*Design of a Family of Telephoto Optical Systems**

EVERETT L. MERRITT,
Photogrammetry, Inc.,
Silver Spring, Md.

ABSTRACT: *This paper describes the optical design and assembly properties of a family of telephoto lens systems. The purpose of the design was a telephoto lens system having improved optical performance and inherent properties of rigorous alignment and spacing. To this end, certain criteria relative to optical performance, structural rigidity, cost of manufacturing, and ease of assembly were imposed on the designs. Six systems are described that fulfill the rather stringent criteria to varying degrees. Each of the six lens designs is, in general, some form of a concentric catadioptric lens system.*

One of the systems has been manufactured and tested by visual collimation and autocollimation. The visual optical evaluation indicates that the systems may be aligned and spaced rigorously with little or no equipment and that the optical performance exceeds that of comparable systems subjected to the same test.

A. DEFINITION

A TELEPHOTO lens is a camera lens of long focal-length but so designed that the distance from the lens to the focal-plane (back focal-length) is shorter than the equivalent focal-length.

Telephoto lenses are employed to photograph objects with or without motion at great distances.

EVERETT L. MERRITT

B. SCOPE

This paper gives the conditions and criteria imposed on the designs, a description of the designs, the method of design, and the procedure for assembly control.

C. CRITERIA IMPOSED ON DESIGNS

The bases for the criteria imposed on the designs are of the utmost importance and therefore are enumerated below:

(1) *Improved optical performance.*
(2) *Larger cone-angle.*
(3) *Equal optical performance over the entire field.*
(4) *Larger relative aperture.*
(5) *Rigorous method of spacing and alignment.*
(6) *Improved balanced distribution of weight within the basic tube.*
(7) *Elimination of air apertures.*
(8) *Elimination of mechanical support* such as the spider usually contained in the Cassegrain or Gregorian type of reflecting telephoto lenses.
(9) *Elimination of aspheric surfaces*

* Presented at the Society's 24th Annual Meeting, Hotel Shoreham, Washington, D. C., March 28, 1958.

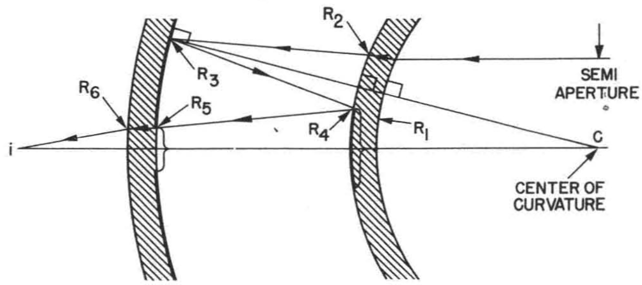

FIG. 1. Basic design principle.

such as contained in the Schmidt or modifications of the basic Schmidt designs.

(10) *Elimination of the film magazine within the lens cell tube.*

(11) *Elimination of elements whose thickness make balance and manufacture impractical.*

(12) *Elimination of elements too thin to structurally preserve the manufactured curvature.*

(13) *Finally no element too small to be supported by the side wall of the lens tube.*

Various telephoto lenses, either commercially available or described in the patent literature, fulfill many of the criteria but fail in some of the others. On the other hand, all the members of the family of the telephoto lenses described herein do not completely fulfill the criteria. Those included in the latter classification are preserved for a special application where the criteria neglected have no meaning.

After attempting many designs based on as many different optical concepts, a concentric catadioptric system appeared to be the only system capable of fulfilling the criteria outlined. While the concept of a concentric catadioptric system is not new, such a system adapted to a telephoto lens system and fulfilling the enumerated criteria is new. The initial system unmodified by lens calculation is illustrated in Figure 1.

While Figure 1 is not exactly like any of the designs, it was the starting point of the six systems that eventually materialized. This family of lenses is designated Mircon with a Roman numeral insofar as they are a combination of concentric mirrors and concentric refractors.

D. TELEPHOTO DESIGN

Each type of optical system embraces problems that are peculiar to the system. It has been established that the radii of a concentric refractor may be adjusted for achromatism or freedom from spherical aberration at will, and that there is a combination that yields correction to both without departure from concentricity. This is only partially true of telephoto concentric catadioptric systems. A nonconcentric element must be introduced to correct for both chromatic and spherical aberrations if the relative aperture exceeds $f/10$. At $f/10$ or smaller, a completely concentric telephoto catadioptric system may be designed, that is corrected for spherical aberration and in which the omitted color correction produces a negligible loss in resolution.

