Demonstration of accuracy and flexibility of using CGH test plates for measuring aspheric surfaces

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ABSTRACT

A method of interferometrically measuring large convex aspheres using test plates with computer generated holograms was developed at the University of Arizona. We present the results from a set of experiments that demonstrate the accuracy, flexibility, and the simplicity of performing the holographic test. A low-cost stand-alone setup was built for implementing this test on a 38-cm convex hyperboloid. A direct comparison of the CGH measurement with results from a classical Hindle test shows excellent agreement. We also demonstrate the unique attribute of this test to measure bare glass surfaces and highly reflective surfaces without making any modifications to the test equipment.

Keywords: optical testing, interferometry, computer-generated holograms, large optics, aspheres.

1. INTRODUCTION

The method of measuring aspheric surfaces using test plates with computer generated holograms was developed at the University of Arizona for measuring secondary mirrors for large telescopes.[1,2] The convex aspheres are measured using full aperture test plates that have concave spherical reference surfaces. The aspheric departure in the mirror is compensated by a computer generated hologram that is fabricated onto the test plate. A facility for manufacturing the holograms and testing convex aspheres up to 1.8 meters in diameter was built at the Steward Observatory Mirror Lab.[3,4] The holographic test is ideal for the giant secondary mirrors because other measuring techniques are prohibitively expensive at this scale. But the holographic test is certainly not limited to large aspheres.

A low-cost system was built to demonstrate the benefits of holographic testing for medium sized convex aspheres. This paper describes this system and compares CGH measurements of a 38-cm hyperboloidal mirror with data from a classical Hindle test. We also demonstrate the tremendous range of the holographic test that allows measurement of both bare glass surfaces and surfaces with highly reflective coatings. No modifications need to be made when switching between bare glass and coated optics.

There are several important advantages to measuring convex aspheres as small as 100 mm using the CGH test:

1. **Accuracy** – The high accuracy of the test is a result of the quality of the hologram and the spherical reference surface. Both can be easily made to achieve $\lambda/100$ accuracy for the measurement of fast aspheres.
2. **Economy** – The hologram and the test plate are made at low cost. The additional optics to perform the test do not need to be of interferometric quality and can be made quickly and economically.
3. **Efficiency** – The CGH test is easily performed and has very little noise from vibration or air motion because the interference cavity is only a few millimeters.
4. **Flexibility** – The holographic test allows general aspheres to be tested. Classical testing methods require the mirrors to be conic sections of revolution. The same holographic test can be used for measuring both bare glass surfaces and mirrors with highly reflective coatings.
5. **Maturity** – The fabrication of the holograms and the implementation of the test have now been demonstrated on 5 convex aspheres from 25 cm to 1.2 meters in diameter.

2. INTERFEROMETRY USING CGH TEST PLATES

Convex spherical surfaces are commonly measured with matching concave test plates. When the test plate is supported near the convex optic and illuminated with sufficiently coherent light, fringes of interference show the shape difference between the two parts. The shape of the concave master sphere may be measured independently from its center of curvature. In a similar manner, convex *aspheric* surfaces may be tested using matching concave aspheric test plates. The obvious difficulty with this method is the requirement of making and measuring a concave master asphere for each convex optic.

The holographic test simplifies this by using a test plate with concave spherical surface, which is easy to manufacture and measure. The aspheric departure of the secondary is compensated by diffraction from a circular computer-generated hologram (CGH) or zone plate that is fabricated onto the concave spherical reference surface of the test. The test is performed by supporting the holographic test plate a few millimeters from the secondary mirror and illuminating with laser light (see Fig. 1). The interference pattern is viewed through the test plate and imaged onto a CCD camera for analysis. By pushing the test plate, phase shifting interferometry is used to obtain high resolution data.

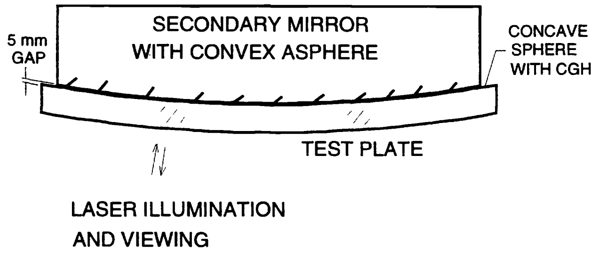


Figure 1. Layout of holographic test of a secondary mirror. The test plate has a reference spherical surface with a ring pattern drawn onto it.

The holographic test uses the interference between a reference and a test wavefront to determine the shape of the convex optic. Light diffracted from the hologram on the spherical surface forms the reference wavefront and light reflected from the secondary forms a test wavefront (see Fig. 2). The test plate is illuminated with light that is transmitted to strike the secondary mirror at normal incidence for all points on the mirror. This light reflects back onto itself to form the test wavefront. The reference wavefront is formed by diffraction from the ring pattern on the reference sphere. The CGH is designed to diffract this reference beam to match an ideal test wavefront, so this beam also retraces the incident path.

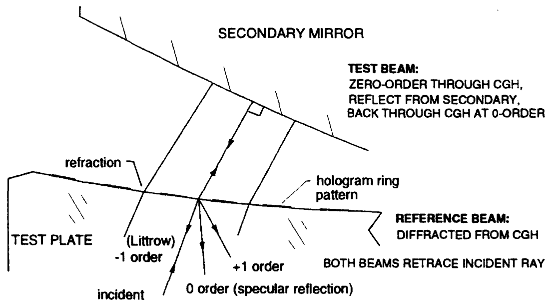


Figure 2. Definition of reference and test wavefronts. The reference beam diffracted from the hologram interferes with the test beam reflected from the secondary.

To perform a measurement, laser light from a point source is expanded. The reflected wavefronts converge to a conjugate image point, where an aperture blocks undesired orders of diffraction. It is important to note that the reference and test beams are coincident everywhere except in the air gap between the CGH and the secondary. So errors in the illumination optics, including refractive index variations in the test plate are common for both wavefronts and do not affect the measurement. This allows low-quality optics to be used for every part in the test except for the spherical reference surface.

