# Null correctors for 6.5-m *f*/1.25 paraboloidal mirrors

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## Abstract

The instruments used to interferometrically measure the optical surfaces of the 6.5-m *f*/1.25 primary mirrors for the MMT conversion and the Magellan telescope projects must compensate over 800 µm surface departure from the best fitting sphere. The errors in the optical test must not contribute more than 0.04 arc seconds FWHM to the final image and the conic constant must be held to 0.01%. This paper presents an overview of the instruments that were built to measure these giant mirrors to such high accuracy.

**Keywords:** optical fabrication, large optics, aspheres, telescope mirrors

## Introduction

Large primary mirrors are tested interferometrically from the center of curvature using null correctors. The null corrector, or null lens, compensates for the asphericity of the mirror surface and allows an accurate, high-resolution measurement of the entire surface. Two instruments were built for interferometric measurements of the 6.5-m primary mirrors for the MMT and Magellan telescopes.[1] An infrared interferometer with a germanium and ZnSe null corrector is used to test the ground surface. The polished surface is measured with a Twyman-Green interferometer with HeNe laser, co-aligned with a BK7 null corrector. Both the infrared and visible systems have been carefully designed to give excellent performance in terms of wavefront correction, alignment sensitivity, imaging of the mirror to the detector, diffraction effects, ghost reflections, and ease of use.[2] The lenses for these instruments were fabricated and measured precisely. The accurate alignment and stable support of these lenses require a well designed and constructed mechanical system. The mounting and alignment methods used for these null correctors follow from the experience of building similar, smaller instruments at Steward Observatory.

We developed an optical test for measuring the null correctors that uses rotationally symmetric computer-generated holograms (CGH's). The holograms synthesize the wavefront that would be reflected by a perfect primary mirror, so the test of a null lens is performed by measuring the CGH through the null corrector. The CGH is made independently from the null corrector, so agreement between the null lens and the CGH indicate that both the null lens and the CGH are correct. The CGH measurements of the IR and visible null correctors have demonstrated that both exceed their specifications.

## Visible null lens

Measurements of the polished surfaces are made with a null corrector that uses visible wavelength light from a HeNe laser. Initially, the interferometer used a frequency doubled YAG laser operating at 530 nm, and a PZT-shifted Shack cube interferometer with a CCD video camera. The CCD detector was connected via a digital interface to a frame grabber operating at 200 frames per second.[3] This allowed phase-shifting interferometry in the presence of vibration. The Shack cube, null lens, and imaging optics were precisely aligned on a single rigid truss. The laser light was fed into the system through a single mode optical fiber. This has recently been replaced by a Twyman-Green interferometer operating at 200 frames per second, with a fiber-coupled HeNe laser source. The reason for changing was to get better wavelength stability, which is important for the CGH certification.

The null corrector shown below consists of the interferometer and three BK7 lenses: a relay lens, and two field lenses. The optical design gives a wavefront error of 4 nm rms and maximum mapping error of 5%. The null corrector is mounted vertically to precise tolerances using the method described by West *et al.*[4] The relative alignment between the system and the mirror is performed by remotely translating the entire unit in three directions and rotating about two flex-pivot axes.

