# Measurement of a convex secondary mirror using a holographic test plate

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## ABSTRACT

A 26-cm diameter aspheric convex secondary mirror was successfully measured using a holographic test plate. This measurement demonstrates the viability of the holographic test plate method for measuring convex aspheres. An optical writer was built and used to demonstrate the ability to write precise holograms on large, curved substrates. The hologram written for this test was fabricated using a thermochemical method that does not require the use of photoresist. The accuracy of the holographic test is demonstrated with a comparison with data from an independent Hindle test.

## 1. INTRODUCTION

A new optical test using holographic test plates is being pursued for measuring secondary mirrors at the University of Arizona. This test, described in another paper in these proceedings,[1] uses a full-aperture test plate with a computer-generated hologram fabricated onto a spherical reference surface. When supported a few millimeters from the secondary and properly illuminated with laser light, an interference pattern is formed that is used to measure shape errors in the secondary mirror. The hologram consists of annular rings of chromium (Cr) drawn onto the spherical test plate surface using a laser writing machine.

A laser hologram writer was designed and built to write the hologram for testing the 260-mm diameter secondary mirror from the current Multiple Mirror Telescope (MMT) located on Mt. Hopkins near Tucson, Arizona. The hologram was written directly onto a Cr-coated substrate using a thermochemical technique. The holographic test of the secondary mirror showed stable fringes with near-perfect contrast. The surface of the secondary was measured to have errors of 44 nm rms. An independent Hindle test was performed which corroborated these results.

## 2. FABRICATION OF HOLOGRAPHIC TEST PLATE

The hologram for this test was fabricated using a laser writer and a thermochemical technique that avoids the difficulties of commonly used photolithographic methods. The rings are defined, one at a time, by focusing a laser beam onto the rotating Cr-coated spherical surface of the test plate. A computer-controlled writing machine is used for control of the radial and axial position and the intensity of the writing beam. The hologram for test of the MMT secondary required 288 chrome rings, with ruling pitch varying from 700 μm near the center to 300 μm near the edge of the part.

## 2.1 THERMOCHEMICAL METHOD OF PATTERN GENERATION

An unconventional technique of thermally selective oxidization is used to transfer the holographic pattern onto the Cr-coated substrate.[2,3,4,5] This method, illustrated schematically in Fig. 1, avoids the use of photoresist, which is difficult to apply and process on the large, steeply curved test plates. To define a ring, the power of the laser beam is adjusted such that it heats, but does not ablate, the Cr coating. The absorbed heat causes the Cr layer to chemically combine with oxygen from the air to form a layer of chrome-oxide ($Cr_2O_3$) in regions exposed by the laser. The thermally induced $Cr_2O_3$ is much thicker that the native oxide typically present on Cr films. After writing the entire pattern, the optic is immersed in an aqueous solution for etching. Since the etching rate of bare Cr is many times that of $Cr_2O_3$, the oxide-coated regions exposed by the laser are protected while the rest of the chrome is entirely dissolved. This leaves a final pattern of chrome that was defined by the writing laser beam.

