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ABSTRACT

The optical elements of a cassegrain telescope are commonly tested individually, with their axes in a horizontal position. When these optical elements are inserted in the telescope, the resulting imagery is often disappointing. The quality of the imagery in the telescope may be predicted more accurately if the primary and secondary mirrors, with their axes in the vertical position, are tested against each other with the aid of null compensating reimaging optics. An example is given to illustrate the application of the technique.

DESCRIPTORS: Lens design, Optical testing, Telescopes, Optical systems

A SUGGESTED PROCEDURE FOR TESTING LARGE CASSEGRAIN OPTICAL SYSTEMS

Large mirrors of extremely high optical quality (rms surface error less than $\lambda/20$) have become a reality only recently, for several reasons. First, the more advanced optical testing laboratories are just beginning to equip themselves with vertical test towers, so that large mirrors may be tested with their axes pointed vertically. This eliminates the need to subtract out the effects of nonaxially symmetric gravitational deformations and vertical air density gradients that are encountered when testing is done with the optical axis near the horizontal. Second, the development of the Offner[1] corrector and the increasing use of interferometric techniques have made possible more reliable evaluations of high-quality mirrors. Finally, the development of mirror materials having ultralow coefficients of thermal expansion has made discussions of the superb optical figure truly meaningful. The above remarks apply especially to concave mirrors of the type generally encountered as primary mirrors in cassegrain telescopes. They apply only to a limited extent, however, to convex cassegrain secondary mirrors.

Cassegrain systems are, in general, tending toward increasingly high numerical apertures and increasingly high amplification factors at the secondary mirror. In the case of some secondary mirrors, obscuration problems may restrict the usefulness of the Hindle[2] system, the most common testing technique for the convex hyperboloids. Often, the periphery of the secondary mirror may extend beyond the test beam, or if the test sphere is fast enough to prevent this, the image may be awkwardly placed. In addition, the figure of the Hindle sphere, which may be several times the diameter of the tested surface, must be maintained to an accuracy of at least half that expected on the tested surface.

The standard cassegrain system appears as shown in Fig. 1. The system may be completely described by the parameters: N, the final focal ratio or f/number of the system; ρ, the ratio of the diameters of the secondary, D_{II}, and primary, D_I, mirrors (for the axial field point); and ω, the image clearance behind the vertex of the primary (normalized to the diameter of the primary). When the desired values of N, ρ, and ω have been assigned, the amplification factor m attributable to the secondary is given by:

$$m = N(\rho - 1)/(\omega - N\rho). \tag{1}$$

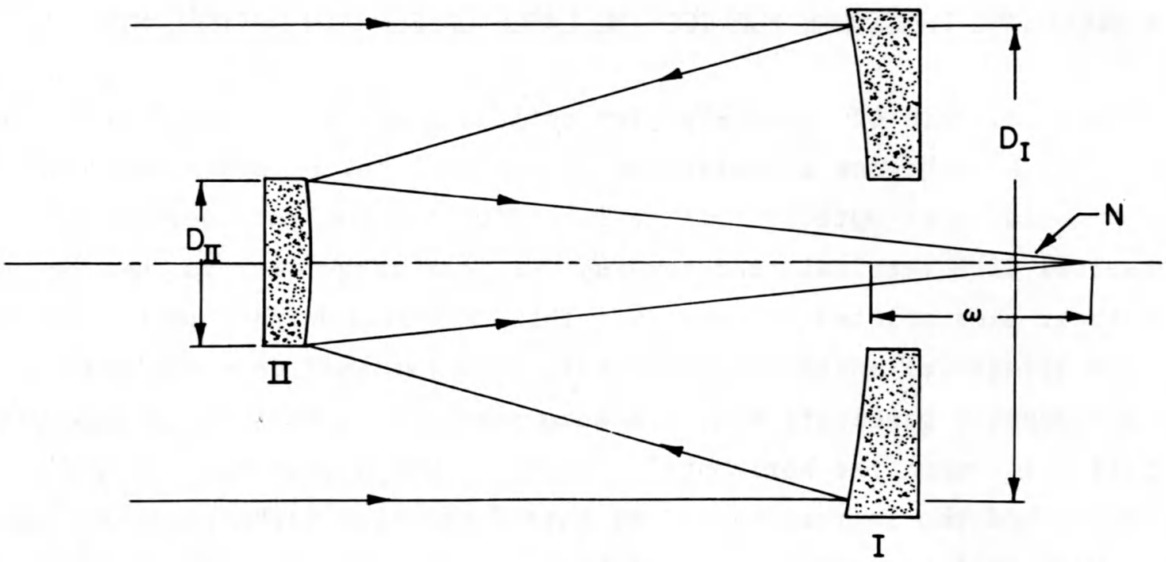

Fig. 1. Schematic diagram of the cassegrain system with the fundamental parameters labeled.