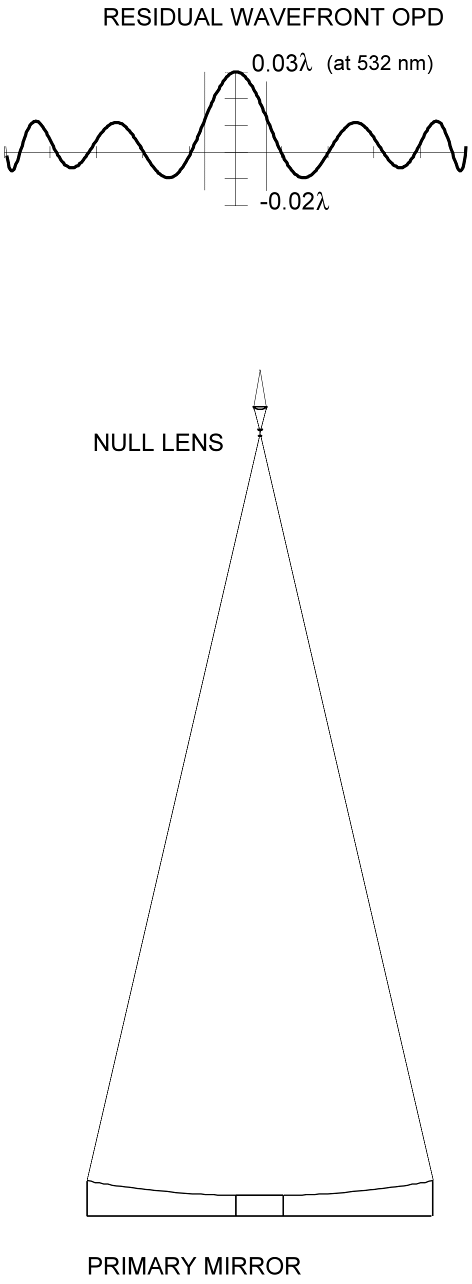

**Figure 1.** Optical layout of the visible null test for 6.5-m *f*/1.25 primary mirrors. The inset shows the residual wavefront.

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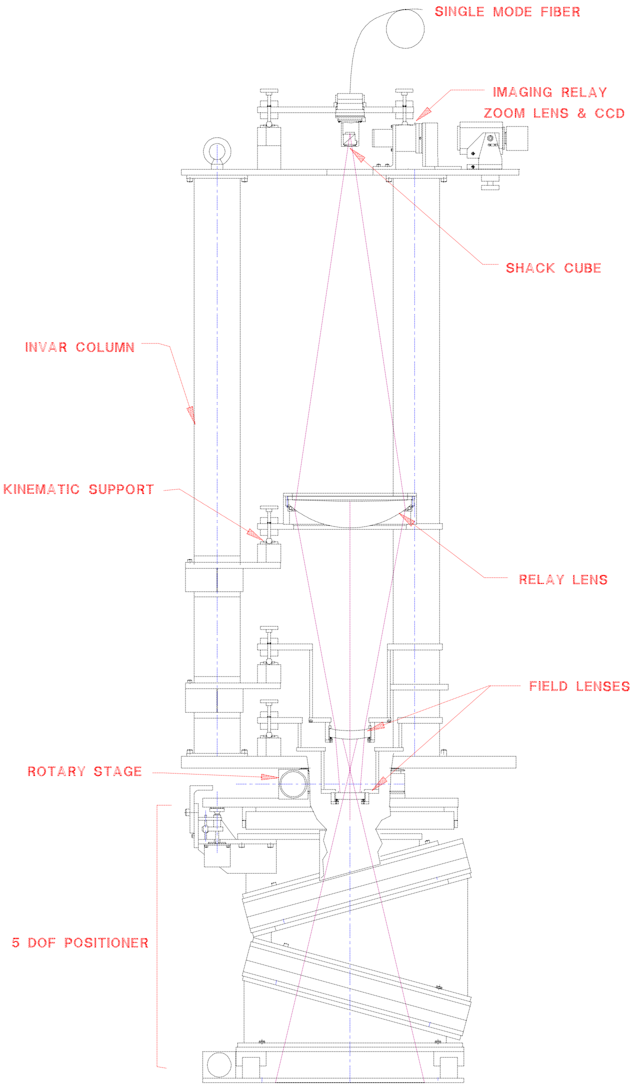

**Figure 2.** Opto-mechanical layout of the visible null lens for 6.5-m *f*/1.25 primary mirrors. This assembly stands about 8 feet tall.

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The imaging system for this interferometer corrects the mapping distortion in the null lens, and provides both zoom and alignment capability, like the popular Fizeau interferometers. The controls are operated remotely to allow the optician to magnify the image and to look with increased resolution anywhere on the mirror. High resolution is thus attained for sub-aperture testing.

