The Optical Design of the 40-in. Telescope and of the Irenee DuPont Telescope at Las Campanas Observatory, Chile

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The optical specifications of two astronomical telescopes designed to permit wide-field photography with critical definition are presented and compared. The 40-in. (1.016-m) and DuPont 100-in. (2.54-m) telescopes use modifications of the Ritchey-Chretién design with Gascoigne correctors. By avoiding the need for field flatteners through choice of mirrors yielding zero Petzval sum (40-in. telescope) or bending of photographic plates to a moderate field curvature (100-in. telescope), it was possible to achieve monochromatic images of ⅕ to ¼ sec of arc over fields of 3° and 2.1°, respectively.

Introduction

The development of telescopes of critical definition over a wide field made a tremendous advance with the introduction of the Schmidt telescope in 1932. Unfortunately, practical considerations limit this design to instruments of medium aperture and focal length. First, the chromatic aberration of even a fused silica corrector plate is such that to achieve ½-sec images over the range 3260 Å to 8000 Å, desirable for any large telescope, it is necessary to use a focal ratio of at least $F = 4.6$.[1] Second, the tube length of a Schmidt is at least twice the focal length. Thus a 100-in. (2.54-m) Schmidt-type telescope satisfying these conditions would be over 920 in. (23.4 m) long or 40% longer than the 200-in. (5.1-m) telescope, thereby causing very serious problems of tube flexure control and dome size.

Another approach to increasing field size was made in 1922 by Chrétien[2] following a suggestion by G. W. Ritchey. By dropping the condition that the primary of a Cassegrain telescope should be a paraboloid, he was able to design a system that was free of both spherical aberration and coma. The first large telescope to use this design was built by Ritchey for the U.S. Naval Observatory in 1934. Astigmatism and field curvature limited the useful diameter of the field of this instrument to about 40 min of arc.

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In 1965, Gascoigne[3] suggested that astigmatism could be eliminated by a Schmidt-type corrector plate placed a short distance inside the focus. In the following year, Schulte[4] designed the 60-in. telescope for the Cerro Tololo Observatory on this principle. Schulte also introduced a double concave lens immediately in front of the focus to flatten the field. By this procedure he achieved a well corrected flat field, 1.5° in diameter. A similar design was used for the Palomar 60-in. In both of these instruments the limit on field size was set by the aberrations, chiefly chromatic and coma, introduced by the field flattener.

The next step in increasing field size was the elimination of the field flattener. For the 40-in. telescope of the Las Campanas Observatory this was done by making the radii of curvature of the primary and secondary equal, thereby achieving a zero Petzval sum and a flat field while astigmatism was eliminated with a Gascoigne corrector. In this instrument it was possible to attain a well corrected field about 3° in diameter. However, to do this it was necessary to use a secondary one-half the diameter of the primary, thereby intercepting 25% of the incident light.

In the Irenee DuPont 100-in. telescope now under construction a moderate field curvature, to which glass photographic plates can be bent, is accepted. This permits the reduction of the diameter of the secondary mirror and its mount to 40% of that of the primary with a resultant light loss of only 16% of the incident light.

This design yields critical definition to the corners of a 20 in. × 20 in. plate or a field diameter of 2.1°. This limit to the field size is set by the chromatic

Table I. Basic Dimensions

	40-in. Telescope		DuPont Telescope	
	inches	millimeters	inches	millimeters
Diameter primary[a]	40	1016	100	2540
Focal length primary	162.1	4118	300	7620
Focal length Cassegrain	280	7112	750	19050
Focal length coudé	—	—	3000	76200
Diameter hole in primary[a]	15.2	386	32.5	826
Diameter secondary[a]	20	508	37.5	953
Diameter corrector plate[a]	15.2	386	29.2	741
Distance between mirrors	93.9	2384	202.9	5153
Focal point distance behind surface of primary	24.0	610	39.9	1013
Radius of curvature of focal surface		∞	356	9042
Plate size	14 × 14	356 × 356	20 × 20	508 × 508
Cassegrain scale	0.0345 mm/sec		0.0924 mm/sec	
Field size allowing 4-mm margin on plate for mounting	168 min × 168 min		90 min × 90 min	

[a]These diameters indicate figured diameter.

aberration of the corrector plate and also by the maximum size of the hole in the primary that is permissible without vignetting the off axis beam after it passes the secondary.

Optical Specifications and Performance

The basic dimensions for the 40-in. and 100-in. telescopes are given in Table I and the mathematical specifications of the optical design are given in Tables II and III.

