Invited Paper

Applications of computer-generated holograms for interferometric measurement of large aspheric optics

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ABSTRACT

Interferometric optical testing using computer-generated holograms (CGH's) has proven to give highly accurate measurements of aspheric surfaces. New applications of CGH interferometry were developed to support the fabrication of the large, steep mirrors required by the next generation ground-based telescopes. A new test to certify null correctors was designed and implemented that uses small CGH's fabricated onto flat substrates. This test solves the difficult problem of verifying the accuracy of the null correctors that are used for measuring primary mirrors. Several new techniques for hologram fabrication have been explored for this application. A second new use of CGH's was developed for measuring convex secondary mirrors using test plates with holograms fabricated onto concave spherical reference surfaces. This test provides efficient and accurate measurement of large aspheric convex mirrors. A polar coordinate laser writing machine was built for fabricating these patterns onto curved optical surfaces up to 1.8 meters in diameter and as fast as *f*/1. These powerful new techniques have been implemented and optimized at the Steward Observatory Mirror Laboratory to guide mirror polishing for large telescope projects. They can be also be readily applied for measuring small aspheres to high accuracy.

Subject terms: Computer-generated holograms, interferometry, optical testing, asphere

1. INTRODUCTION

It is well known that the use of aspheric surfaces in optical systems allows improved performance with fewer elements. The performance of these systems depends on the ability to figure, and ultimately the ability to measure aspheric surfaces. The mirrors for large, fast telescopes require surfaces that depart from the nearest spherical shape by hundreds of waves, yet they must be accurate to a small fraction of a wavelength. To achieve the required figure, the mirrors must be measured using techniques that are accurate to a hundredth of a wave. Interferometry using computer-generated holograms has been demonstrated to provide these measurements for large concave and convex optics.

Computer-generated holograms are extremely powerful for interferometric measurement of aspheric surfaces because the holograms can change a wavefront into virtually any shape the computer can specify. The holograms, which consist of patterns of lines or rings, are now readily manufactured using equipment from the microelectronics industry and new circular writers optimized for hologram fabrication.

This paper reviews and classifies CGH testing and presents two new applications of circular CGH's that were developed and implemented at the Steward Observatory Mirror Laboratory to support the production of large, highly aspheric telescope mirrors. We discuss hologram fabrication and present new methods of making holograms using conventional microlithography equipment as well as custom-built polar coordinate hologram writers.

0-8194-1937-0/95/$6.00

2. OPTICAL TESTING WITH COMPUTER-GENERATED HOLOGRAMS

Computer-generated holograms are used in optical testing because they accurately diffract laser light to give virtually any phase distribution. Interferometry measures the phase difference between two wavefronts, one affected by the test optic, the other a reference wavefront with a known shape, typically spherical. CGH's are used for measuring aspheric optics by altering the test wavefront, the reference wavefront, or a combination of the two, so the two wavefronts are identical.

Optical testing of aspheric surfaces using computer-generated holograms has been used for many years.[1] A hologram is generally used to modulate the phase or amplitude of a wavefront, causing it to propagate to form a desired phase front or intensity distribution. A photographically produced hologram is used to store and play back an existing wavefront. Synthetic holograms are specified by a computer and written with an electronic plotter. Computer-generated holograms for optical testing usually consist of patterns of curved lines drawn onto or etched into glass substrates. These patterns act as diffraction gratings that use variations in the spacing to control the slope of the diffracted light. Material properties and duty cycle control the amplitude. A simple way to think of the hologram at *m*th order is that it adds *m* waves to the phase for each line in the ruling. The amount of light in the *m*th order is predicted using Fourier theory. Since the measurements use only the phase of the diffracted light, accurate control of the amplitude is not important.

It is straightforward to compute the effect of hologram distortion, which limits test accuracy. The hologram used at m^{th} order adds *m* waves per line, so the phase error due to a line shift is

$$\Delta W(x,y) = -m\lambda \frac{\varepsilon(x,y)}{s(x,y)} \tag{1}$$

where $\varepsilon(x, y)$ = CGH position error in direction perpendicular to ruled fringes
$s(x, y)$ = local center-to-center ruled fringe spacing
$\Delta W(x, y)$ = wavefront phase error due to pattern distortion at position (x, y) on CGH.

The holograms for optical testing are designed so that light in a single order of diffraction gives the desired phase relationship when isolated from the other orders. The holograms must be designed and manufactured with some "carrier" that serves to fully isolate light in the desired order, which is passed through a spatial filter that blocks the other orders. The tests are usually designed so that the minimum carrier frequency is used to fully separate the order because the errors caused by hologram distortion vary inversely with the spacing. Most holograms use tilt, or straight lines, as the carrier to fan the orders laterally. In the case of testing axisymmetric optics with annular pupils, it is easier to use power as the carrier. This type hologram consists of a ring pattern that spreads the orders out axially, bringing them to focus at different places along the axis. The use of circular holograms for optical testing has been demonstrated by several groups,[2, 3] and comparisons between testing with circular and tilt carrier holograms show that circular holograms are better suited for some applications.[4, 5] There are several advantages to using rotational holograms for testing axisymmetric optics. By preserving the axial symmetry, the hologram design, analysis, and fabrication is reduced from two dimensions to one. The symmetry allows direct certification of the hologram by measuring ring diameters.

