Design, tolerancing, and certification of a null corrector to test 8.4 meter mirrors

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Abstract

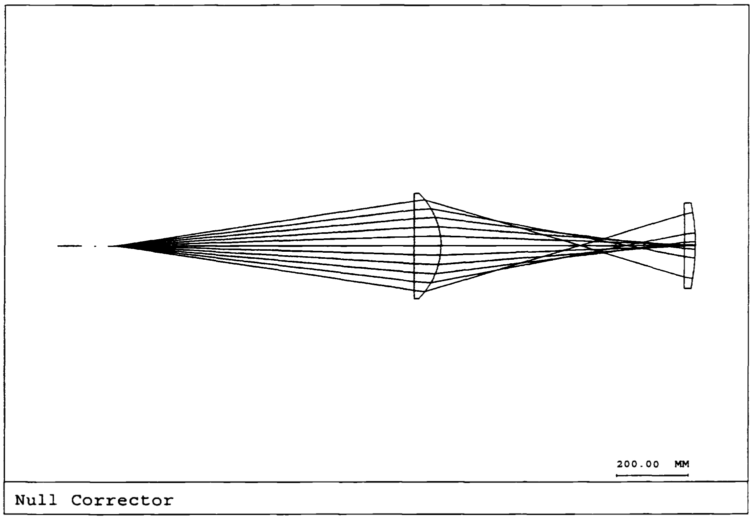
We present a design and new approach to certify a null corrector with tight manufacturing tolerances. This involves a diamond turned asphere and a hologram that provide certification redundancy.

Keywords: Optical testing, null-correctors, optical certification, aspheric surfaces, optical design

Introduction

The University of Arizona is building the Large Binocular Telescope (LBT) which requires of twin 8.4-meter diameter, *f*/1.14 paraboloidal primary mirrors. These primaries have a 1.38 mm aspheric departure from the best fitting sphere and therefore their testing requires of a null corrector. The design, manufacture, and certification of the optical system that allows interferometric testing of such mirrors poses considerable difficulty. This paper presents our design, tolerancing, and certification approach of a null corrector to test such giant mirrors.

Fig 1. Null corrector to test a fast and large mirror.



The laboratory testing of large astronomical optics has been simplified with the use of null correctors. A null corrector is a system of lenses that corrects the nominal aberration of the aspheric mirror under test when it is tested at its center of curvature. The Offner[1] null corrector is often used because it can provide a good correction. It consists of two positive plano-convex lenses: the field and relay lenses. Both lenses are located near the center of curvature of the mirror under test and therefore they are significantly smaller than the test mirror itself. The function of the field lens is to rearrange in a linear way the rays that arrive to the relay lens. The function of the relay lens is to introduce the bulk of the optical correction and to obtain a null test point. To test a large and fast mirror it is necessary to modify the basic Offner corrector[2,3]. Maintaining reasonable lens sizes and providing a way to certify the correction introduced by the null corrector are of prime importance. We have been able to produce a design with a relay lens aperture in the order of 250 mm that is capable of testing the twin 8.4 m paraboloidal primaries of the LBT.

Design

Our null corrector design is shown in Fig. 1, which shows rays from the null test point, the relay lens, and the field lens. Note that the field lens re-arranges the rays in such a way that they arrive to the test mirror in a linear way. The relay and field lenses have clear apertures of 252 mm and 182 mm respectively. The size of the relay lens is about 1/34 the test mirror diameter. The distance from the null test point to the field lens is 1583 mm. The relay lens is a plano-convex lens and the field is a concave-convex lens; both are made out from Bk7 glass. The field lens is inside the caustic. This has the disadvantage of creating two spurious interference rings by retro-reflection of caustic rays, and increasing the amount of wavefront residual. However, it is important to minimize the size of the mirror and hologram used to certify the null corrector. This occurs when these certifying elements are located at the paraxial center of curvature of the paraboloid. The primary mirrors have a hole diameter of 900 mm. This unused portion helps to improve the wavefront residual or to reduce the size of the lenses.