The design of the holographic test is divided into the hologram design and the illumination optical system design. The hologram designs involve calculating the ring positions to give the desired phase of the reference wavefront and fixing the width of the rings to match the amplitudes of the test and reference beams. The illumination system is designed to force all the rays to hit the secondary at normal incidence and must allow a distortion-free image of the secondary at the camera plane. The techniques for designing these systems are given in detail elsewhere.[5,6]

The wavefront diffracted by the hologram must include power so that different orders of diffraction will come to focus at different axial positions. A stop at the correct position is used to isolate the desired diffracted order. The size of this stop is determined largely by the quality of the illumination optics. The design of the test for the 38-cm optic allows errors in the illumination optics that correspond with slopes of $\pm$ 1 milliradian (mrad) at the hologram.

The ring positions are placed to control the phase of the reference wavefront and the width of the rings is used to control the relative amplitudes of the test and reference wavefronts. Generally the duty cycle (ratio of line width to pattern period) of the rings is picked to match the intensities of the test and reference wavefronts, giving a high contrast interference pattern. Both reference and test beams are modulated by the hologram, and the far-field distribution is calculated using Fourier techniques. Figures 3 and 4 below show the calculated diffraction efficiencies and fringe contrast for the hologram and test beam as functions of duty cycle. The pattern for the 38-cm mirror was written with 30% duty cycle, which gives good contrast for bare glass and coated surfaces.

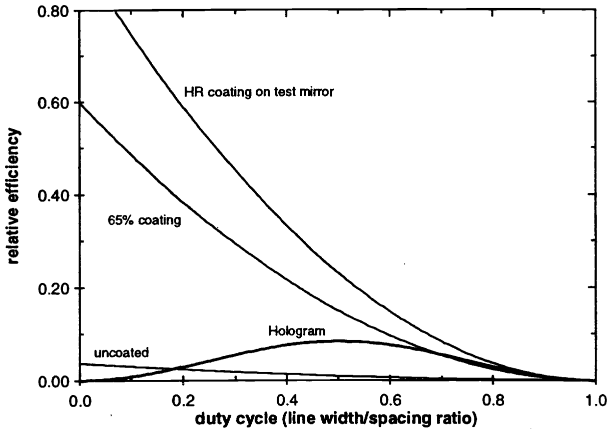


Figure 3. Diffraction efficiency for the reference beam (hologram) and for three different test surfaces: uncoated, with 65% reflective coating (like spray silver or chrome), and with 100% reflective coating.

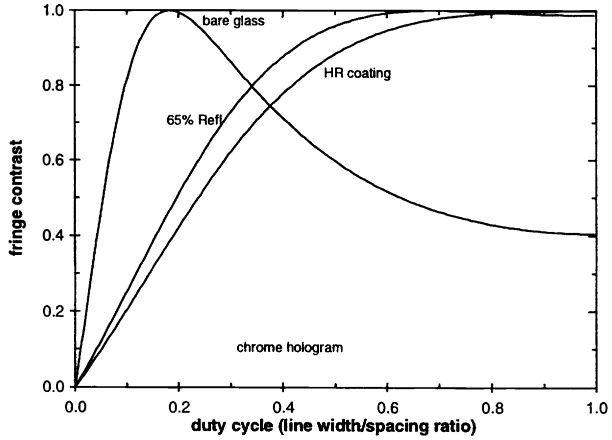


Figure 4. Fringe contrast calculated from the efficiency shown in Fig. 3. The hologram for the 38-cm mirror was written with 30% duty cycle.

3. IMPLEMENTATION OF CGH TEST FOR 38-cm ASPHERE

The system for measuring the 38-cm mirror was built onto a stand-alone frame shown in Figs 7 and 8. The aspheric mirror is supported with its convex mirror surface facing up on a 5-axis adjustable stage. The fused silica holographic test plate is supported 5 mm above the asphere. Mounted in the same cell as the test plate, an acrylic lens is used for illuminating the test. A 20-cm flat mirror folds the beam into a box that has the laser and CCD camera.

The hologram design for the 38-cm test achieves a good balance between separating the diffraction orders without making the hologram fabrication overly difficult. Plots of the wavefront shape and the ring spacing are shown in Figs. 5 and 6 for the CGH test of the secondary mirror for the 38-cm mirror. The dashed curves show the effect of changing power in the holograms. Since power is always a free variable in the design, it would be possible to use designs corresponding to these dotted curves.

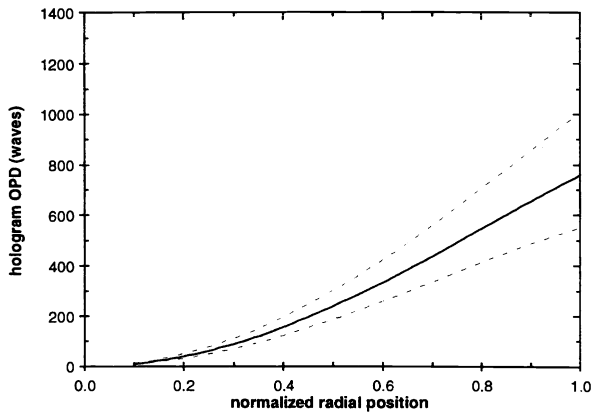


Figure 5. Variation of optical path function defined by hologram with radial position for different amounts of focus.

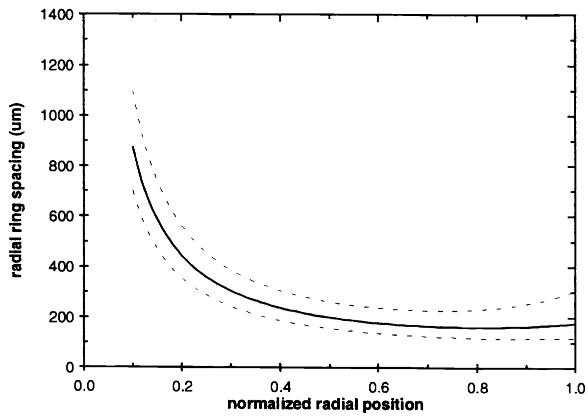


Figure 6. Center to center ring spacing as function of radial position for different amounts of focus.