Interferometric testing of concave aspheric optics is commonly performed using a single- or multi-element null lens that corrects the wavefront from the test optic to match the reference wavefront, giving a null interferogram.[6] The interferometer measures the combination of the null lens and the asphere, so the accuracy of the test depends on the quality of the null lens. A schematic drawing of a typical configuration for measuring an aspheric mirror using a null lens is shown in Fig. 1.

A common configuration for using a CGH for optical testing is shown in Fig. 2.[7] The CGH is placed at an internal image of the test optic and both the test and reference beams go through the hologram. The diverger lens may produce either a spherical wavefront or a partially compensated aspheric wavefront. The hologram is designed based on a ray trace simulation of the entire system. This allows errors in the diverger to be compensated by the hologram. This configuration is advantageous because both beams travel through the hologram together, minimizing the sensitivity to surface figure and refractive index inhomogeneity of the hologram substrate. Also if the hologram is used in collimated light, the alignment requirements are greatly reduced.

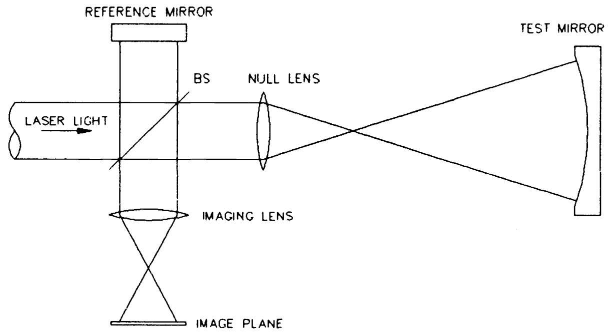


Figure 1. Test of an asphere using a null lens.

There are numerous other configurations for measuring aspheres with CGH's. The most common use of a CGH is in the test arm of the interferometer. Here the hologram acts as an element in a null lens (see Fig. 3). This technique is used for measuring mild aspheres with existing Fizeau interferometers.[8] To assist alignment precise fiducial marks or reference holograms may be fabricated outside the clear aperture. Since light diffracts twice from the hologram, it is important that these elements are made to achieve fairly high diffraction efficiency. A chrome-on-glass pattern yields only 10% efficiency, which results in 1% for the CGH used as a null lens (light must diffract twice from this element). The diffraction efficiency for each pass is improved to 40% by phase etching the hologram.

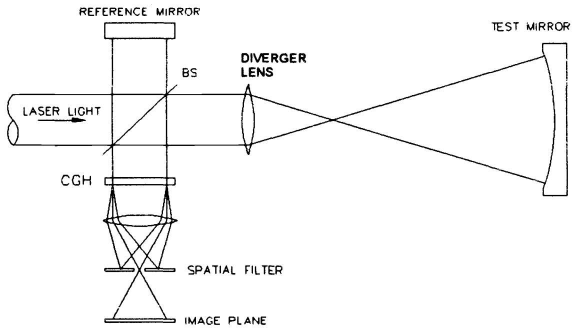


Figure 2. A common implementation of CGH for measuring an aspheric optic.

The CGH may also be used in the reference arm of the interferometer, as shown in Fig. 4. This hologram must add exactly the aberration expected from the test arm (assuming a perfect test optic). A convenient configuration uses the hologram in reflection to replace the reference mirror.

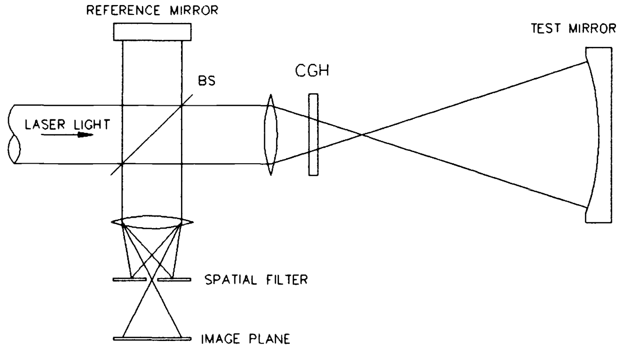


Figure 3. Optical measurement using CGH as null lens.