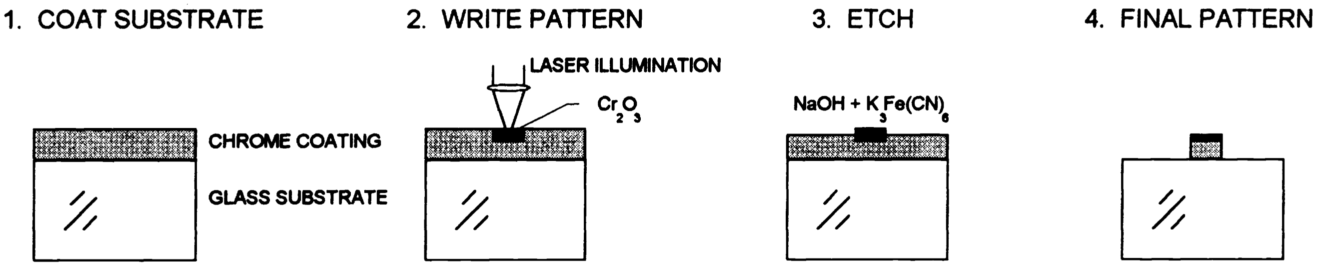

**Figure 1.** Pattern generation using laser induced oxidation.

## 2.2 HOLOGRAM WRITER

To fabricate the holograms, a writing machine that controls the position and intensity of the exposing laser beam was built at the Optical Sciences Center. This machine, shown schematically in Fig. 2, consists of four main components: a 1.2 Watt argon-ion laser used at 0.488 µm, an interferometrically-controlled three-axis stage, a rotary air bearing spindle, and an optical head assembly. The holograms are written on this machine by taking advantage of the rotational symmetry of the holographic pattern and writing the rings sequentially. The hologram writer uses the air-bearing spindle to rotate the test plate at 2 rpm under the focused laser beam. The three-axis stage is used to position the writing beam at the proper radius and to adjust for the correct focus.

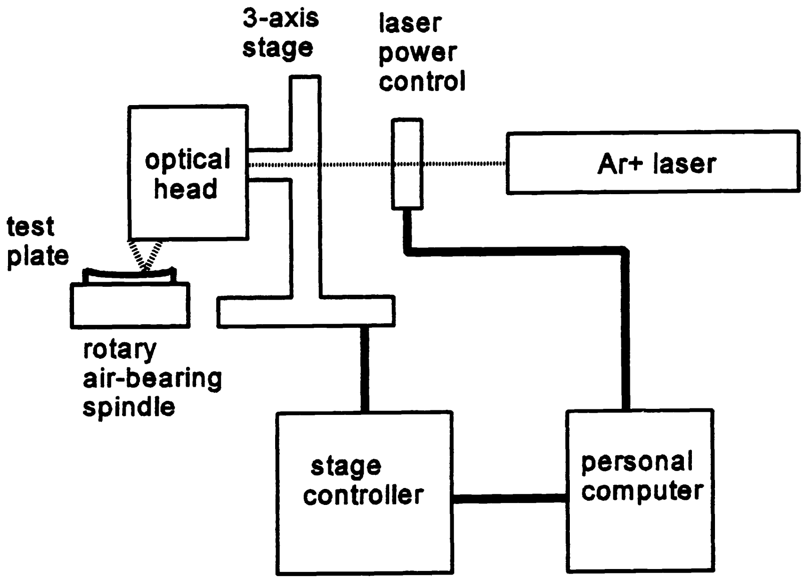

**Figure 2.** Schematic layout of the laser writing machine

Precise control of the laser position and beam power is necessary to make accurate exposures. Stage movement is controlled to precision of ±0.2 µm in three Cartesian axes using feedback from distance measuring interferometers. The precise motion of the stage results from using linear motors and air bearings for the horizontal motion and a drive screw and air bearings for vertical motion. Movement commands originate in a computer that communicates over a digital interface to the stage controller. The laser power is servo-controlled to within 1% of nominal, as monitored by a photodetector on the writer head. An acousto-optic modulator mounted near the output of the laser is used to control the writing power. The laser power settings are communicated through a digital-to-analog converter.

A layout of the optical head assembly is shown in Fig. 3. Collimated light from the laser is first passed through a beam splitter prism. The prism splits off some of the incident light to a silicon detector, which provides the feedback for laser power control. The transmitted light is focused by an objective lens onto the surface of the test plate. Some of the light incident on the test plate is reflected back into the optical system. A portion of this returned light is used for alignment purposes by reflecting off the prism beam splitter and being directed to a CCD camera by a turning mirror. Images from the camera are used to find the center of rotation and to determine when the writing spot is focused on the optic. To determine the vertex position and the tilt of the axis, the laser beam is focused on the surface near the center and at a position near the edge of the substrate. For writing the hologram, the writer follows the trajectory defined by the spherical surface with the known tilt and a desired offset focus. No focus measurement is made during writing. The details of this hardware and the alignment procedure will be published in a subsequent paper.