In designing these telescopes, general third-order relationships were first developed expressing the coma and astigmatism of a Cassegrain system in terms of the variation with distance off axis of the radial radius of curvature of the primary and secondary mirrors.[1] Likewise, formulas for the coma and astigmatism introduced by the corrector plate were developed in terms of the radius of curvature of the mirror for which the plate would serve as a Schmidt corrector. On the basis of these relationships, preliminary specifications were set up for the optical system, and the system was ray-traced using a computer program (Polypagos). The residual coma and astigmatism caused by higher order terms were measured and the parameters of the system changed to introduce compensating third-order aberrations. Finally, small adjustments were made in the coefficients of the sixth-power terms to optimize the system.

Because the refractive index of the corrector plate varies with wavelength, the plate can give exact correction for astigmatism at one wavelength only. However, the strength of the plate also varies as the square of its distance from the focus. By varying this distance, it is theretore possible to produce exact correction at the center of any desired wavelength band. In the case of the 100-in. telescope, a separation of $L = 1000$ mm between the rear of the corrector and the focus yields optimum correction for a refractive index of $n = 1.47$, corresponding to $\lambda = 4020$ Å for fused silica. For other wavelengths the best correction is obtained when L is changed by an amount

$$\Delta L = 590\Delta n/(n-1) = -1250\Delta n, \tag{1}$$

in which Δn is the difference between the index at the center of the wavelength band to be used and 1.47. Table IV lists a few representative values for these displacements.

Table II. Optical Specifications for the 40-inch Telescope

Primary
$x = -6.0709 \times 10^{-5}y^2 + 1.417 \times 10^{-13}y^4 + 5.018 \times 10^{-21}y^6$
2383.8[a]
Secondary
$x = -6.0709 \times 10^{-5}y^2 + 7.500 \times 10^{-12}y^4 - 3.95 \times 10^{-19}y^6$
2484.5[a]
Corrector
$x = 0$, plane
10.0[a] $n = 1.46667$
$x = -1.518 \times 10^{-5}y^2 + 3.927 \times 10^{-10}y^4 + 1.82 \times 10^{-16}y^6$
500.0[a]
Focal surface
$x = 0$, plane

[a]Distance between surfaces on axis. All values are in millimeters.

Table III. Optical Specifications for the DuPont 100-in. Telescope

Primary
$x = -3.2808 \times 10^{-5}y^2 + 7.037 \times 10^{-15}y^4 + 3.00 \times 10^{-23}y^6$
5152.6[a]
Secondary
$x = -6.0793 \times 10^{-5}y^2 + 1.654 \times 10^{-12}y^4 - 6.00 \times 10^{-20}y^6$
5155.8[a]
Corrector $x = 0$, plane
10.0[a] $n = 1.47$
$x = -7.104 \times 10^{-6}y^2 + 4.894 \times 10^{-11}y^4 + 8.75 \times 10^{-18}y^6$
1000.0[a]
Focal surface
$x = -5.53 \times 10^{-5}y^2$

[a]Distances between surfaces on axis. All values are in millimeters

Table IV. Distance of Corrector from Focus as Function of Wavelength for the DuPont 100-in. Telescope

λ(Å)	n	Δn	ΔL	L
3500	1.4770	0.007	−8.8	991.2
4020	1.4700	0	0	1000.0
4500	1.46565	−0.00435	+5.4	1005.4
5000	1.4624	−0.0076	+9.5	1009.5
6000	1.4581	−0.0119	+14.9	1014.9
7000	1.45535	−0.01465	+18.3	1018.3

persion of the corrector plates for the wavelength ranges listed. Especially near the edge of the field, most of the light is concentrated in a much smaller range than the value listed.

The corrector plates for the 40-in. and 100-in. telescopes have approximately the curves of Schmidt plates for mirrors of about 1100 mm and 2200 mm radii, respectively, but differ in the coefficient of the y^6 terms.