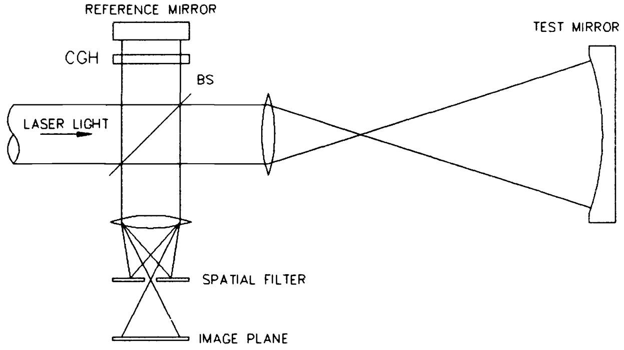


Figure 4. Optical measurement using CGH in reference beam.

The hologram may also be used as the beamsplitter of the interferometer that separates and recombines the reference and test wavefronts. Two tests using this configuration are the zone plate interferometer and the holographic test plate, shown in Figs. 5 and 6. Similar to the scatterplate interferometer, the zone plate interferometer achieves stability by focusing the reference beam onto the test optic.[9,10] The CGH test plate uses a Fizeau interferometer with the hologram on the reference surface.[11] Typically, the hologram alters the reference reflected wavefront and simply passes (0 order) the test wavefront. This new test is described in detail in Section 4.

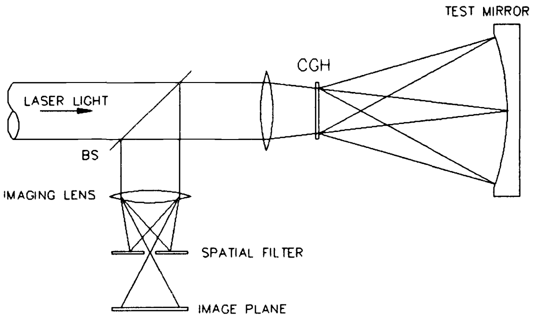


Figure 5. Zone plate interferometer.

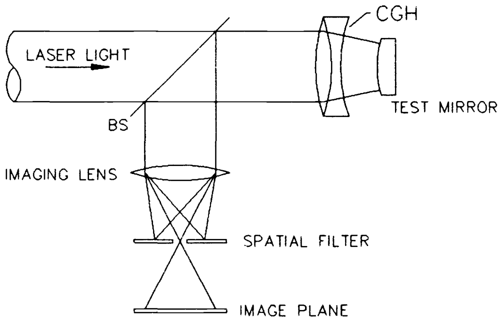


Figure 6. CGH test plate.

A final configuration for CGH testing uses a hologram to certify a null lens directly by using a CGH that exactly duplicates the phase reflected by a perfect aspheric optic.[12] These holograms are unique because they are used generally at the *focus* of the aspheric light rather than near a pupil. This application is described more fully in Section 3.

3. CERTIFICATION OF NULL CORRECTORS WITH CGH'S

In fabricating an asphere, the optical surface is polished to precisely match results from the measurement. In the event of a measurement error, the final shape of the optic will be incorrect. Two recent telescopes had flaws in their primary mirrors because of errors in the null correctors used to measure them -- the Hubble Space Telescope[13] and the European New Technology Telescope[14]. If accurate testing of the null correctors had been performed, the errors would have been discovered and corrected in the shop. Instead, the errors were not discovered until the finished mirrors were operational in their telescopes.

In the CGH null lens test, the test asphere is replaced by a computer-generated hologram located at the paraxial focus of the aspheric wavefront. The hologram is made so it will appear to the null corrector as if it were a perfect aspheric mirror. The test is easy to perform to high accuracy for several reasons: it is a null test, it is insensitive to alignment errors, and no optics other than the hologram are required.

The CGH certification for the measurement of a 6.5-m primary mirror[15] is shown in Fig. 7. No modifications are made to the null lens for performing this test; the null corrector tests the hologram in exactly the same manner used to test a primary mirror. The alignment of the test is surprisingly simple. Since the CGH appears to the null corrector as a complete primary mirror with the correct shape, the alignment of the hologram is exactly like that of the actual primary. The CGH is positioned at paraxial focus of the light from the null corrector. Once the CGH is near the correct position, the shape of the fringe pattern in the interferometer is used to align the hologram. It is shifted laterally to eliminate tilt, axially to eliminate power, and tilted to eliminate coma. Thus the hologram is insensitive to precisely the same errors as the test of the mirror, but it has no ambiguity in the measurement of spherical aberration and other errors caused by misalignment

The holograms are designed to give 4% diffraction efficiency into the desired order. This matches the intensity reflected off the bare glass reference surface, giving a high-contrast interference pattern. A pinhole positioned near the Shack cube rejects the stray orders of diffraction and passes only the desired order. The size of the pinhole is optimized so that image of the mirror is free from spurious orders, but the spatial frequency cutoff caused by the aperture is acceptable.