The performance of the null test requires accurate and stable alignment of the lenses. The null lens is aligned onto an Invar frame to provide stability and rigidity. For alignment the entire null lens is rotated about a precisely maintained axis and the runout (or wobble) of each surface is mechanically measured and reduced to less than 5 µm. The spacings between the elements are measured using special metering rods and set to an accuracy of about 5 µm.

The rigid assembly is mounted to a set of stages that provide translation in *x, y,* and *z* and rotation about the lateral axes for alignment to the primary mirror.

Since the specification on the primary mirror is in terms of structure functions,[5] the error analysis of the null corrector also uses the functions.[6] The tolerance analysis of the interferometric test was performed by computing structure functions for all of the independent parameters in the system and adding them. Structure functions derived from direct dimensions (spacings, curvatures, refractive index, misalignments, etc.) were computed by ray-trace simulation and analysis of the system. Structure functions from the surface figures of the optical elements were estimated using data from finished optical surfaces. Refractive index inhomogeneity structure functions were estimated for H5 quality glass using melt data and assuming a linear dependence of rms phase difference on point separation. The structure functions from all parameters in the null test are added to give the total test optics structure function. The analysis does not take into account the ability to measure and remove errors in the null lens using the CGH null lens test.

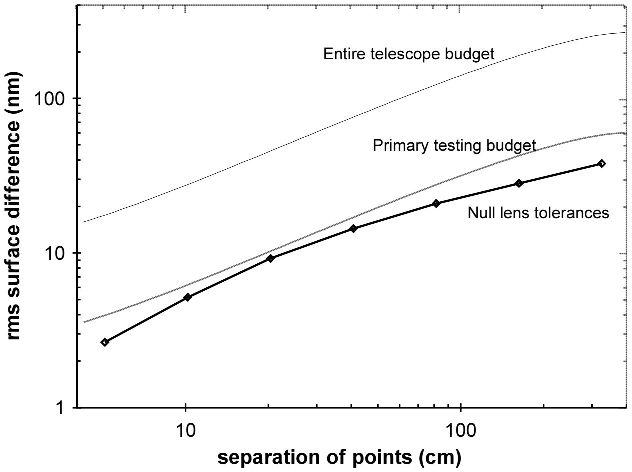

**Figure 3.** Structure function from the error analysis of the visible null corrector for the 6.5-m *f*/1.25 primary. The telescope and test optics specifications are based on a tilt-corrected Kolmogorov model of the atmosphere with a relaxation at small spatial scales.
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The telescope error budget allots primary mirror testing a structure function corresponding to $r_o$ of 270 cm with 0.04 arc-sec FWHM atmospheric seeing. The tolerance analysis shows that the null corrector will meet this at all spatial scales, with a net uncertainty in the measurement of 21 nm rms. The resulting structure function for the null lens optics is shown in Fig. 3.

Distinct from the structure function requirement is a tolerance on the conic constant of the primary. The null lens described introduces an uncertainty of the conic constant of ±0.00009, which is equivalent to 22 nm rms spherical aberration in the surface. Also, the analysis does not take into account the ability to measure and remove errors in the null lens using a rotation test or the CGH null lens test.

This null corrector has been used to measure two 6.5-m primary mirrors through completion of polishing. The most recent was the first of two primary mirrors for the Magellan Telescope, shown here as a gray-scale plot with 14 nm rms surface errors.