The primary mirror, properly supported on the polishing turntable, may be tested vertically with a high degree of precision. However, since the Hindle test of the secondary may be somewhat less dependable, unforeseen headaches may be prevented by testing the elements together before installation in the finished instrument. Although the complete system may be tested (and usually is) by utilizing a stellar object as a source of collimated light, the test may be complicated by atmospheric degradation of the incident wavefront, deficiencies of the mirror support system, and other problems. If it is finally determined that refiguring is required on one or both mirrors, they may have to be removed for return to the optical shop.

The complete optical train may be tested autostigmatically in the optical shop, where atmospheric effects and mechanical support are more easily controlled. To accomplish this (Fig. 2), the secondary is suspended above the primary, which is mounted on the polishing turntable, at a distance slightly in excess of their normal separation in the telescope. A point source O is then imaged by an array of small lenses at O', which lies at a distance S_1 from the vertex V of the primary. S_1 is chosen such that the convergence angle of the reflected cone of light matches the angular subtense of the secondary, as seen from its center of curvature. This occurs if

$$S_1 = 2m/(m+1). \tag{2}$$

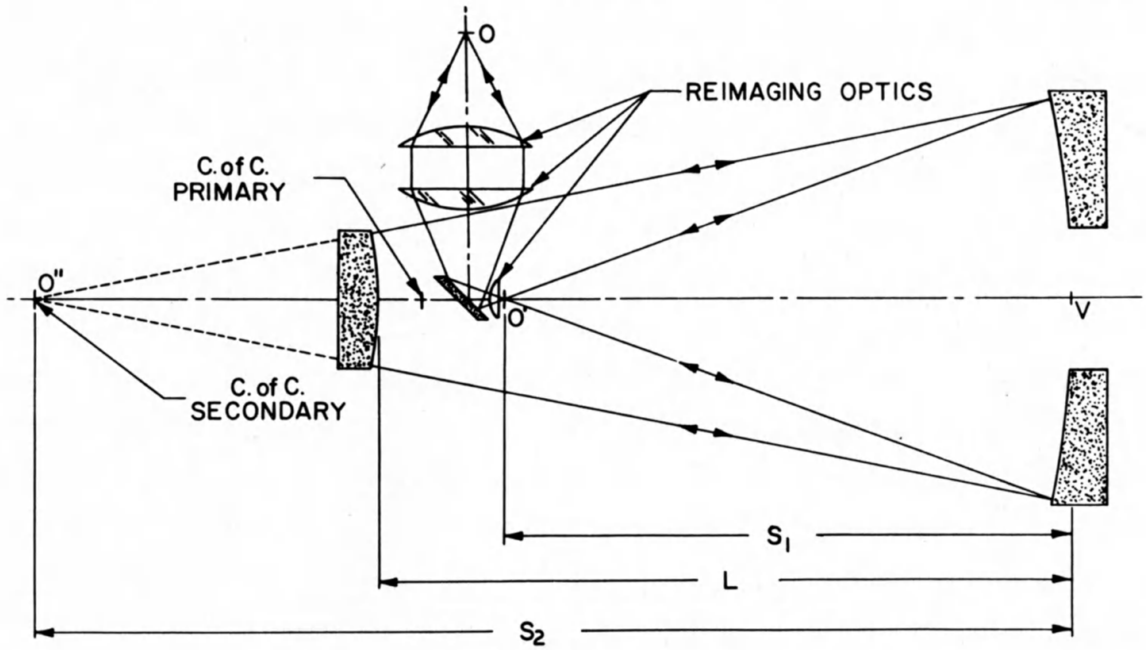

Fig. 2. Primary and secondary mirrors tested together. The optical system is illustrated here in the horizontal position, but it should be deployed vertically. The diagram is not to scale, the sizes of the folding flat and reimaging optical system being exaggerated for clarity.