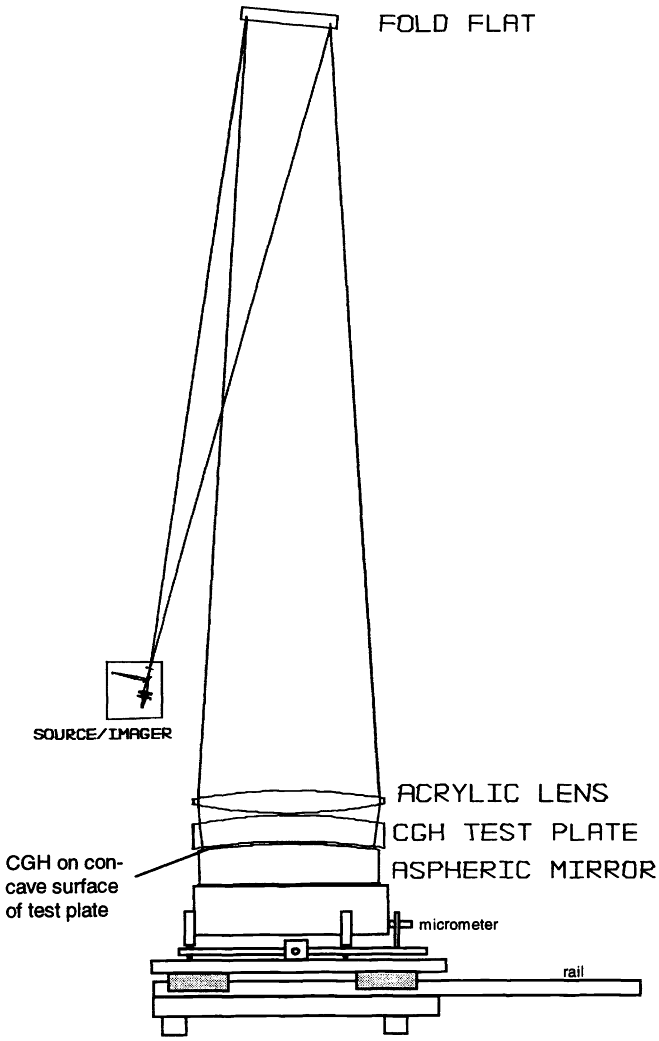


Figure 7. Optical layout of test system for 38-cm mirror, showing optics and edge rays. The whole stand is about 8 feet tall.

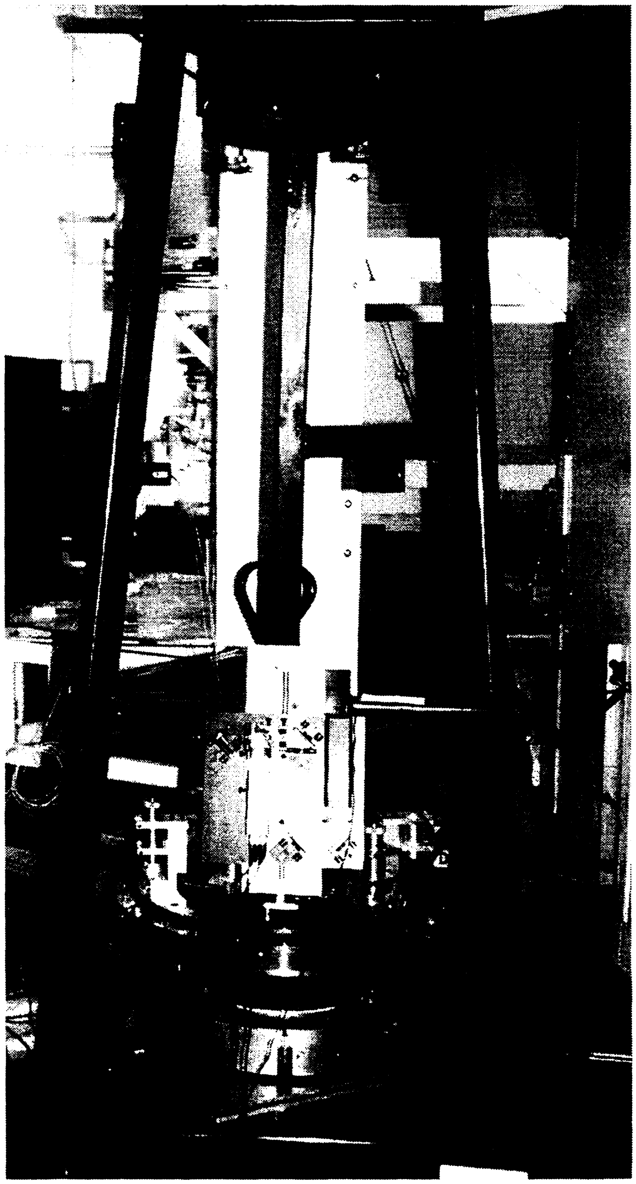


Figure 8. Test system for 38-cm mirror. The tripod supports a 20-cm fold flat. The test plate and acrylic lens are mounted in a cell that can be rotated 360° with respect to the test mirror.

The fused silica test plate and the acrylic lens are both supported in a single 400 mm barrel. The barrel is pushed with three PZT's to allow phase shifting interferometry. The entire cell can also be rotated 360° to allow measurements of the asphere with the test plate at different angular orientations. The fine alignments for testing are made with the 5-axis system that supports the secondary mirror. This system uses micrometers for positioning of the secondary in lateral (x-y) and axial (z) translation and tilting about lateral axes. The system uses two stacked linear translations for x and y motion. The secondary itself rests on a foam pad on a rigid aluminum support. This support is held by a tripod of three micrometers. The combination of tip, tilt, and z motion is made using these three adjustments. This system is adequate to align the test, but it is not optimal. To adjust focus, all three screws must be turned the same amount.