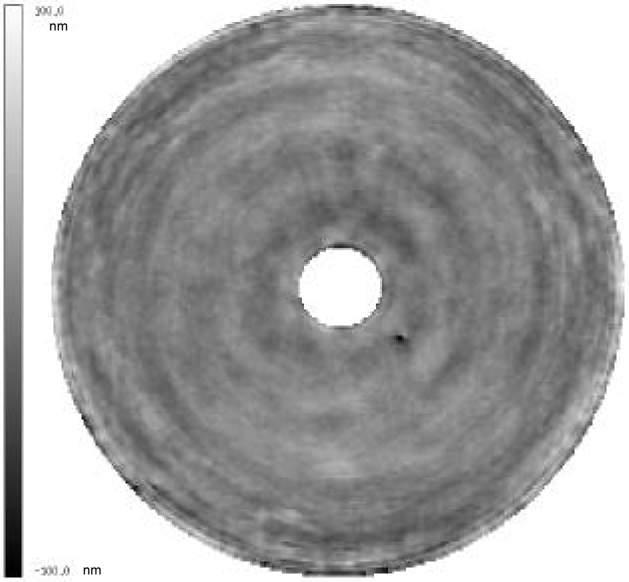

**Figure 4.** Null lens measurement of the first Magellan 6.5-m *f*/1.25 primary mirror. The gray scale plot shows figure errors of 14 nm rms after astigmatism, the lowest bending modes of the mirror, are corrected.

## Infrared null lens

A null corrector made with germanium and ZnSe elements was fabricated to interface with an interferometer that uses 10.6 μm infrared light from a $CO_2$ laser. The null corrector, shown in Fig. 5, consists of three lenses: an aspheric ZnSe diverger, a plano-convex germanium relay lens, and a plano-convex ZnSe field lens. The optical design uses the aspheric surface to give a near-perfect wavefront error of 0.0014 λ rms and mapping error less than 1.3%. The aspheric surface for this null corrector was diamond turned and measured with a profilometer. The null corrector is mounted horizontally and aligned to the collimated output from a Twyman-Green IR interferometer. The relative alignment between the system and the primary mirror is adjusted by translating the assembly in three directions and steering the beam with a fold flat.

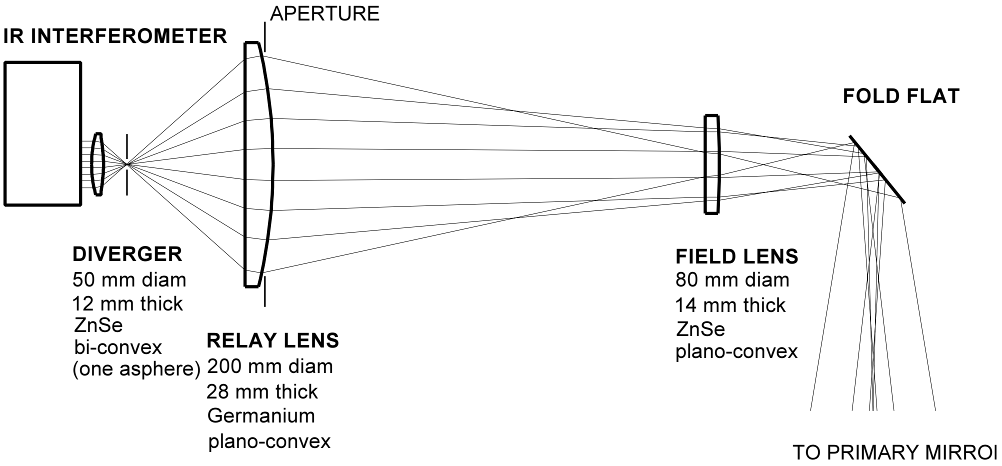

**Figure 5.** Infrared null corrector for the testing of a 6.5-m ƒ/1.25 paraboloidal primary mirrors.
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The elements in this null lens are the smallest that will work when aligned to machine tolerances (±50 µm over 200 mm). The lenses were carefully made free of wedge so that they could be mounted in a simple accurately machined cell for alignment and spacing. A tolerance analysis of the system indicated that the null lens would contribute surface measurement errors of 1.5 µm rms. Most of this predicted error is due to refractive index inhomogeneity of the large germanium lens. We have used holograms to certify that the null lens is actually much better than predicted.

## Certification of null correctors using computer generated holograms

However apparently well made, there is always a possibility that the null correctors can be flawed. If undetected, a null corrector error would result in the final shape of the mirror being incorrect. Several recent telescopes had their primary mirrors made to the wrong shape because of errors in the null correctors.