The primary and secondary mirrors closely ap-

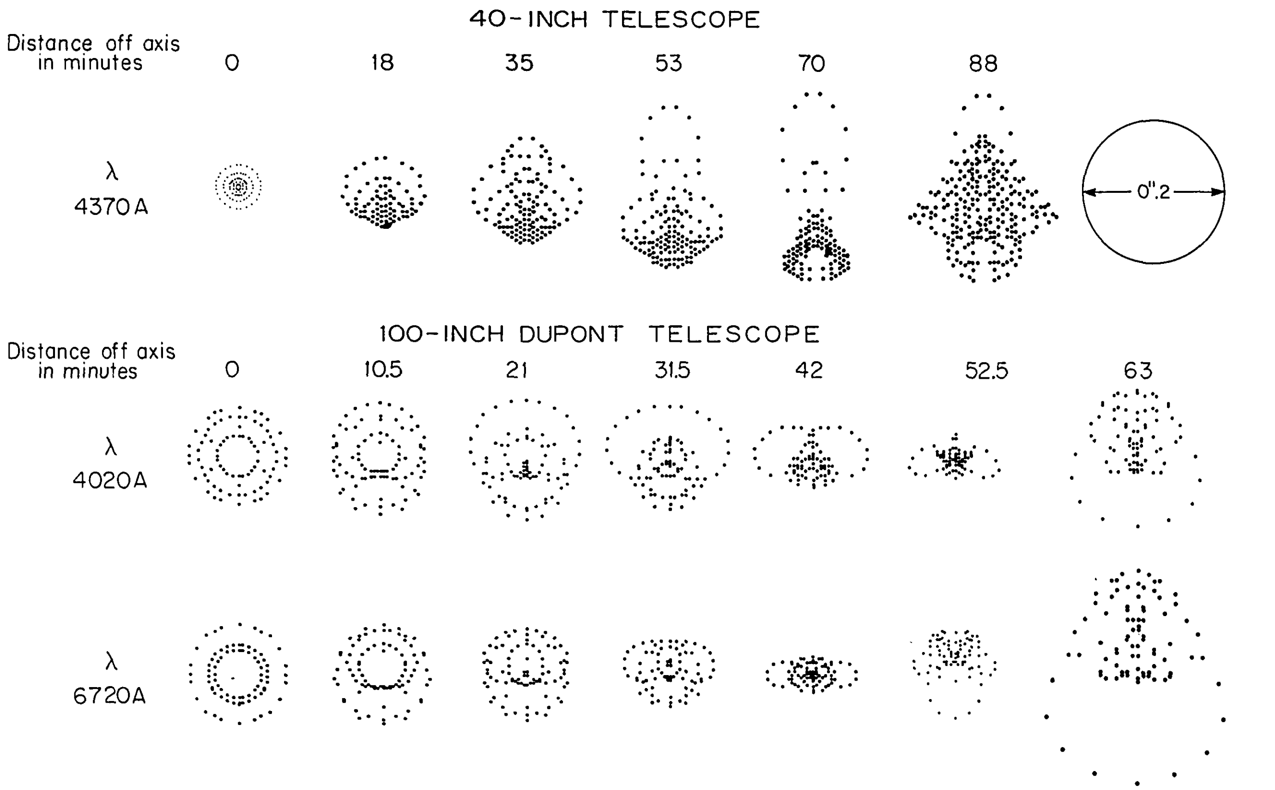

Fig. 1. Monchromatic images. On-axis images are shown on the left in each panel. All off-axis images have been turned 90° clockwise. Distances of corrector from focus are those given by Eq. (1) for the 100-in. telescope at the wavelengths indicated.

Figure 1 shows the monochromatic spot diagrams formed at various distances off axis by the 40-in. telescope for the case defined by the refractive indices and separations given in Table II. Similar diagrams are given in Fig. 1 for images formed by the 100-in. DuPont telescope under the conditions given in Table III and also for the case n = 1.456 (λ6720 Å), with the corresponding adjustments of L as given by Eq. (1).

Tables V and VI summarize the sizes of the monochromatic images for the 40-in. and 100-in. telescopes, respectively. The tables also list the maximum spread of the images caused by the dis-

Table V. Aberrations of the 40-in. Telescope[a]

Distance off axis in minutes	88	70	53	35	18	0
Wavelength range λλ3460–5000 Å, n = 1.4776–1.4624						
Radial size of image in seconds of arc						
Monochromatic	0.25	0.25	0.22	0.14	0.09	0.06
Chromatic spread	1.27	0.51	0.48	0.33	0.22	0.08
Sagittal size in seconds						
Monochromatic	0.21	0.09	0.13	0.15	0.11	
Chromatic spread	0.53	0.31	0.13	0.01	0.07	

[a] See Table III.

Table VI. Aberrations of DuPont 100-in. Telescope

Distance off axis in minutes	63	52.5	42	31.5	21	10.5	0
Wavelength range 3460–5000 Å, $n = 1.4776–1.4624$							
Radial size of image in seconds of arc							
Monochromatic	0.19	0.06	0.08	0.14	0.16	0.15	0.13
Chromatic spread	0.83	0.36	0.30	0.25	0.21	0.18	0.09
Sagittal size							
Monochromatic	0.18	0.12	0.16	0.17	0.15	0.12	
Chromatic spread	0.10	0.04	0.02	0.05	0.08	0.10	
Wavelength range 6000–7680 Å, $n = 1.4581–1.4539$							
Radial size of image							
Monochromatic	0.30	0.12	0.05	0.09	0.13	0.14	0.14
Chromatic spread	0.23	0.10	0.08	0.07	0.06	0.05	0.03
Sagittal size							
Monochromatic	0.25	0.11	0.12	0.12	0.12	0.14	
Chromatic spread	0.03	0.01	0.01	0.01	0.02	0.03	

proximate hyperboloids, the differences again being in the coefficients of the y^6 term. The differences from the hyperboloids are very similar to those obtained by Chretién in his original solution for the combination of two mirrors yielding zero coma. In the case of the 100-in. it was found that out to 52.5 min off axis the solution with hyperboloid mirrors gave approximately the same image sizes as the optimum solutions listed in Table III. At 63 min off axis the image formed by hyperboloids was 56% larger; however, vignetting at this distance off axis reduced the image size to about 20% above the value of the table. Because of the greater ease of testing a hyperboloid secondary using the Hindle method, it was decided to substitute for manufacturing purposes the hyperboloid modification of the design. With the larger field of the 40-in. the difference between the hyperboloid and the optimum design is much greater, and consequently the optimum design was followed.