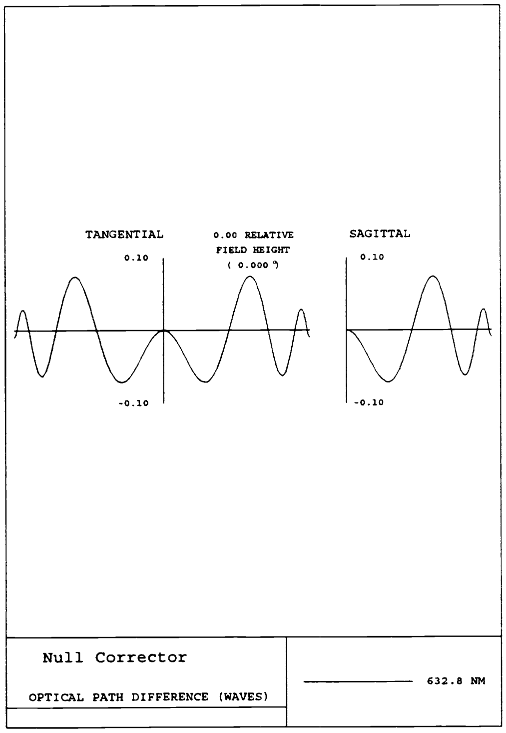


Fig.2 Wavefront residual with low slope errors.

The wavefront residual as shown in Fig. 2 is less than 1/5 of a wavelength peak-to-valley at 632.8 nm. Note that attention has been placed to minimizing slope errors.

Tolerancing

The figure requirements for the LBT primary mirrors are to be paraboloidal. The maximum departure allowed from the nominal conic constant of -1 is 0.01%. The maximum RMS departure from a true conic mirror is 100 nm. The null corrector is nominally designed for a paraboloidal mirror with a vertex radius of curvature of 19200 mm.

We have produced tolerances (and sensitivities) to the nominal design values for our null corrector as shown in Table 1. In the tolerancing and actual test the mirror position is used as a compensator for focus, tilt, and coma. Parameter changes that affect the axial symmetry of the test are compensated by moving the mirror axially and by changing its conic constant. Parameter changes that break the axial symmetry are compensated by tilting and displacing the mirror. Both the null corrector and the interferometer are handled as a single unit.

Parameter	Design value	Tolerance	Change in Conic	rms wavefront
NOMINAL				28 nm
Test Point Distance	806.002	0.05	0.0038%	30 nm
Radius of Mirror	-19200	0.5	0.0025%	28 nm
Relay Lens				
Diameter	292			
Clear aperture	252			
Radius 1	Infinite	½ wave sag	0.0005%	28 nm
Radius 2	-202.977	0.05	0.0038%	35 nm
Thickness	74.00	0.05	0.0025%	29 nm
Airspace	673.117	0.01	0.0039%	29 nm
Index	1.515089	5 ppm	0.0011%	29 nm
Tilt Surface 1		0.1 degrees		45 nm
Tilt Surface 2		0.1 degrees		46 nm
Field Lens				
Diameter	222			
Clear aperture	182			
Radius 1	-6666.581	1.0	0.0014%	30 nm
Radius 2	-606.54600	0.02	0.0032%	35 nm
Thickness	30.00	0.01	0.0028%	29 nm
Index	1.515089	5 ppm	0.0007%	29 nm
Tilt Surface 1		0.01 degrees		38 nm
Tilt Surface 2		0.05 degrees		47 nm

Table 1. Tolerances for null corrector. Units are mm unless listed. The conic constant and the mirror position were used as compensators.

By applying the RSS rule the expected total change in conic constant is 0.009% and the expected change in RMS is 35 nm for a total of 63 nm. Note that we have toleranced the separation between the interferometer test point and the null corrector and the radius of curvature of the mirror. The largest contributions to the change in RMS come from surface tilts. The tolerances shown in Table 1 are tight but within the state-of-the-art of manufacturing.

Diamond turned certifier

One well-known problem of null correctors used to test astronomical optics is the potential error that they can introduce in the surface under test. This error results from the fabrication or assembly errors of the null corrector itself. One solution to this problem is to certify the null corrector using a computer generated hologram[4]. The holograms are manufactured with a circular laser writing machine, and have demonstrated accuracy of 0.01 waves rms for mirrors as fast as f/1.1. The holograms are designed and manufactured independent from the null correctors, so when the null corrector and the hologram agree, we are assured that both are correct.

After using holograms to certify over 10 null lenses for primary mirrors, we are considering a new philosophy in optical testing. We can build the null corrector at low cost if we do not require absolute accuracy from it, and we can adjust the null lens to match the hologram. However, this eliminates the redundancy in our process -- an error in the hologram would result in a mis-aligned null corrector that would cause the mirror to be made to the wrong shape.