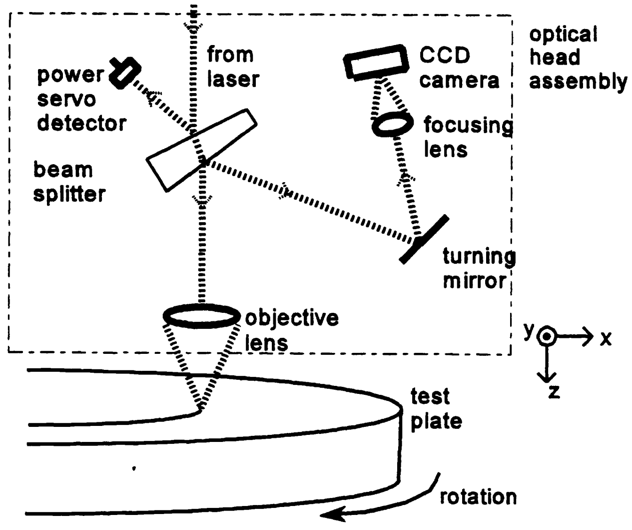

**Figure 3.** Schematic layout of the optical head assembly

## 2.3 FABRICATION OF HOLOGRAM FOR SECONDARY TEST

The hologram for measuring the MMT secondary mirror was fabricated using this writer. The radial locations and width of the rings that form the hologram pattern are contained in a data file. After alignment, the head moves under computer control to the first radial location where a ring is to be written. To write one ring of the pattern, the laser is to turned on during the 30 second rotation cycle of the test plate. After a ring is written, the head moves to the next radial position and the process is repeated.

The width of the rings that formed the hologram pattern for the MMT secondary test ranged from 60 µm to 135 µm. We used a constant focus position of the laser beam that allowed 30 µm wide lines to be written at any radial position during one revolution of the substrate. To write the lines of the required width, we used consecutive traces that overlapped by 15 µm. With this method, rings that had a width of 60 µm were written using three consecutive subrings. The MMT test plate hologram required a total write time of approximately 10 hours during which 288 rings were written. The number of sub-rings contained in the radial ring pattern was 1120.

## 3. MEASUREMENT OF SECONDARY MIRROR

The hologram was used to measure a convex aspheric secondary mirror. The interferometric test of the mirror, shown in Fig. 4, used an aspheric plastic lens for illumination. The secondary mirror was pushed with a piezo-electric transducer (PZT) to allow phase shifting interferometry. The interference pattern had nearly perfect contrast allowing low-noise measurements. A large central region was not tested because the plastic illumination lens had a sharp zone near the center. The 10.25-inch secondary mirror was measured to have a shape error of 44 nm rms, most of which was due to a quarter wave of astigmatism. A synthetic interferogram representing the measured shape of the secondary is shown in Fig. 5.