The shape of the phase function created by the hologram looks conical with little slope change over most of the CGH (see Fig. 8). This fortunate shape allows the CGH to work

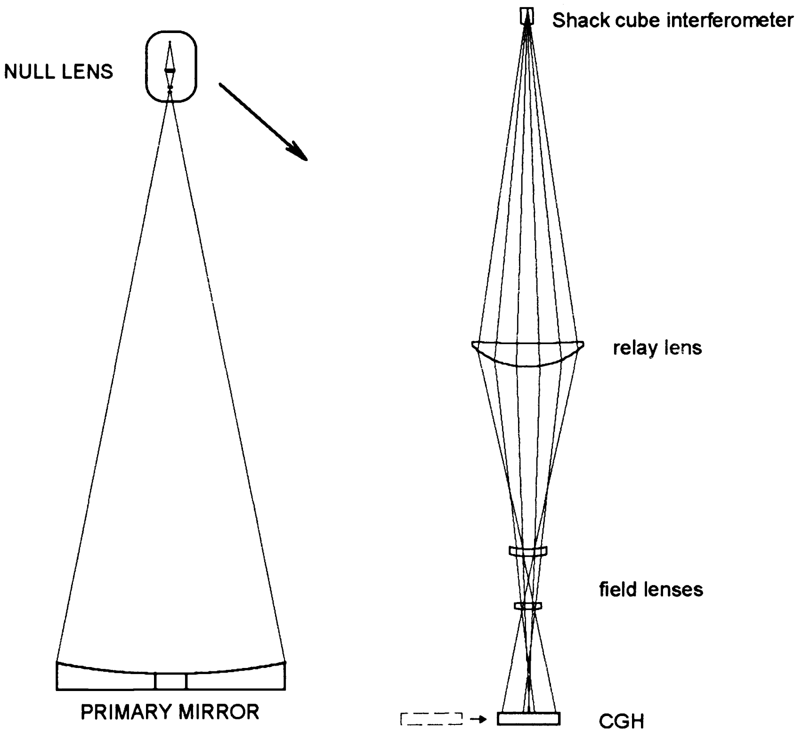


Figure 7. Layout of CGH test of the null lens for a 6.5-m primary mirror.

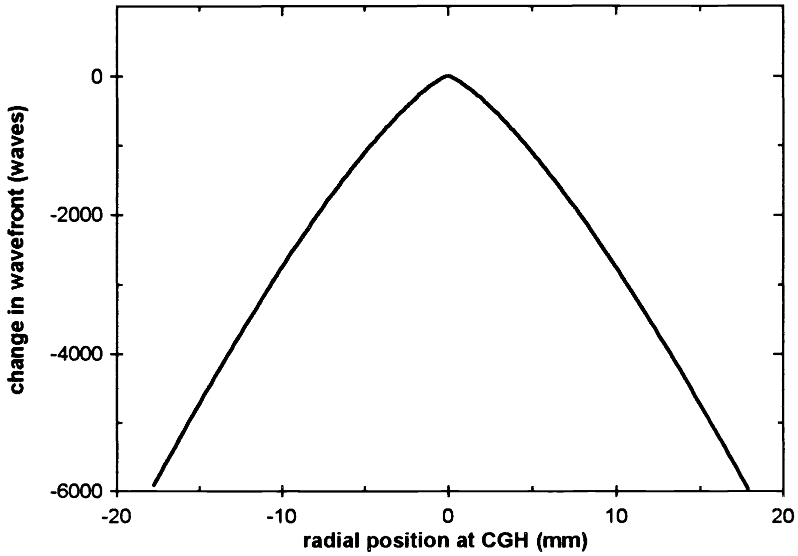


Figure 8. Wavefront phase function for a CGH made for certifying the null corrector for a 3.5-m $f/1.75$ primary mirror.

with no carrier at all. The radial slope in the wavefront itself is sufficient to act as a circular carrier with ring spacing nearly constant over most of the hologram.

The CGH null lens test has been demonstrated to certify the conic constant of null tests to better than 0.01% and has been use to measure and remove figure errors as small as 5 nm rms. These measured results, shown in Fig. 9, confirm a detailed error analysis that was made of the test.[16] Further verification came from measuring a null lens for a 3.5-m mirror that was altered to introduce a known error. Within the measurement uncertainties, the measured spherical aberration matched that predicted by a ray trace simulation of the null lens.

Note that an error in the CGH would not result in an error in the shape of the primary mirror. It would result in a discrepancy between the CGH and the null lens that would have to be tracked down to determine which was in error. The CGH design is based directly on the shape of the primary mirror, not the null lens, so it gives a fully independent test of the null lens.