The conjugate focus, coincident with the center of curvature of the secondary, lies at O", a distance

$$S_2' = -2m/(1-m) \tag{3}$$

from the primary. S_1 and S_2 are expressed here in units normalized to the focal length of the primary, as is L, the separation of the mirrors in the testing configuration. The proper separation is

$$L = \frac{2m}{1-m}(\rho-1). \tag{4}$$

From Eq. 1, we see that generous image clearance, ω, is obtained in fast systems only at the expense of very high obscuration ratios and secondary amplification factors. In Fig. 3, obscuration ratio ρ is plotted against amplification m for f/6 systems (N = 6.0) having image clearances of 0, 0.2, 0.5, and 1.0. In the case of an f/16 system, the price paid for image clearance is not as high (Fig. 4). Note (Eq. 1) that the curves for $\omega = 0$ are identical for all N.

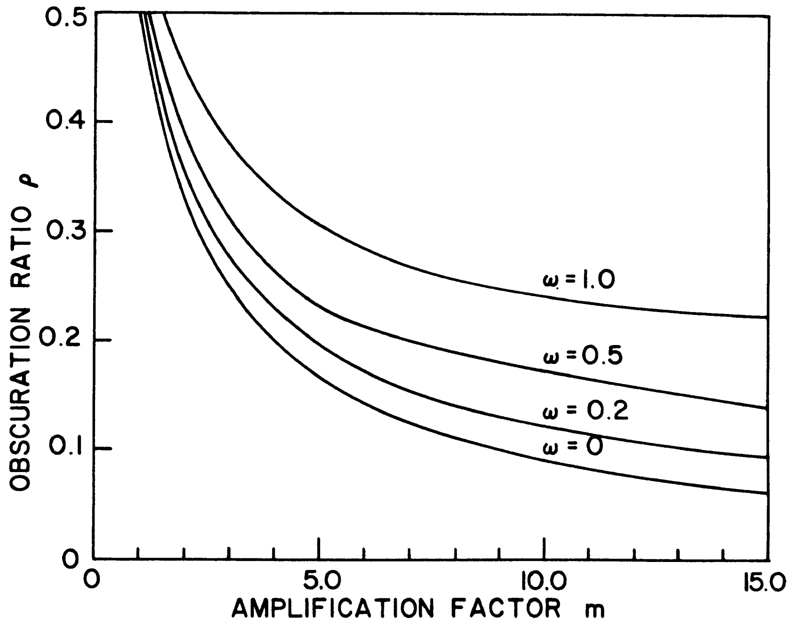

Fig. 3. An f/6 system. Obscuration ratio ρ is plotted as a function of secondary mirror amplification m for image clearance ratios of 0, 0.2, 0.5, and 1.0. Liberal clearance is obtained only when ρ or m is very high.

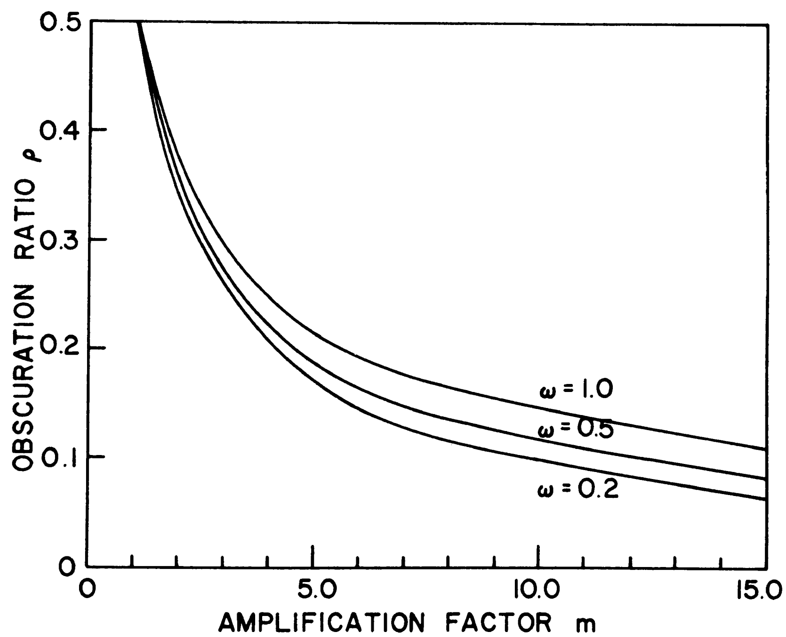

Fig. 4. An f/16 system. Obscuration ratio ρ is plotted as a function of secondary mirror amplification m for image clearance ratios of 0.2, 0.5, and 1.0. In a slow system such as this, a wide range of image clearance is possible at little expense to obscuration or magnification.