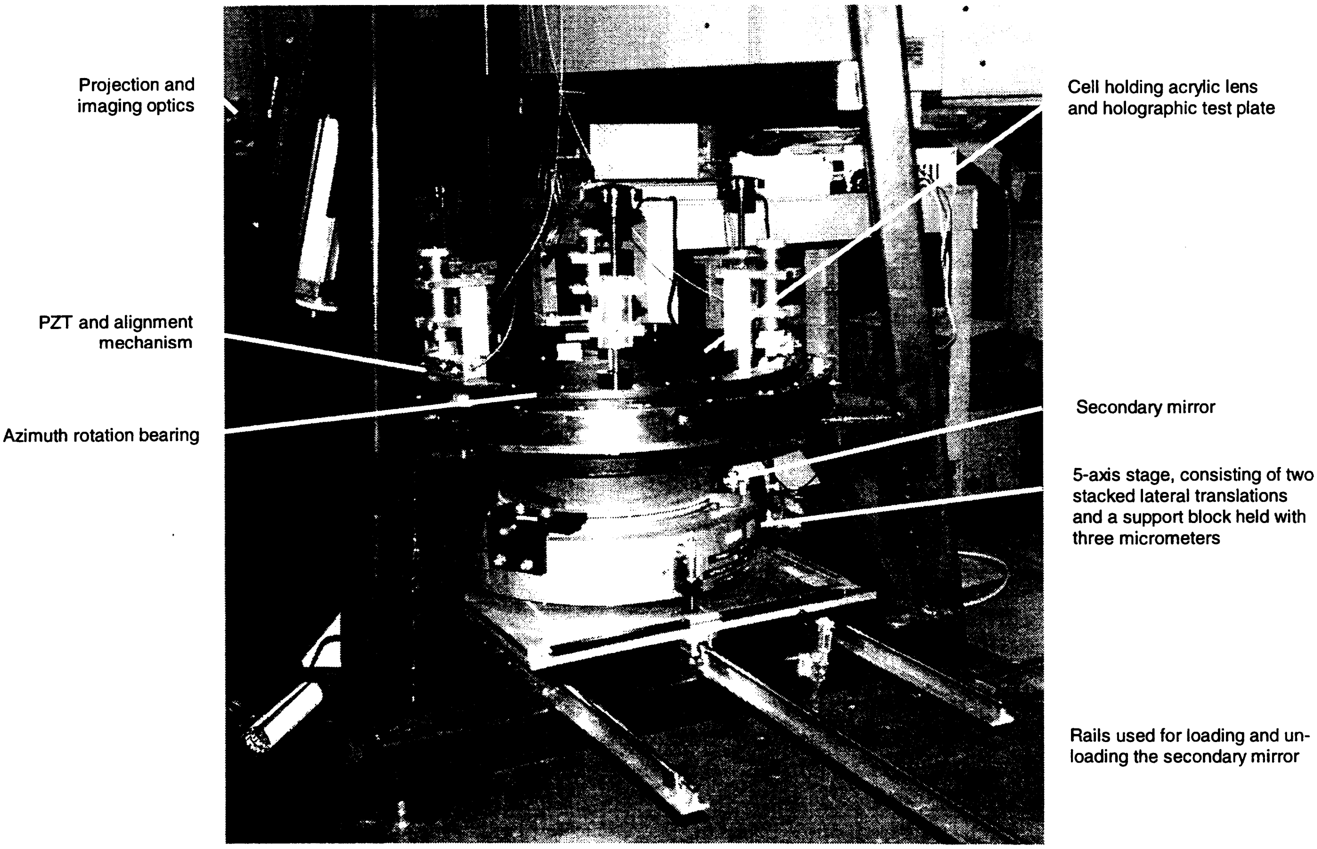


Figure 9. Base of test system showing mounting details.

A simple optical system was built to project the laser beam and to split off the return light and image it onto a CCD camera. This system, shown in Fig. 10 was mounted to a translation stage on the tripod. A HeNe laser is expanded, reflected off a beamsplitter and brought to focus at the order selection aperture. It goes through this iris, reflects off the fold flat and illuminates the holographic test. Both return wavefronts, reference and test, are brought to focus at the order selection aperture. This iris passes the correct orders of diffraction but blocks the inappropriate orders which are out of focus. The return light is transmitted by the beamsplitter and imaged onto a CCD camera.

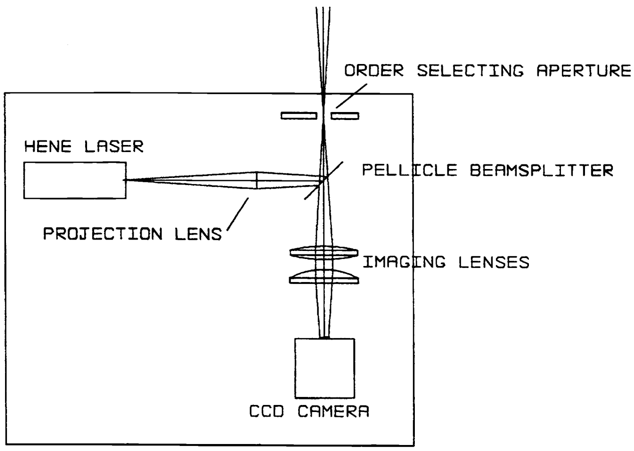


Figure 10. Layout of projection and imaging optical system.

The alignment of the test is surprisingly easy. First the projection and imaging optics were aligned in the box shown in Fig. 10. Then the hologram was aligned by tip/tilt of the cell and of the flat mirror. This was done to create a good image at the order selection iris. Then the aspheric mirror was aligned coarsely using the 5-axis positioner to get the test beam through the iris. Then the fringes were used to guide fine alignment of the asphere. The mirror was moved to eliminate fringes of tilt, focus, and power from the interferogram. Then surface measurements were made using phase shifting interferometry.