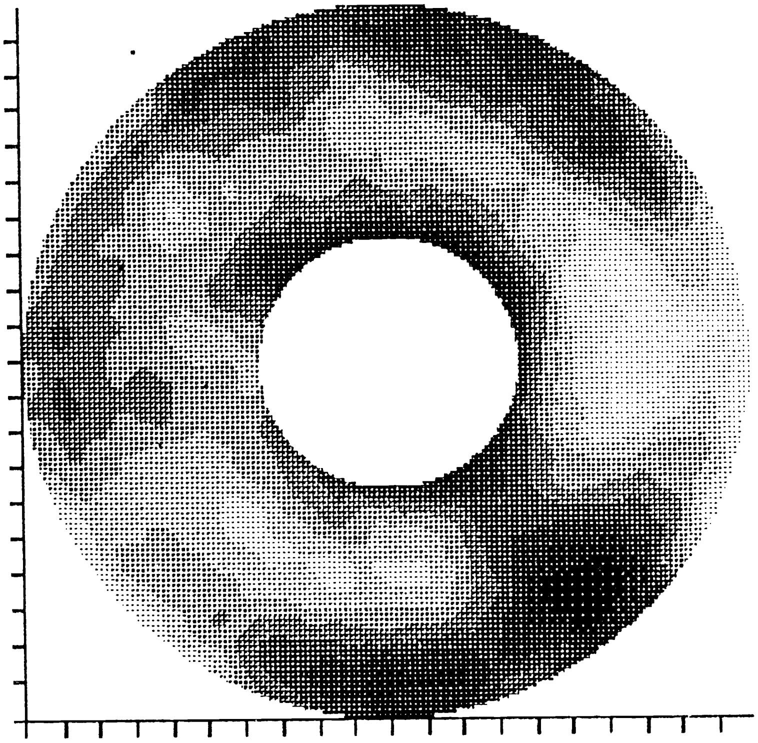


Figure 9. Contour map showing measured error of 0.0085 λ rms for a null lens used to measure a 3.5-m primary mirror. The surface errors are plotted with contours at λ/200 intervals over a full range of λ/20 (at 632.8 nm).

The difficulty with this test has been fabricating high-quality holograms. The holograms are used in reflection, so the surface figure must be excellent. Small patterns, up to 40 mm, have been successfully made by contact-replicating an e-beam-written mask onto an ultra-flat substrate. However, larger patterns with less than 3 μm features have suffered local distortion from the printing. The effects in the interferogram appear as small phase steps that make the null lens measurement impossible. The fabrication errors are not well understood, and we have not studied this problem because we have neither the equipment nor the expertise in microlithography.

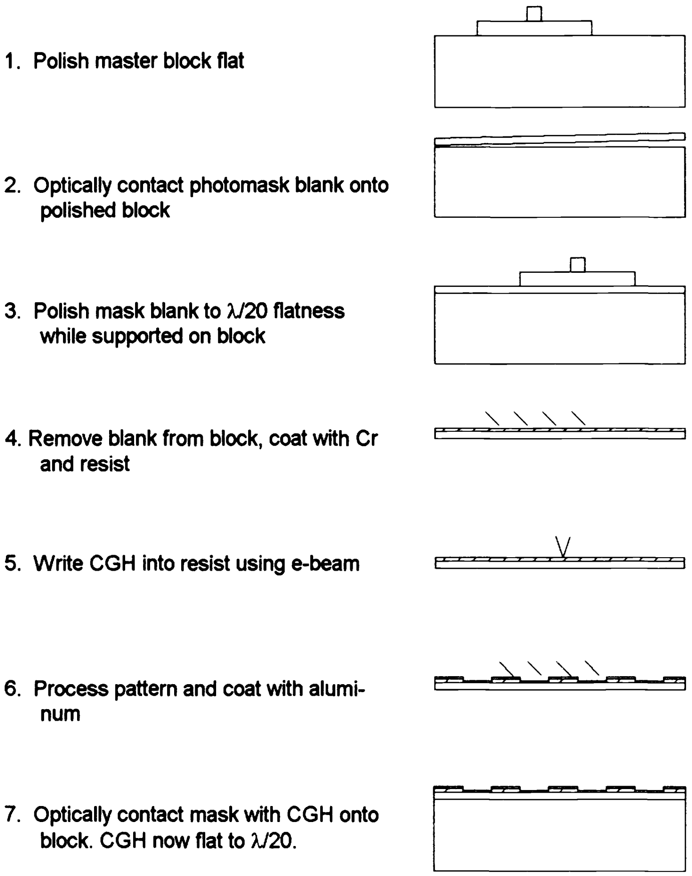
The replication errors can be avoided by eliminating the printing step from the fabrication process. This may be done by writing the hologram onto its final substrate with the e-beam writer, so that no transfer of the pattern is required. Since the flatness of the hologram surface is critical, special substrates must be prepared that are flat to λ/20. The substrates must be coated, e-beam written, and etched. Unfortunately, the e-beam writers will only accept standard size substrates that are very thin and are difficult to polish to such precision. The standard 4009 substrate is 100 mm square and only 2.3 mm thick, so it deflects according to its support forces.