The curves of Fig. 5 represent the separation, L, of the mirrors required to test systems of specified obscuration ratio and secondary amplification. Curves similar to those of Fig. 3 and Fig. 4 are superimposed to illustrate that cassegrains of fairly conventional form may be tested in systems whose lengths are approximately equal to the radius of curvature of the primary. In the case of an f/10 system with $\omega=0.5$, for example, an obscuration ratio of 0.2 (requiring $m \simeq 5.0$) may be tested in a system whose length is almost exactly twice the focal length of the primary. If we reduce m to about 2.0 ($\rho \simeq 0.4$), however, the testing system becomes approximately 50% longer. Systems in the gray region are those in which $S_1 > L$. In such cases, the object position O' lies to the left of the secondary mirror. Fortunately, most conventional cassegrains do not lie in this region.

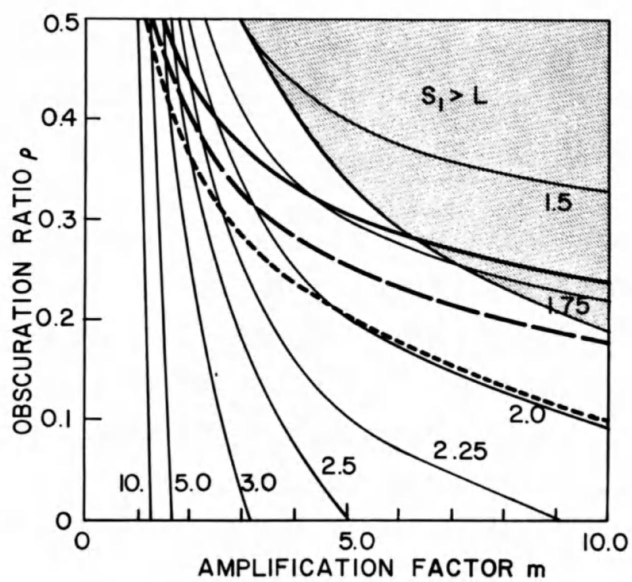

Fig. 5. Testing system length. L is plotted as a function of obscuration ratio ρ and secondary amplification m for several different values of L. In the gray area, $S_1 > L$, yielding an impractical system. Note that very low amplification factors require unwieldy testing systems. Three sample curves similar to those of Figs. 3 and 4 are superimposed. Solid heavy line is $N=6.0$, $\omega=1.0$; dashed heavy line is $N=10.0$, $\omega=1.0$; dotted heavy line is $N=10.0$, $\omega=0.5$. The test system length for a cassegrain system is represented by the crossing of its heavy line with a line representing $L = const.$ For example, an f/10.0 cassegrain system having $\rho \simeq 0.3$, $m \simeq 3.0$, $\omega=0.5$ requires a test system whose length is between 2.0 and 2.25 times the focal length of the primary.

The test described above is convenient from the standpoint that a folding flat, which is reflective on both sides, may be combined with two field lenses in a cell that may be rotated to switch over to an Offner corrector array (Fig. 6). In this manner, the figure of the primary mirror may be monitored at any time during the testing of the complete system.

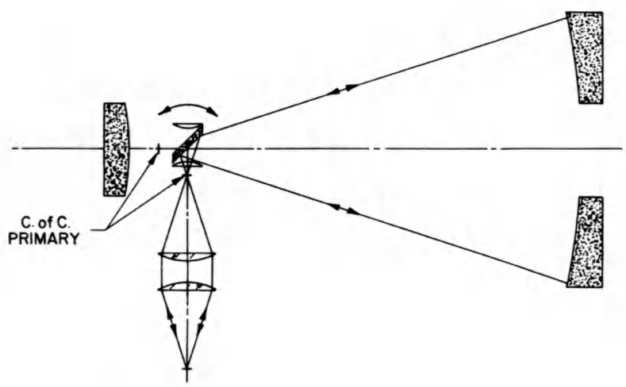

Fig. 6. The Offner corrector in use. The optical system is illustrated here in the horizontal position, but it should be deployed vertically. The cell containing the folding flat and field lenses has been rotated so that the figure of the primary may be checked.