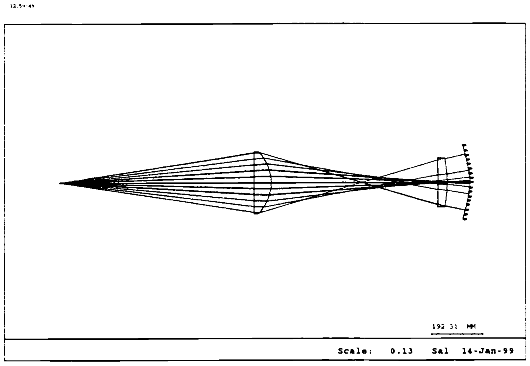


Fig 3. A refractive null corrector and its aspheric certifying mirror.

A mirror with a diamond turned aspheric surface can be used to provide the redundancy required to insure that the primary mirrors are properly made. The added cost of a single diamond turned asphere is easily justified by the cost savings from making the null corrector to low tolerances.

Such certifying mirror is placed almost in contact to the null corrector and retro-reflects the light so that a null test condition is maintained. Every ray from the null corrector reaches the certifying mirror at normal incidence and is therefore reflected back on its incoming path. Provided that the certifying mirror is accurate then any error in the null corrector will be shown as an aberration at the ideal null test point.

In addition to a hologram, we plan to use diamond-turning technology to manufacture the certifying mirror that we need to properly test the twin 8.4 meter LBT paraboloidal mirrors. Companies that specialize in manufacturing diamond turned mirrors can deliver surface finishes of 100 Angstroms RMS and 300-nm peak-to-valley in parts that are less than 200 mm in diameter. Mechanical profilometry, test data, showing the departure from the ideal surface is also supplied.

We found that the standard aspheric surface provided in lens design programs cannot describe properly the surface of the certifying mirror even if many aspheric coefficients are used. The reason is that near the caustic produced by the normals of a paraboloidal mirror there is a strong non-linearity in the behavior of the rays. Therefore we had taken a different route to find the surface description of the certifying mirror. This involved setting a set of equations that fortunately we were able to solve in closed form. As a function of the normal angle θ with respect to the optical axis the sag z and the transverse coordinate y of the certifying mirror are given by:

$$z = \frac{1}{2}\left\{2P\cos(\theta) + \frac{R}{\cos^2(\theta)} - R\right\} - P \quad \text{and} \quad y = R\tan(\theta) - P\sin(\theta), \qquad \text{Eq. 1}$$

where R is the vertex radius of the paraboloid, and P is the vertex-to-vertex distance between the paraboloid and the certifying mirror. In these equations the trigonometric functions can be eliminated to obtain a relationship between z and y only. This is,

$$\begin{aligned}&y^2\left(4P^4-4R^3z-4P^3[3R+4z]+4y^2\left[y^2+z^2\right]+R^2\left[y^2+32z^2\right]-\right.\\&4P\left[R^3+5Ry^2-16R^2z-2y^2z+12Rz^2\right]-\\&\left.4R\left[5y^2z+4z^3\right]+4P^2\left[3R^2-11Rz-2\left[y^2+z^2\right]\right]\right)\\&+4z(2P+z)\left((P-R)^2-2Rz\right)^2=0\end{aligned}\tag{Eq. 2}$$

This closed form can be used in a ray-tracing program to user define the certifying mirror. Our certifying mirror is designed with aluminum 6061 and therefore temperature effects need to be considered. A one degree change in temperature changes the certifying mirror in size by 24 ppm. This in turn produces an error in the conic constant of 0.002%. Thus the certifying mirror test temperature and the null corrector certification temperature must be within 1 degree to avoid a significant error in the final conic constant of the LBT primary mirrors.

Conclusion

In this paper we have presented a null corrector to test 8.4 m paraboloidal mirrors. The corrector uses lenses that are about 1/34 the mirror diameter. This makes the lens manufacturing and packaging easier. We have designed a diamond turned aspheric mirror that in conjunction with a hologram will provide null corrector certifying redundancy. The surface description for such aspheric certifying mirror cannot be described with the standard aspheric surface used in lens design programs. Introducing redundancy in our certification approach will permit our null corrector to be properly adjusted despite tight tolerances.

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