Dave Anderson at Steward Mirror Lab worked out a technique, shown in Fig. 10, to get around this problem. The thin substrates are mounted onto a master flat that is thick enough to hold its figure when simply supported. The van der Waals forces hold the back surface of the thin hologram substrate to be in intimate contact with the reference surface of the thick master.[17] This is a common technique, referred to as optical contacting or direct bonding, that opticians use for holding thin optics. The front surface of the hologram substrate is then polished to λ/20 as it is supported on the contact block. When removed and placed back on to the master flat, the surface repeats its flatness.

To fabricate the hologram, the flat substrate is removed from the master block, coated with chrome and photoresist, and written by the e-beam writer. When removed from the master block, the figure is no longer flat. This does not affect the fabrication of the CGH: the commercially available "ultra flat" substrates are only flat to 2 μm. After processing the resist and possibly etching and coating the surface, the substrate with the hologram is contacted back onto the master block to regain its figure for use in the measurement.

This technique was demonstrated using a 4009 substrate with a 50 mm hologram consisting of a straight line ruling with 5 μm center-to-center spacing. The hologram substrate was polished to a figure of 0.007λ rms and was contacted, removed and recontacted several times, causing figure changes on the order 0.003λ. It was processed, etched, and coated to form the final hologram. It was then contacted back onto the master flat to recreate the original flatness. The +1 and -1 orders were measured using a Fizeau interferometer. The average of these two measurements gives the surface figure to be 0.011 λ rms. Using the difference between the two measurements, the diffraction errors from distortion in the hologram were determined to be 0.003 λ rms. Thus, this technique was proven to yield accurate holograms.

A second fabrication technique avoids the use of an e-beam writer altogether by using polar-coordinate laser writers that were built for writing circular holograms directly onto the thick substrates. This fabrication method is described in Section 5.



1. Polish master block flat
2. Optically contact photomask blank onto polished block
3. Polish mask blank to λ/20 flatness while supported on block
4. Remove blank from block, coat with Cr and resist
5. Write CGH into resist using e-beam
6. Process pattern and coat with aluminum
7. Optically contact mask with CGH onto block. CGH now flat to λ/20.

Figure 10. Technique for fabricating ultra-flat holograms on standard substrates by contacting to a rigid master reference block.

4. MEASUREMENT OF CONVEX ASPHERES USING CGH TEST PLATES

Traditional techniques for measuring steep convex aspheres are difficult and expensive because they require large, high-quality auxiliary optics. The difficulty measuring convex secondary mirrors for astronomical telescopes has led to the development of a new holographic test that is highly accurate, efficient, and economical.

The classical Hindle test[18] for a hyperboloidal surface, shown in Fig. 11, uses the fact that a point source at one focus is imaged to a perfect (virtual) point at the other focus. A spherical wave interferometer is placed at the first focus, *f1*. The light reflected from the hyperboloid diverges as a spherical wave centered on the second focus point *f2*. A spherical mirror centered on this point reflects the light back on itself to the secondary and to the interferometer as a spherical wavefront. The drawbacks to this test are the requirement of a large, fast, accurate sphere, and its sensitivity to vibration and air motion due to the long path lengths.

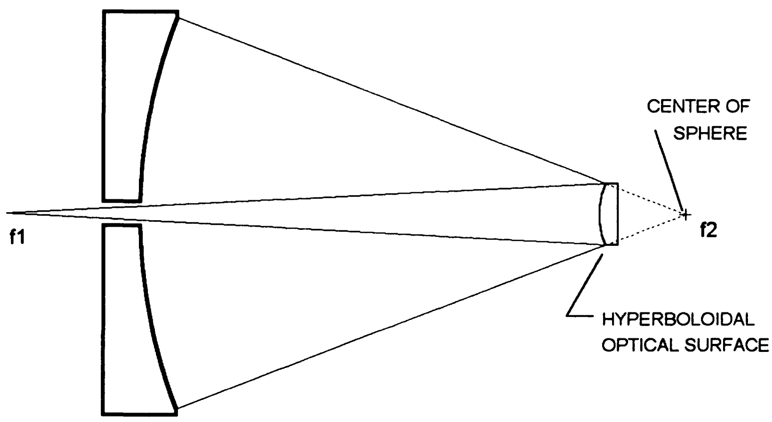


Figure 11. Hindle test of a hyperboloidal optic.

Several other tests for convex aspheres are shown in Fig 12. The Hindle shell uses the same principle as the test described above, but this test uses a spherical shell held close to the asphere. Since the test wavefront must travel through this optic, variations of refractive index in the glass limit the test. Convex aspheres may be tested using test plates with matching concave aspheric surfaces. As a Fizeau test the glass quality is not critical because both the reference light and the test light travel through the glass together. The cost and difficulty fabricating and testing the concave asphere limit the use of this test. Convex aspheres made of solid glass may be measured using a null lens looking through the back of the blank. Refractive index inhomogeneity limits the application of this test to small mirrors. Also, convex optics can be measured mechanically using a profilometer. It is costly and extremely difficult to obtain optical accuracy with such an instrument.