It is obvious that O' (Fig. 2) will not be reimaged stigmatically upon itself; but the reimaging optics may be designed to yield a wavefront that, when modified by the finished primary mirror, matches the desired aspheric profile of the secondary mirror. The reimaging optics and primary mirror, then, may be viewed as a null corrector for the secondary, the system being autostigmatic and symmetrical about the secondary mirror.

Although a detailed discussion of the problems involved in designing reimaging optics for this system is beyond the scope of this paper, the author's experience seems to indicate that the spherical aberration residual due to the primary mirror-secondary mirror combination is usually of the same order of magnitude as that due to the primary alone. This is true especially in the case of faster systems ($6 \leq N \leq 8$), in which the magnitude of the residual aberration of the combination seldom exceeds 125% of that of the primary alone. In slower systems ($8 \leq N \leq 12$), the spherical aberration of the combination may approach 200% to 400% of that attributed to the primary. Fortunately the asphericities encountered in the slower systems are milder than in the fast systems. In essence, it appears that if the primary alone is amenable to null correction, then the combined system will likewise be correctable.

An analysis of the sensitivity of the system to errors in manufacturing and alignment has not been carried out. The tolerances, in all likelihood, will not be liberal. However, because this system sufficiently resembles the Offner and Hindle systems, it should be a reasonably practical arrangement that will provide a means of laboratory testing a set of cassegrain optics in a relatively unobscured configuration of compact dimensions. Most important, if the cassegrain components are tested in this fashion, a considerable amount of redundant information may be acquired that will provide a much-needed verification of the test results for the individual elements.

Calculations have been carried through to higher orders for an entire sample system (mirrors and reimaging optics). The example chosen is the 396-cm (156-in.) aperture cassegrain telescope being constructed by the Kitt Peak National Observatory in Tucson. Tentative constructional parameters for the optical system are tabulated below.

Constructional parameters of 396-cm-aperture cassegrain telescope

Parameter	Dimensions in cm	
	Primary mirror	Secondary mirror
Diameter	396.2	118.0
Radius of curvature	2133.6 concave	964.3 convex
Aspheric deformation		
4th power	1.41391×10^{-11}	7.38423×10^{-10}
6th power	1.50185×10^{-18}	-1.1294×10^{-15}
Mirror separation	749.05	

Calculating the fundamental first order descriptive parameters, we get: $m = 2.93286$; $\rho = 0.297857$; $\omega = 0.46154$. The normalized dimensions for our test system are then: $S_1 = 1.491464$; $S_2 = 3.034738$; $L = 2.13082$, and the actual (non-normalized) values become: $S_{1(\text{actual})} = 1591.093$; $S_{2(\text{actual})} = 3237.46$; $L_{(\text{actual})} = 2273.16$.

In the process of designing the reimaging optics (null corrector), a slight adjustment of these quantities was necessitated by the fact that the rays in the real system carry significant amounts of aberration and do not precisely adhere to the paraxially-calculated ray paths.

It was decided somewhat arbitrarily that, in the interest of convenience, diameters of the imaging lenses in the reimaging array should not exceed 5% of the diameter of the primary mirror under test. In the case of the 396-cm telescope, this corresponds roughly to 20 cm (7.8 in.). The test system illustrated in Fig. 7 represents one possible solution to the problem. A number of solutions exist, however, and this example is not necessarily the optimum one. This solution suffers, in particular, from the fact that surface 4 serves to compensate the bulk of the aberration present. The remaining surfaces essentially aid in establishing a balance of the higher-order aberrations. Surface 4, then, may be expected to have greater sensitivity to errors in construction and alignment than if surfaces 1, 2, 3, and 4 shared more equally the compensation of the bulk aberration.