Six catadioptric systems are described in this section. These are designated

		f/no.	F
Mircon I	Telephoto	10	60 Inches
Mircon II	Telephoto	3.6	50 Inches
Mircon III	Telephoto	3.2	44 Inches
Mircon IV	Conventional	3.8	22 Inches
Mircon V	Telephoto	8.0	57.6 Inches
Mircon VI	Telephoto	8.0	58.3 Inches

The six designs are shown in Figures 2 and 3. Lens calculations disclosed that there was no unique axial intercept for the four rays representative of a system corrected for chromatic and spherical aberration unless a nonconcentric radius was introduced. The last radius R_6 was chosen as the nonconcentric element in order that the system could preserve the property of self-spacing and self-alignment, and in order that the residual coma, astigmatism, and distortion introduced as a consequence of the nonconcentricity would be a minimum. Analysis demonstrated that color correction could be achieved by varying the last radius for any arbitrarily chosen value of R_1 providing the focal-length was permitted to vary. Thus the variables were R_1, R_6 and F. An R_1 was assumed after which R_6 was adjusted to yield achroma-

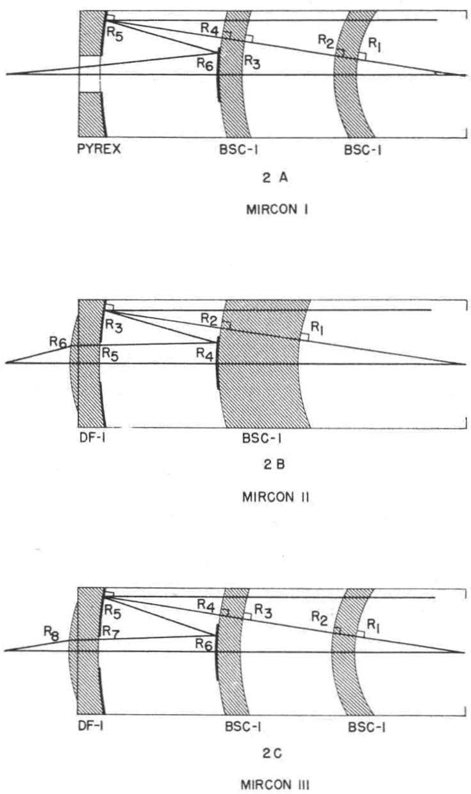

FIG. 2. Mircon I, Mircon II, Mircon III.

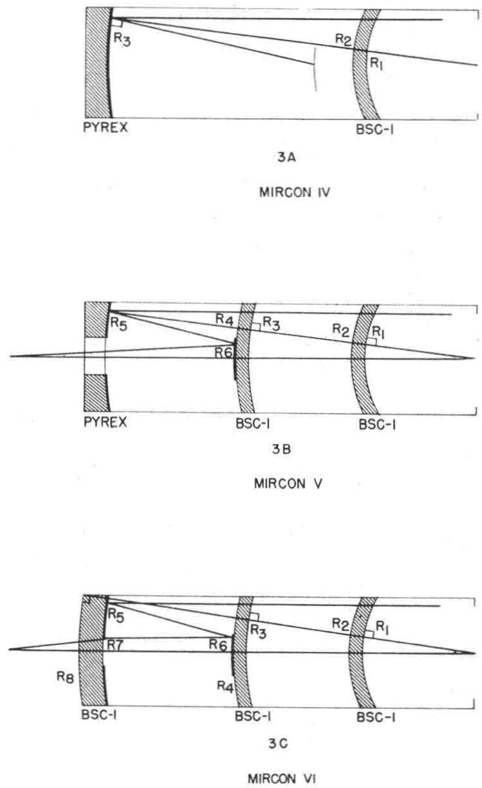

FIG. 3. Mircon IV, Mircon V, Mircon VI.

tism. Marginal and paraxial rays were traced through the system after each achromatic adjustment of R_6 for each assumed R_1. Thus each array of radii and focal-length was achromatically related, and therefore the computed spherical aberrations of the marginal and paraxial rays were a direct function of achromatism. In that manner R_1 plotted against spherical aberration disclosed by computation the R_1 value producing correction to both spherical and chromatic aberration. The value of R_1 providing the desired correction resulted in an excessively thick negative concentric refractor shown in Figure 2. This meant that two of the fourteen criteria had not been fulfilled. These criteria deviations are residual coma, astigmatism, and distortion, as a consequence of the back nonconcentric element and excessive thickness resulting in excessive weight, cost, and manufacturing problems. The design was scaled to one-third size to eliminate the unacceptable properties of an excessively thick lens. Scale reduction of the design resulted in a telephoto zenith type camera with a focal-length of 16 inches, a relative aperture of 3.6 and a useful cone-angle of 8 degrees.