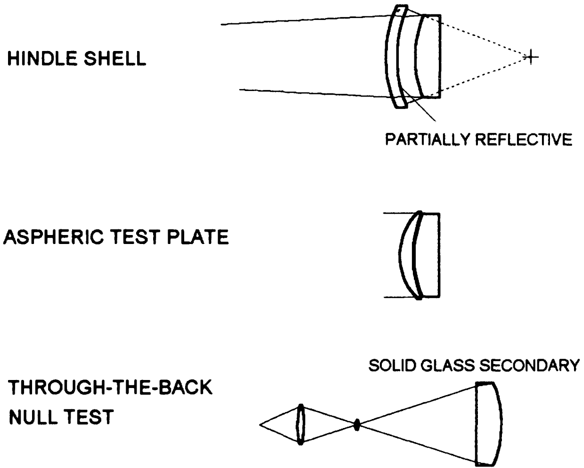


Figure 12. Other optical tests for convex aspheres.

A new interferometric test has been developed to allow efficient and accurate testing of highly aspheric convex optics. This test is a hybrid of two optical measurement techniques, Fizeau test plate interferometry and the use of computer-generated holograms. The aspheric optics are measured using spherical test plates with computer-generated holograms, as shown in Fig. 13. The holograms, consisting of annular rings of chrome, are written onto a concave spherical reference surface. The positions of the rings are chosen to give the desired shape of the diffracted wavefront, and the width of the rings is controlled to give high fringe visibility. The test is performed by supporting the holographic test plate a few millimeters from the asphere and illuminating with laser light. The interference pattern is viewed through the test plate and imaged onto a CCD camera for analysis. By pushing the secondary mirror or the test plate, phase shifting interferometry is used to obtain high resolution data.

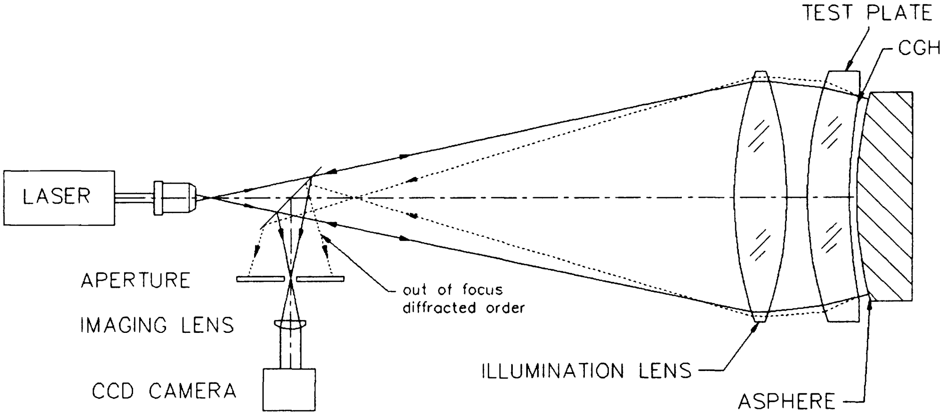


Figure 13. Configuration for CGH test plate measurement of a convex asphere.

The large optics required for this test are the test plate and the illumination optics. The test plate is only slightly larger than the test asphere. It has a concave spherical reference surface and does not require high quality glass. The illumination optics must be slightly larger, but the quality need not be high since this is a Fizeau test. Errors in the illumination system affect the test if they are larger than the separation of the orders of diffraction, causing the orders to overlap in the interferogram. Ray slope errors of up to 1 mrad from the illumination optics are typically permitted. The illumination optics generally need to have one low-quality aspheric surface to meet this specification.

The benefits of this test over existing methods of measuring convex aspheres are its inherent accuracy, the efficiency, and the overall cost. As a Fizeau test, this is a differential measurement between a reference surface and the optic being tested that are separated by a short distance, typically 5 mm. This short path length minimizes errors due to illumination, vibration, and seeing. Unlike the Hindle shell test or the use of a null lens looking through the back surface, refractive index variations in the large optics do not affect the measurement. The accuracy of the test is limited only by the quality of a concave spherical surface and the accuracy of the ring locations. Both are readily made and verified to high accuracy. The reference surface is a concave sphere, so its figure can be readily measured from the center of curvature using the zero-order from the hologram. Since the test of the asphere is not affected by vibration and seeing, it is quickly performed without struggling to control the environment. The alignment of the test is easily accomplished by moving the test plate to null the fringe pattern. A measurement of the full aperture, with hundreds of points across the diameter, can be made to nanometer precision in a few minutes.

The holographic test uses the interference between a reference and a test wavefront to determine the shape of the convex optic. 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 test wavefront passes through the hologram twice at 0 order, so it is not deflected by the hologram. The reference wavefront is formed by the -1 diffraction order 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. The test beam and the reference beam coincide everywhere in the system except in the gap between the secondary and the test plate. This configuration is shown in Fig. 14.