Vignetting

For secondaries whose diameters are those listed in Table I the nonvignetted fields at the plate have diameters of 9.4 in. = 239 mm for the 40-in. and 18.9 in. = 481 mm for the 100-in. Losses caused by vignetting are 5% at the edge of the field (88 min off axis) in the 40-in. and 3% at the corner of the plate (63 min of axis) in the case of the 100-in.

Shielding

If limiting exposures are to be made with any Cassegrain telescope it is necessary to shield the photographic plate from light coming around the secondary mirror. Unfortunately for these wide field instruments the usual shield in the form of a tube extending forward from the photographic plate is not effective.

In the 40-in. a concentric series of slightly conical shields was placed at the upper end of the telescope tube as shown in Fig. 2A. Obscuration by these shields is constant over a field whose radius is the semiangle of the cone. This uniformity is desirable for photometric observations.

Shields of this type are too large and cumbersome

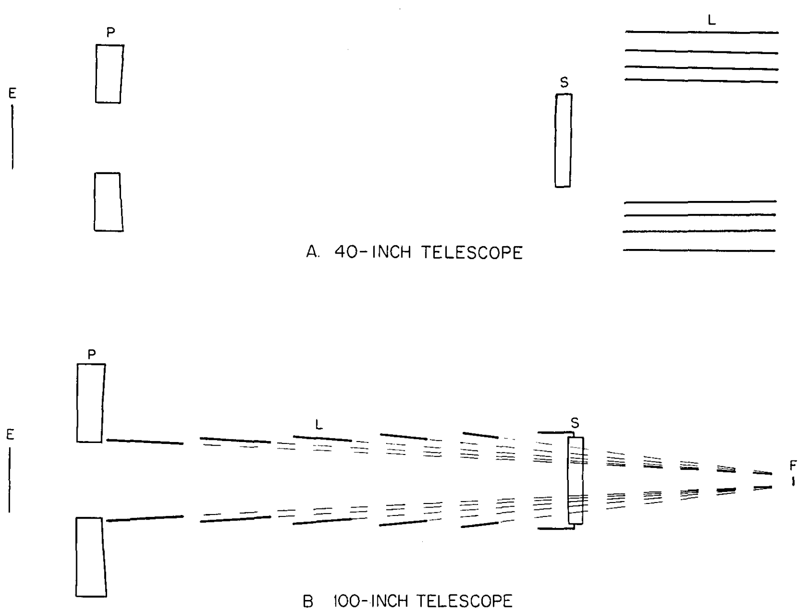

Fig. 2. Optical layouts illustrating configuration of sky shields L, primary mirror P, primary focus F, secondary mirror S, and photographic plate E. In the 40-in. the inner three shields are cones of 0.75° half-angle. In the 100-in. all shields except the one at S are sections of cones that intersect a 3-in. circle at F.

for use on a telescope as large as the 100-in. They were therefore replaced by a series of conical baffles located in the space between the incoming beam as it approaches the primary and the return beam from the secondary to the plate, as shown in Fig. 2B. In order to provide more room for these shields between the incoming and return beam, a cylindrical shield is placed around the secondary extending its diameter to 42 in. The reduction in the number of baffles that this increased space permits largely compensates for the light loss caused by this extra 42-in. shield. The cones comprising the shield, if extended upward, would pass through a circle 3 in. in diameter centered on the focal point of the primary mirror. As a result, the total light intercepted by all shields is uniform and equal to 6.49% over the central area of the plate out to a diameter of 7.5 in. A further loss of 3.8% occurs at the corner of a 20 in. × 20-in. plate.

The chief disadvantage of these shields, aside from the light intercepted, is the diffraction pattern produced by them. However, theoretical considerations indicate that in the DuPont telescope these diffraction effects should not be appreciable on star images within 5 to 6 magnitudes of the plate limit.

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Ira Bowen (who was director of both Mount Wilson and Palomar Observatories), left, Walter Adams (who succeeded Hale as director of the Mount Wilson Observatory), Lee DuBridge (then president of Caltech), and Evelina Hale at the dedication ceremonies of the Hale 200-in. telescope on 3 June 1948.

(Niels Bohr Library)

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