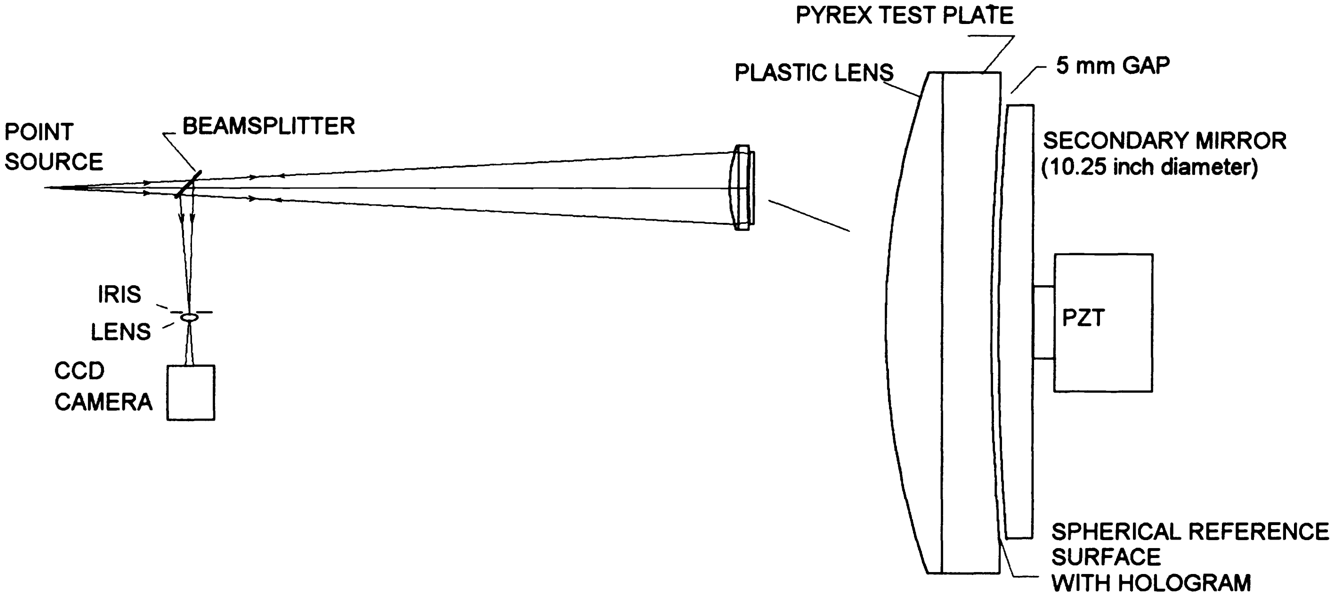

**Figure 4.** Layout of holographic test plate measurement of an MMT secondary mirror.

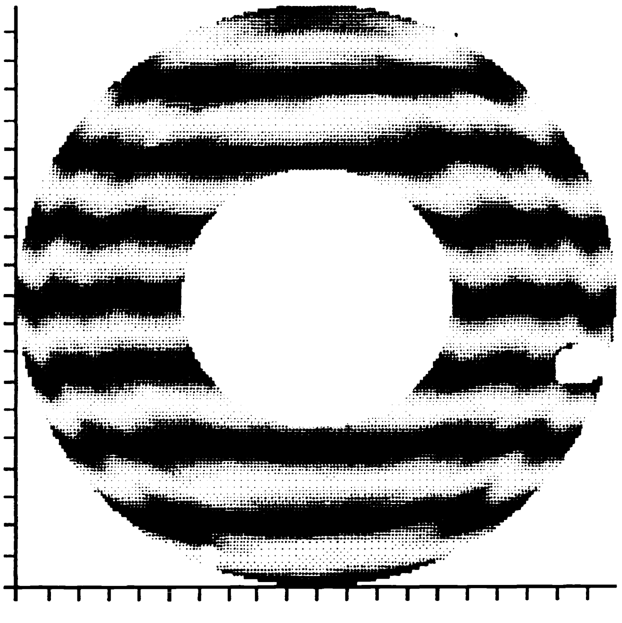

**Figure 5.** Interferogram computed from the holographic test plate measurement of the MMT secondary.

The azimuthal component of the secondary test was determined using a rotation test. Also, the spherical reference surface was measured, using the zero-order diffraction from the hologram, to be 16 nm rms. Most of this error was astigmatism. The azimuthal errors due to the ruling were determined to be 2.9 nm rms (after the removal of 6 nm rms astigmatism), and are shown in Fig. 6. These residual errors appear to originate from regions on the hologram that did not get fully etched.

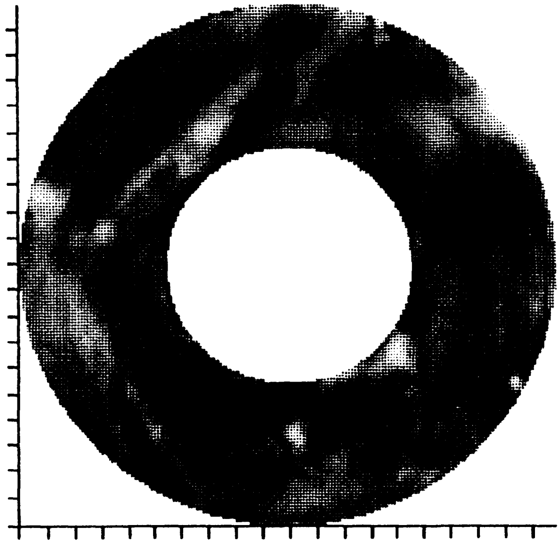

**Figure 6.** Azimuthal component of hologram errors shown in gray scale. This map has 2.9 nm rms variation after removing 6 nm rms astigmatism.