Table 1. Parameters for the holographic test of the 38-cm secondary mirror.

Diameter of secondary mirror	376 mm
Clear aperture for secondary mirror	353 mm
Secondary mirror radius of curvature	1360.55 mm
Secondary mirror conic constant	-1.6899
Amount of 4^{th} order aspheric departure in secondary	105 μm
Secondary mirror blank	Solid fused silica
Gap between CGH test plate and secondary mirror	5 mm
Radius of curvature of test plate reference surface	1401.9
Test wavelength	0.63283 μm
Number of rings in hologram	730
Hologram duty cycle	0.30
Test plate	Fused silica 400 mm diameter 57 mm thick

4. FABRICATION OF HOLOGRAM

The hologram was written at the University of Arizona using the large computer-generated hologram writer built at the Steward Mirror Lab. This machine writes binary zone plates onto spherical surfaces up to 1.8 meters in diameter and with focal ratios as fast as *f*/1. It writes 6 μm to 150 μm wide zones with radial position accuracy better than 1 μm rms over the full diameter. Several holograms up to 1.2 meters across have been successfully written and tested.

Circular patterns are optimally fabricated using polar coordinate machines that expose rings by rotating the substrate under a fixed writing beam. The hologram accuracy depends on the quality of the rotation bearing, the ability to control the radial position of the writing beam, and the ability to locate the center of rotation. This geometry has been used by several groups for writing accurate zone plates onto small, flat substrates.[7,8,9] The unique machine at the University of Arizona achieves high accuracy using laser interferometers, active control for laser beam drift, a rigid athermal support frame, and a temperature controlled enclosure.

We avoid the use of photoresist by writing the image directly onto a chrome film with a laser beam using a thermo-chemical effect shown in Figure 11 and described more completely elsewhere.[10] The laser exposes the chrome by heating it, which causes an oxidation layer at the surface. After writing the complete pattern and creating this oxide latent image, the optic is immersed into a caustic bath that dissolves the bare chrome preferentially to the chrome oxide. So after developing, a pattern of chrome remains where the laser had exposed the surface and created the oxide layer.

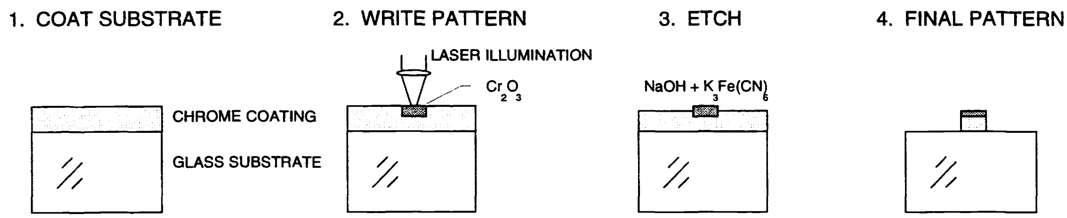


Figure 11. Pattern generation using laser induced oxidation.

The procedure for writing the holograms is to first align and calibrate the machine so that the metrology is accurate, the servos are properly tuned and the beam shape is optimized. Then the substrate is mounted, centered and leveled, and the center of rotation is defined. A small test pattern is written outside the clear aperture to help define the target writing power. The hologram is written, generally starting on the outside. When the writing is finished, we verify the center of rotation to measure any shifts that may have occurred during writing.

The computer generated hologram for the 38-cm mirror was written on a 40 cm diameter fused silica substrate. The pattern consists of 730 rings varying in width from 50 to 130 μm over an annular region with 38 cm OD and 4 cm ID. The hologram was generated with 30% duty cycle to allow testing of both bare glass and coated surfaces.

The hologram is shown in Fig. 12. The reflection from the chrome shows up light in this picture. The rings near the center and outside are test patterns that were written to calibrate the laser power required for an optimal exposure. The dark shapes near the edge are fiducial marks that were used for alignment.

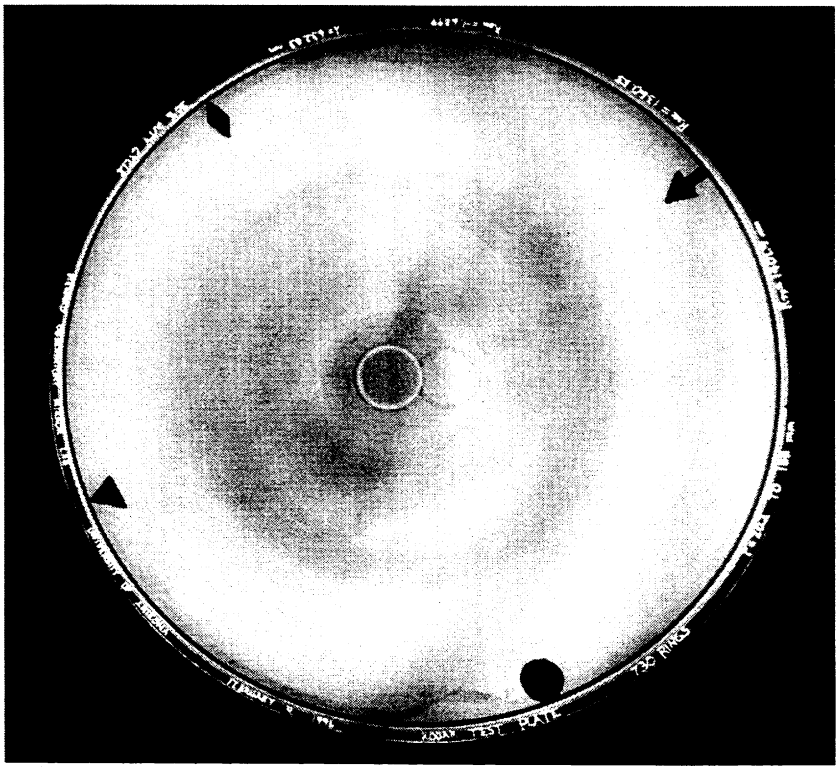


Figure 12. Photo of computer generated hologram.