The original intent was a long focal-length telephoto tracking camera lens. The design thickness of $t_1 = R_2 - R_1 = 13$ inches prohibited its use as such. A negative concentric is a weak lens and as such can only correct for spherical aberration by making a telephoto system with a steep slope or a short radius and hence excessive thickness. It was then decided to achieve spherical correction by replacing the single thick negative concentric with two thinner negative concentrics having essentially the same zone deviation. A thickness of 2 inches was considered to embrace sufficient rigidity to structurally support its own manufactured curvature. R_2 and R_4 were established in the previous design as essential.

In the second design, designated Mircon III, the additional negative element introduced two more radii. The final adjustment in Mircon III produced a telephoto objective with a focal-length of 44 inches, a relative aperture of 3.2, and a useful cone-angle of $7\frac{1}{2}$ degrees. The only deviation of Mircon III is the residual coma, astigmatism, and distortion introduced by the nonconcentric radius R_s. Correction for color necessitated the nonconcentric element and the steep slope accompanying wide relàtive aperatures introduced the chromatic aberration corrected with the nonconcentric element. From this it may be concluded that a specified smaller relative aperture would introduce little or no chromatic aberration.

Mircon I is a wholly concentric telephoto lens corrected for spherical aberration with the chromatic aberration sufficiently small to be neglected by the choice of aperture. This system fulfills all the criteria except the primary perforation at the expense of aperture. Refraction through the back surface was omitted to minimize color dispersion. Micron I has a focal-length of 60 inches, a relative aperture of 10, and a cone-angle of 3 degrees.

Mircon IV, shown in Figure 3, is a fully concentric system without the middle element and secondary reflector. The elimination of the middle element removes the focal-length expansion factor and hence Mircon IV is not a telephoto system: The image surface is formed inside between the refractor and primary. R_1 and R_2 are computed to remove spherical aberration. Color correction is neglected by virtue of the small aperture. Mircon IV deviates from the criteria in the image surface being formed inside the tube between the lens elements. This design has a focal-length of 22 inches, a relative aperture of 3.8, and a useful cone-angle of 10 degrees.

E. Test of One of the Designs

It was decided to manufacture Mircon I inasmuch as it represented the smallest outlay of funds. To this end, glass blanks were purchased from which the two negative concentrics and the primary reflector could be ground. Only after seeing the blanks was it appreciated that the 2-inch thickness imposed on Mircon III was excessive on Mircon I. As a consequence of this realization, the radii of Mircon I were recalculated with and without a perforation in the primary, resulting in Mircon V and VI shown in Figure 3b and 3c. Mircon V therefore is the design manufactured and tested.

The lens cells and tube are constructed with a series of rings spaced to provide structural rigidity, to reduce nonimage-forming light, and to achieve the property of alignment and spacing by fixed autocollimation at the center of curvature.

The rings bounding each lens cell contain adjustment screws whereby the position and orientation of the lenses may be established. The tube construction is shown in Figure 4. The aperture stop is situated at the center of curvature located 15 inches in front of the incident lens.

Initially the absolute radius and variation of radius with zone height was measured by a method of autocollimation at the center of curvature. While the absolute radii departed as much as 0.06 inch from the designed value, the departures from concentricity and permissible radii variation were less than one-tenth the specified value.

The adaptation of the components and the tube to rigorous alignment and spacing was quite gratifying. A 10-power autocollimating eyepiece was situated at the geometric center of the tube at a point equal to the radius of the primary in front of the tube. The primary was positioned and oriented until autocollimation at the center of curvature was achieved. This placed the line defined by the vertex and center of curvature in the center of the

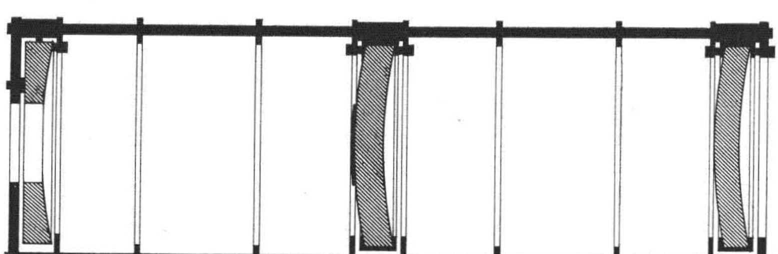

FIG. 4. Tube construction.