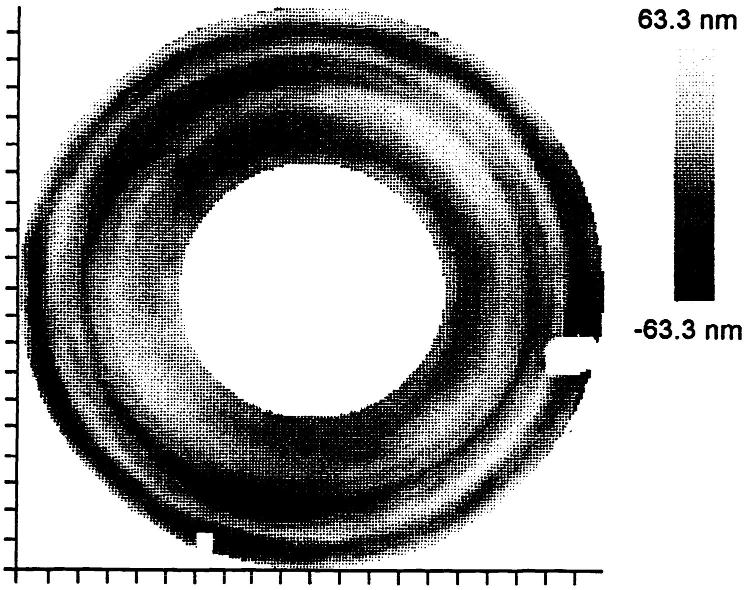

**Figure 7.** Phase map showing figure of the secondary mirror as measured by a holographic test plate. The surface has 19.5 nm rms variation after 35 nm rms astigmatism has been removed.

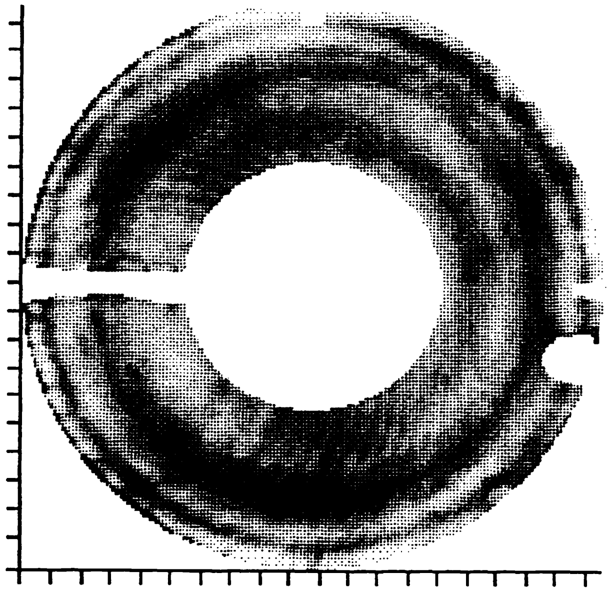

**Figure 8.** Map of the secondary from the Hindle test. This surface map, which closely matches that in Fig. 7, has 20.9 nm rms variation after 41 nm rms astigmatism has been subtracted.

A comparison of the CGH measurement is made with results from an independent Hindle test in Figs. 7 and 8. The astigmatism is removed from these maps because a reference in the Hindle test was astigmatic by an unknown amount, and because it is difficult to see the other features in the presence of the large astigmatism. The two maps differed in astigmatism by 24 nm rms. Even though the Hindle test data is quite noisy due to vibration, air motion, and spurious reflection problems, it provides an excellent confirmation of the CGH measurement.

## 4. CONCLUSION

Optical metrology with holographic test plates has the promise of highly accurate and efficient, yet economical measurements of convex aspheres. We have demonstrated a method for fabricating the holograms that can be used for very large test plates. The accurate measurement of an aspheric secondary mirror using this technique demonstrates that the test performs as expected. This verification gives the confidence needed to implement the test for the large secondary mirrors required by the University of Arizona telescope projects.

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