5. MEASUREMENT OF THE ASPHERIC SURFACE

A holographic measurement was compared with results from a classical Hindle test of this mirror, verifying the accuracy of the holographic test. Also, the mirror was successfully measured holographically with the optical surface uncoated, spray silvered, and with a high reflectance coating.

The secondary was manufactured at Kodak using a Hindle test. This test configuration is shown in Fig. 13 with the convex optical surface looking upward. The Hindle sphere is interferometrically calibrated *in situ* and its 0.06 λ rms figure error is removed from each measurement. The convex secondary was measured in four 90° orientations with 8 averages from interferograms each. The interferograms were reduced by digitizing and using standard fringe center evaluation techniques. With this test and evaluation technique, we feel that we know the large-scale figure of the convex secondary to 0.005 λ rms. This method does lose information on the high frequency figure errors.

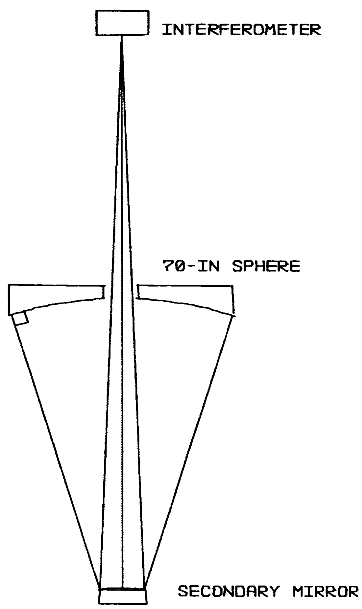
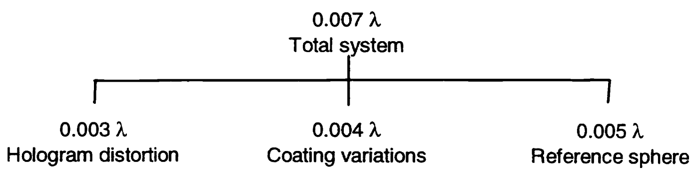


Figure 13. Hindle test for 38-cm mirror.

The 38-cm mirror was measured at the University of Arizona using the holographic test plate described above. Measurements were made with the test plate rotated to 12 positions 30° apart and averaged. The 0.013 λ rms figure of the test plate was measured and subtracted from the data. Since the interference in this measurement is between two surfaces that are only 5 mm apart, this test sees very little effect of vibration or air motion. A detailed tolerance analysis of the CGH test of this mirror indicates measurement accuracy of 0.007 λ rms.

Summary of error budget



The data from these two measurements are compared below in Figs 14 - 16. The excellent comparison of feature size and placement can be seen in the gray scale of the surface maps plotted in Figs. 14 and 15. Both are shown with the same scale.

Figure 14. Measurement from CGH test plate, showing 0.028 λ rms figure errors, plotted in gray scale with 100 nm P-V.

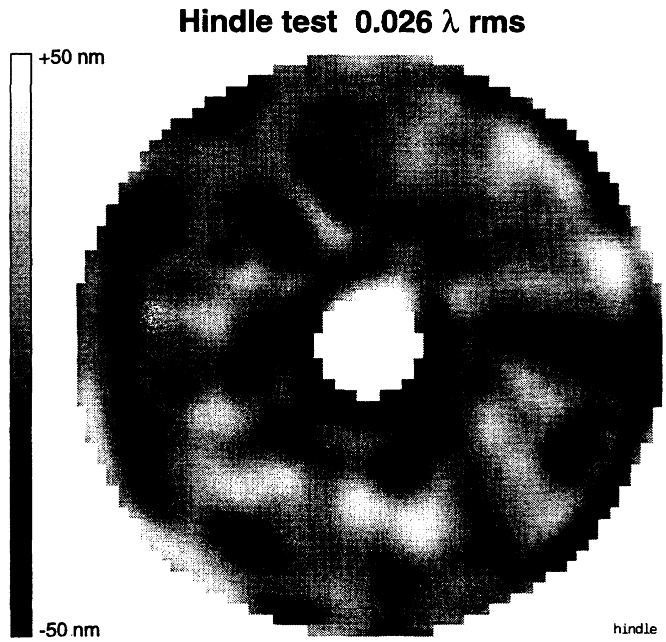


Figure 15. Measurement from Hindle test, showing 0.026 λ rms figure errors, plotted in gray scale with 100 nm P-V.

A direct subtraction of these two maps was attempted to quantify their differences. This difference map is limited by two effects in the data processing. The Hindle test used fringe tracing which has the result of smoothing the data, so the sharp features appear slightly reduced in magnitude and broadened. A second effect that limits our comparison is the ability to overlay the two data sets exactly for subtraction. This effect can be seen in the difference map where figure errors appear which look like the derivative of the surface maps.

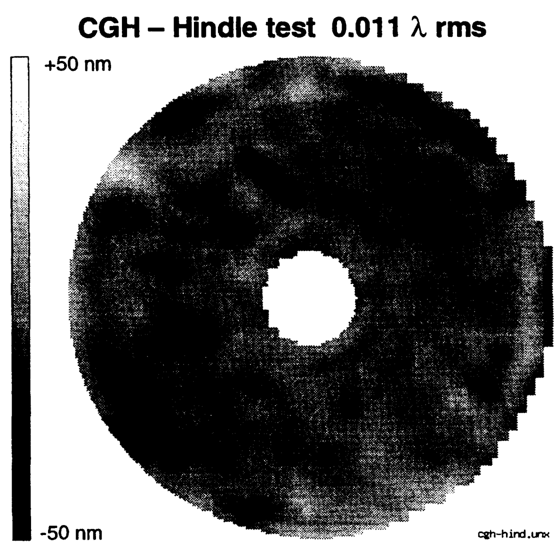


Figure 16. Subtraction of Hindle measurement form CGH measurement, showing 0.011 λ rms difference, plotted in gray scale with 100 nm P-V.