An optical test using computer-generated holograms is used to qualify the null correctors for the 6.5-m primary mirrors. The technique employs a rotationally symmetric computer-generated hologram (CGH) that tests the null corrector directly by synthesizing a wavefront that would be returned by a perfect primary mirror. The test, which is quick and highly accurate, has been demonstrated for numerous null correctors for smaller mirrors that are now in working telescopes.[7]

The CGH test is insensitive to alignment errors and uses no optics other than the hologram. Since the null corrector and CGH are fabricated independently, agreement between the two indicates a high probability that both are correct. A layout of the CGH null test, shown in Fig. 6, depicts the null lens and CGH. No modifications are made to the null lens to perform this test. The null corrector tests the hologram exactly as if it were measuring the mirror itself.

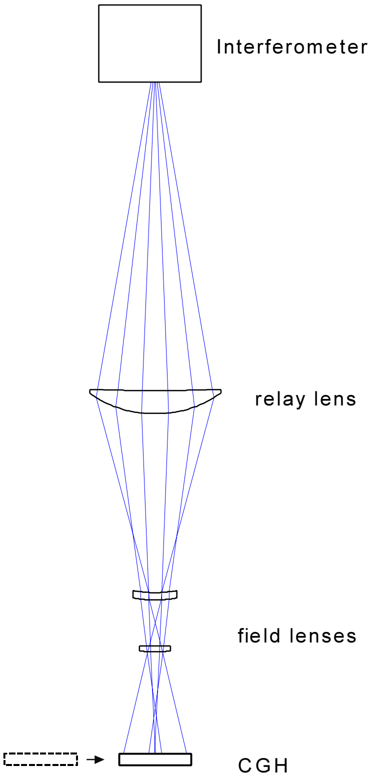

**Figure 6.** Layout of CGH test of null lens.
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The CGH null lens test has been demonstrated to certify the conic constant of null tests to better than 0.01% and has been used to measure and remove figure errors as small as 5 nm rms. These measured results confirm a detailed error analysis that was made of the test.[8] Further verification has come from measuring a null lens that was altered to introduce a known error.

The holograms for the 6.5-m mirror were made by a group led by A. G. Poleshchuk from the Russian Academy of Sciences. They use a circular laser writing machine to expose the ring patterns with positional accuracy of 0.1 µm.

The IR null lens was measured with two separate CGH's that were fabricated by the Russian group. The measurements were virtually identical, showing 0.02 λ rms error (at 10.6 µm). The fact that this is nearly 5 times better than the predicted error shows that the refractive index inhomogeneity of the single-crystal germanium lens is much better than expected. After calibrating the null lens with the CGH, we expect the IR measurement to be accurate to 100 nm rms.

**Figure 7.** Measurement of the infrared null lens using a CGH, showing 0.02 λ rms error ( at 10.6 µm) in the null lens.

The CGH for certifying the visible null corrector was also fabricated by Poleshchuk. This 136 mm hologram has about 32,000 rings and was written onto a λ/20 flat. The measurement of the visible null lens, shown in Fig.8, shows null lens errors of 17 nm rms spherical aberration plus 12 nm rms surface irregularity (with spherical aberration removed). This agrees with the null lens tolerance analysis which indicates 22 nm rms spherical aberration and 21 nm rms irregularity.

**Figure 8.** Measurement of the visible null lens using a CGH showing 0.035 λ rms error in the null lens (at 632.8 nm). The residual after removing 0.027 λ rms spherical aberration is 0.019 λ rms.

## Conclusion

The 6.5-m *f*/1.25 primary mirrors are measured accurately using two interferometers with null correctors, one with infrared and the other with visible wavelength light. These systems were independently certified with computer generated holograms. We are now building on this success to develop the test optics for 8.4-m diameter, *f*/1.1 primary mirrors for the Large Binocular Telescope.[9]

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