIENTS

Surface	D	E	F	G
1	4.17945E-8	1.31689E-12	2.20107E-18	3.37041E-22
2	3.73032E-8	-9.89380E-13	4.55841E-18	-5.17062E-22
3	-1.82044E-9	-8.22809E-13	-1.87360E-16	3.43881E-21
4	6.93312E-10	-1.02849E-11	-6.15062E-16	-3.49979E-21
5	3.90419E-9	2.55914E-14	-2.45441E-18	1.77286E-21
6	2.39406E-10	3.79397E-13	-1.33413E-18	5.10860E-22

GENERAL QUALITATIVE RESOLUTION



RESPONSE AT 25 CYCLES/mm



VIII. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Catadioptrics

For the class of catadioptrics that was studied, the use of aspherics invariably resulted in greatly improved optical performance. Applying aspherics to the baseline design at least doubled its optical quality On the other hand, it cannot be said that by simply adding aspherics (no matter how complex) the weight will be reduced. This is accomplished only when the aspherics allow the elimination of at least one major lens, or when an intrinsically lighter aspheric configuration can replace a fundamentally different all-spherical design.

The Schmidt-Cassegrain configuration is not able to compete with the baseline design when it is specified that the field be uniformly corrected. We conclude that these designs are unacceptable.

The aspheric, two-lens crown-flint corrector designs are optically and physically competitive with the baseline design. They would provide up to a one-third reduction in the weight of the optical glass without reducing the image quality.

The folded Schmidt design, with its image plane falling between the mirrors, is the lightest possible configuration with satisfactory image quality. It would permit at least a 50% reduction in the weight of the optical glass required. If the plates were made of plastic the total weight of the refracting elements would be inconsequential by comparison with that of the mirrors.

It can be concluded that the Cassegrain form of design with a convex secondary is an optically difficult situation that could be remedied by the acceptance of a buried image tube. High voltage on the image intensifier (up to 40 kV) causes coronal arcing, and the difficulty of field replacement makes a "buried" intensifier unacceptable at this time.

Purely Refractive Lenses

The findings are far from conclusive because the behavior of the aspheric air-spaced triplet is more complicated than we would have expected. When only conic surfaces were allowed, the design's correction differed in degree, but not in character, from a lens designer's extrapolation. The situation was entirely different when general polynomial surfaces were introduced because the results were contradictory to expectation. By virtue of using a powerful, unprejudiced computer program we discovered some of the unexpected peculiarities of such designs.

While it is risky to generalize from so small a body of evidence, the following points are noted in regard to all of our triplets.

1. Each design has approximately the same amount of secondary color, even though the computer automatically tries to minimize this. Consequently, it is probable that aspherics cannot greatly improve a design that is already limited by secondary spectrum.
2. When we compare drawings, all the triplets look basically alike. One complaint the reader can make is that the computer was prejudiced because each triplet started from a fairly well-corrected prototype of spherical form. However, a better observation might be that any well-corrected lens, whether aspheric or not, should have its Seidel aberrations reasonably under control. The requirement for a flat field depends on the vertex curvatures and is independent of asphericity. This would then cause all triplets to be widely spaced. To control lateral color the front and rear "power" must be balanced in proportion to the dispersion of the glasses. Consequently, we can make a good case for the argument that aspheric lenses *should* look like ordinary, spherical lenses.

The designing of an aspheric lens is an expensive and time-consuming task because controlling only a few zones is insufficient. We must also be open-minded because the nature of the aberration balances and corrections is not usually the same as that in a spherical lens, except in the case of conic surfaces.

Aspheric Lenses

As we have shown, it is difficult to conduct a generalized study of the aspheric lens. Just as we limited ourselves to a single catadioptric aperture and speed that were of practical importance, we should do the same with the aspheric lens. A spherical telephoto lens with moderate aperture, wide field, and higher than normal speed would benefit most from aspherics. If the weight, size, and residual color in one of these can be significantly reduced, it would find immediate acceptance for high-resolution aerial photography. Aspherics could make a major contribution in increasing the speed possible in apochromatic lenses.

Plastics

The problem of using plastics in catadioptric designs is fairly well understood and is not insurmountable if durable plastics, or coatings, can be produced.

There are many purely refractive lenses that cannot be replaced with catadioptric designs. Some of these with speeds of f/4 and focal lengths of 36 in. or more are extremely heavy and, of course, expensive. If we could athermalize aberration correction in a plastic lens, the weight of such a glass lens would be reduced by two-thirds. Again, there is little prior art, or publication, on athermalization except for maintenance of focus.

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