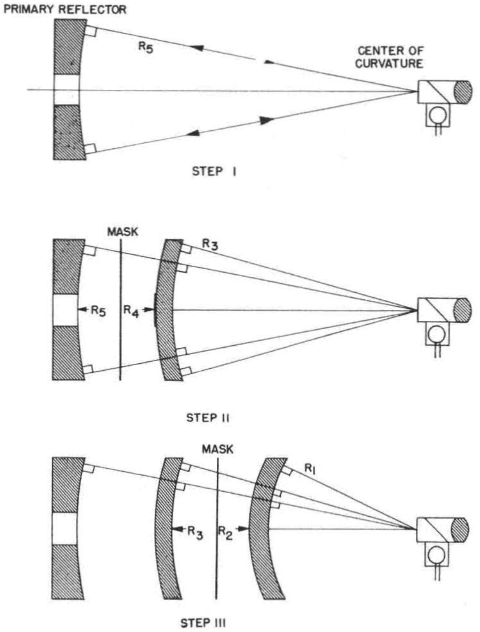

FIG. 5. Alignment and spacing procedure.

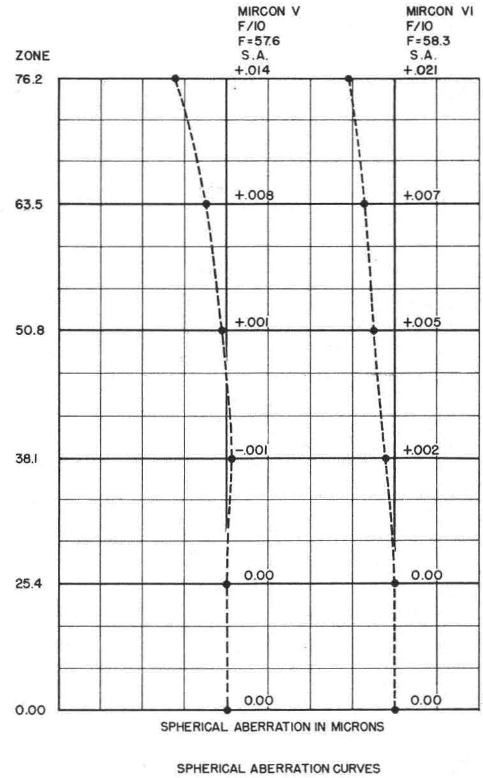

FIG. 6. Spherical aberration curves.

tube. The tube and autocollimating eyepiece were then clamped in position. The concentric negative next to the primary was then positioned and oriented until autocollimation was again achieved. To this end the primary was masked off while the refractor was treated as a reflector. Finally the front concentric negative was positioned and oriented, until autocollimation was achieved, with the middle refractor masked off.

The procedure is illustrated in Figure 5.

Thus rigorous spacing and alignment are achieved by successive autocollimations from back to front at a unique center of curvature. The entire operation does not take over an hour.

Having completed alignment and spacing, a resolution target was autocollimated in the focal-plane to an optical flat in object space. Previous correlation of the resolution of a collimated pattern with an autocollimated pattern indicated that we had equal visual resolution of 126 lines over the entire field. The high resolution count over the field may be attributed to the rigorous alignment and spacing procedure and the fact that coma, astigmatism, and distortion are zero, and finally to the high degree of spherical correction. These curves are shown in Figure 6.

While a visual test is not conclusive there is every indication that subsequent photographic tests to be conducted in the ensuing six months should produce a telephoto system applicable to astronomy, ballistics, missile flight and satellites.

The bulk of the effort and material on Mircon V was give without remuneration by the staff of Photogrammetry, Inc. I take this opportunity therefore to express my gratitude publicly to Jim Lucas, John Creeden, Charles Peckinpaugh, John Rosenfield, and in particular to Carl Markwith and Doris Rock.