6. MEASUREMENT OF SURFACES WITH REFLECTIVE COATINGS

As described above, the amplitudes of the diffracted light can be controlled by adjusting the duty cycle of the holograms. We demonstrated this with a set of experiments on 1-inch substrates, with interferograms shown below in Figs. 17 – 19. Holograms with different duty cycles were used to measure bare glass, chrome coated (R = 65%), and highly reflective (R>99%) coated surfaces. The results confirm the theoretical models shown in Figs. 3 and 4. They also show that the interferograms give high quality sinusoidal fringes, even for testing with the highly reflective coatings. The test of the secondary described in this paper was made using a hologram with 30% duty cycle.

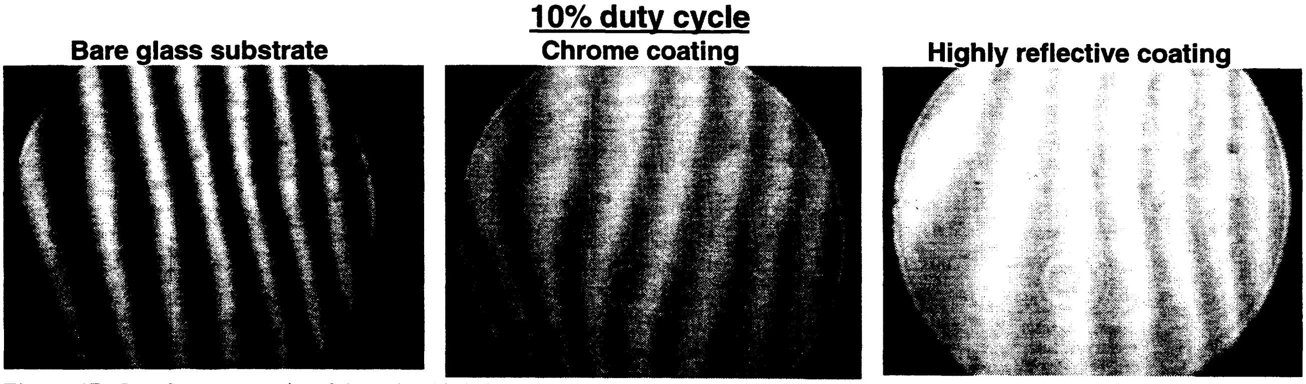


Figure 17. Interferograms using CGH with 10% duty cycle. This pattern gives good contrast for the bare glass substrate, but is poorly suited for measuring the coated surfaces.

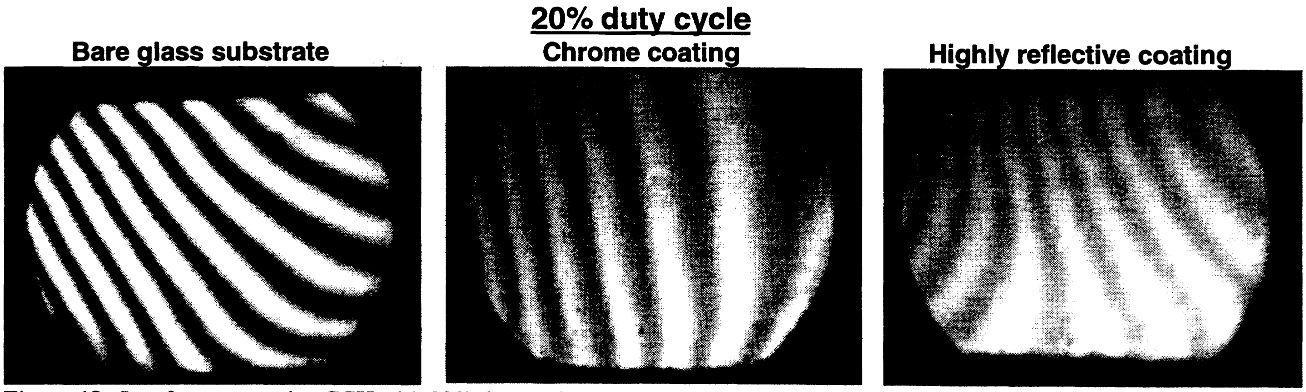


Figure 18. Interferograms using CGH with 20% duty cycle. This pattern gives perfect contrast for bare glass surfaces, but it still does not work well for measuring the coated optics.

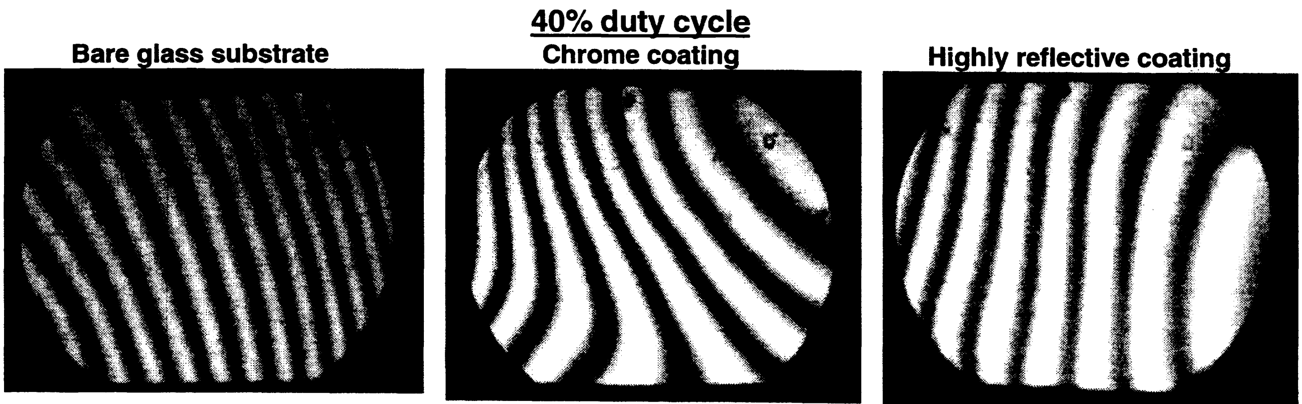


Figure 19. Interferograms using CGH with 40% duty cycle. This shows good fringe visibility for all surfaces.