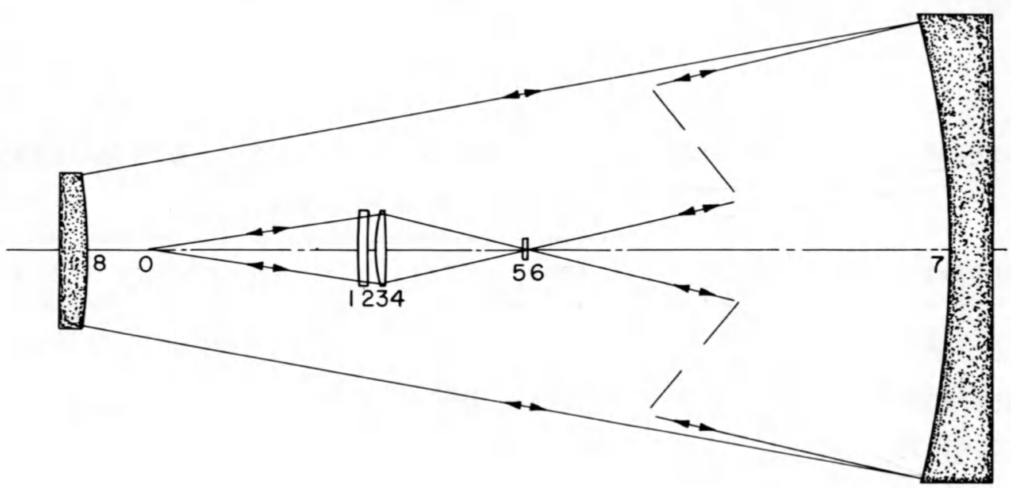

Fig. 7. A possible test system for the 396-cm telescope. The system, illustrated here in the horizontal position, should be deployed vertically. For clarity, the dimensions of the primary and secondary mirrors are not to scale. Constructional parameters of the system (in centimeters) are tabulated below. Test wavelength is 0.6328 μm.

Surface	Radius of curvature		Thickness following	Medium following	Diameter
0	--		114.515	Air	0
1	234.36	convex	2.540	BK7	20.32
2	451.066	concave	2.473	Air	20.32
3	29.231	convex	2.54	BK7	20.32
4	230.323	convex	79.324	Air	40.64
5	∞		0.508	BK7	2.54
6	50.726	convex	1590.07	Air	2.54
7	(Primary mirror)		2277.40	(Reflector)	
8	(Secondary mirror)				

The residual wavefront spherical aberration of the complete system is plotted in Fig. 8.

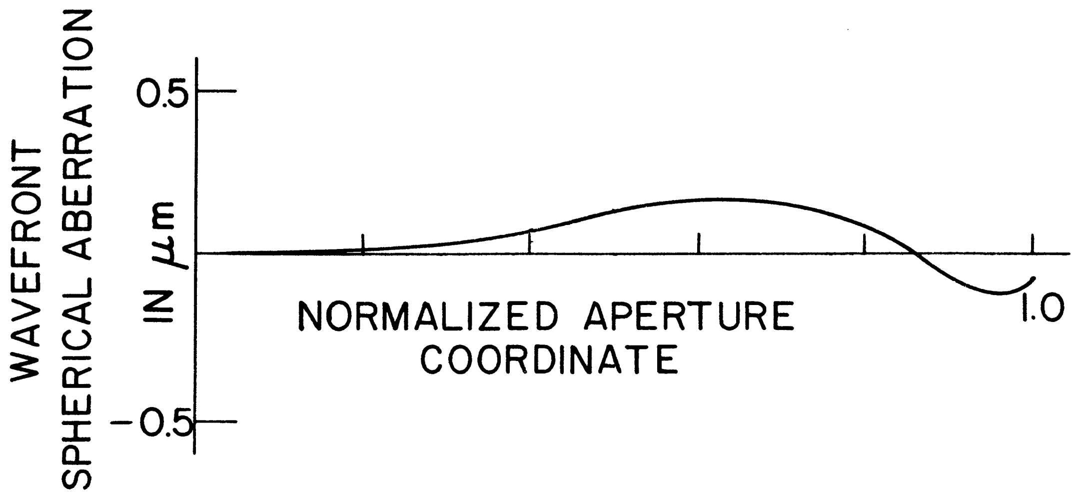

Fig. 8. Wavefront spherical aberration residual. The aberration residual in micrometers is plotted as a function of the normalized aperture coordinate.

REFERENCES

[1] Abe Offner, "A null corrector for paraboloidal mirrors," *Appl. Opt.* 2(2): 153-155, Feb. 1963.

[2] J. H. Hindle, "A new test for cassegrain and gregorian secondary mirrors," *Roy. Astron. Soc. Monthly Notices* 91(5):592-593, 1931.