The 38-cm mirror was measured uncoated, with a spray silver coating, and with a highly reflective (> 99%) coating. The holographic test was set up at Kodak's facility in Rochester and demonstrated to work extremely well for all three cases. The data below show photos of interferograms and phase shift measurement from measuring the bare glass and the highly reflective surface. Unfortunately, when these measurements were made, the pellicle beamsplitter was damaged, which resulted in artifacts in the data.

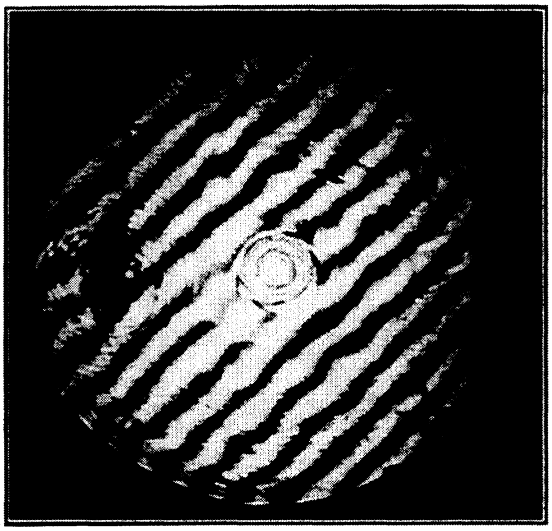


Figure 20. Interferogram from the bare glass surface of the 38-cm mirror. A damaged beamsplitter caused the irregularities in the image.

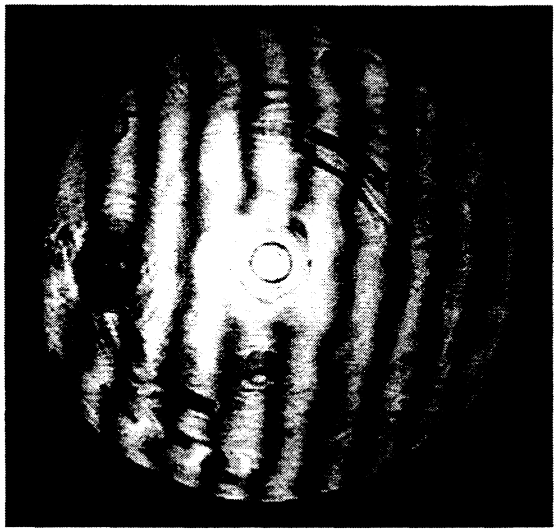


Figure 21. Interferogram from the 38-cm mirror with a coating giving it > 99% reflectivity. A damaged beamsplitter caused the irregularities in the image.

The phase measurements of these surfaces were virtually identical, showing 0.039 λ rms for the reflective coating and 0.036 λ rms for the bare surface. Both measurements show low-order errors that are attributed the figure of the test plate as it was supported for these tests. After subtracting these low order errors, both surface measurements match the data shown in Figs. 14 and 15.

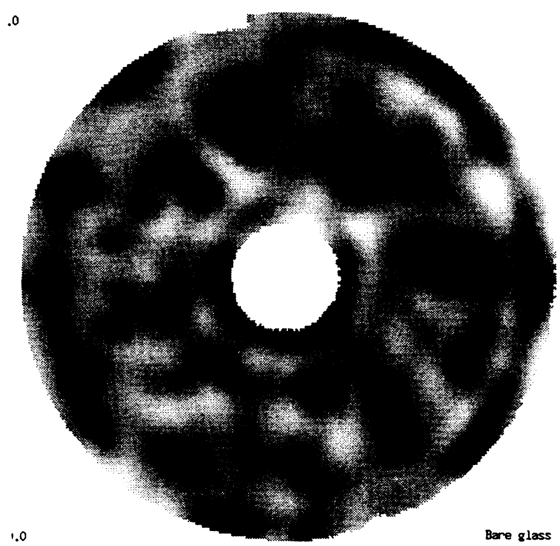


Figure 22. Phase map from measurement of bare glass surface, showing 0.028 λ rms figure errors.

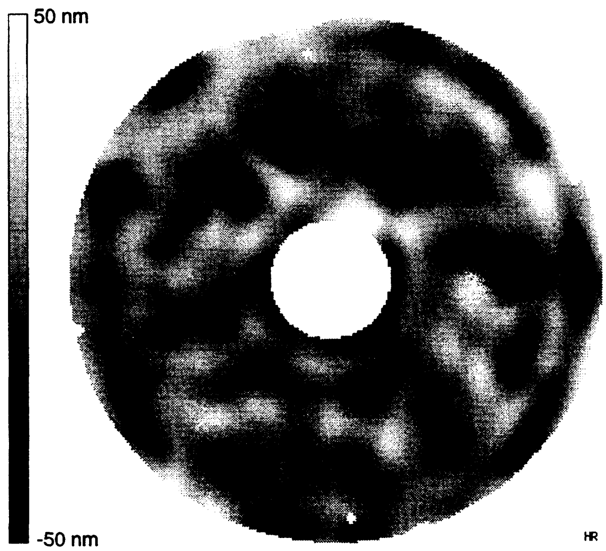


Figure 23. Phase map from measurement of highly reflective coated surface showing 0.027 λ rms.

7. CONCLUSION

We have demonstrated the advantages of using interferometry with CGH test plates for measuring convex aspheres. This successful demonstration, along with other tests at the University of Arizona, have given us the confidence to rely on the holographic tests for mirrors in production.

8. ACKNOWLEDGMENTS

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