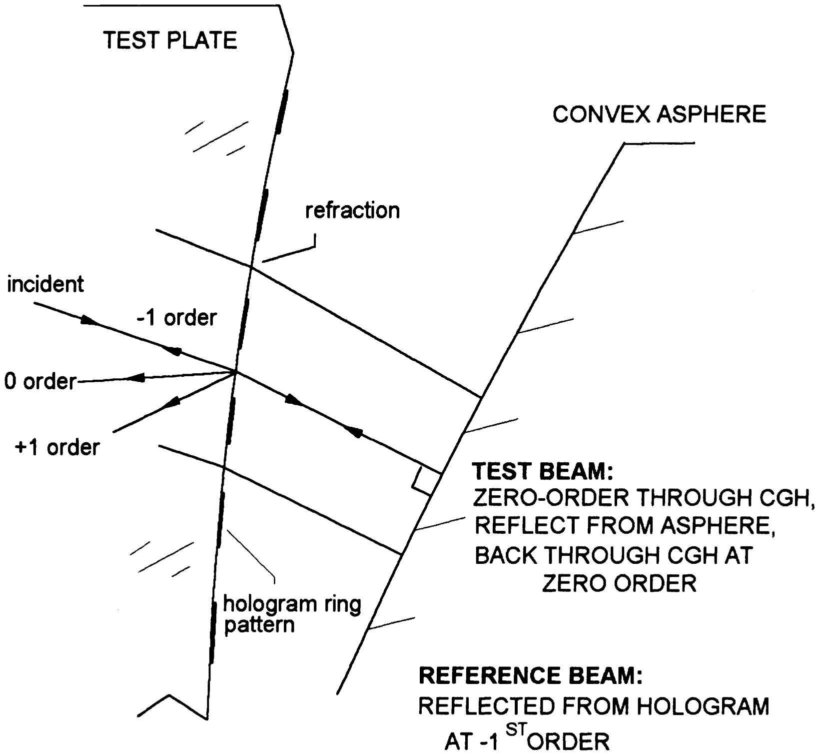


Figure 14. Definition of wavefronts for CGH test. A reference beam diffracted from the hologram interferes with a test beam reflected from the asphere.

A second optical configuration, shown in Fig. 15, uses the asphere in transmission and uses only the reflected-diffracted wave from the test plate. Since this test requires only diverging illumination, it is more economical for solid glass aspheres. The illumination system consists of a low quality null lens, similar to that used for the through-the-back null lens test of the asphere.

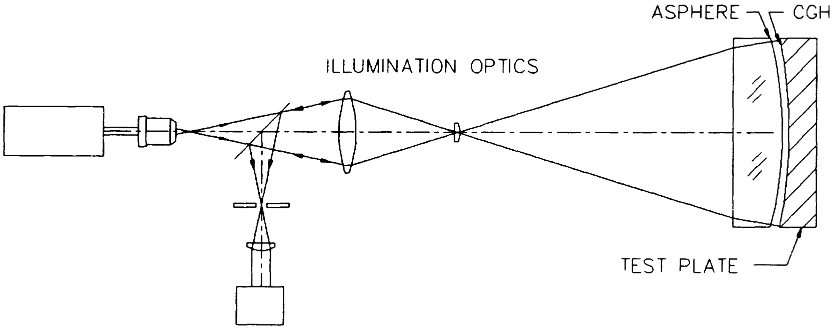


Figure 15. Alternate configuration for CGH test of convex aspheres.

The separation of the orders of diffraction requires a trade-off in the design of the test. Large errors in the illumination optics can be tolerated if a large amount of power is built into the CGH, which causes the orders to be widely separated. However, more power in the CGH requires more rings with tighter spacing, which makes the hologram more difficult to fabricate. A compromise between these two effects led to hologram designs for secondary mirror testing that allows slope errors of 2 mrad without causing any order leakage. Even for a perfect illumination system, the aperture may not be made arbitrarily small because the stop acts as a low-pass spatial filter on the surface measurement. For coherent illumination, the spatial frequency cutoff of the filter is derived using Fourier optics[19] as

$$\xi_c = \frac{\theta_f}{2\lambda} \tag{2}$$

where ξ_c = spatial frequency of cutoff (cycles per meter at mirror)
θ_f = full angular size of aperture, as viewed from the secondary (radians)
λ = wavelength of light (m).

So a 2 mrad wide aperture gives 1700 cycle-per-meter resolution.

A 260 mm secondary mirror from the Multiple Mirror Telescope on Mt. Hopkins was successfully measured using a holographic test plate.[20] The hologram, consisting of 300 rings with spacing varying from 700 μm to 250 μm, was fabricated on a prototype hologram writer at the Optical Sciences Center at the University of Arizona. The interferometric test of the secondary mirror used an aspheric plastic lens for illumination. The secondary mirror was pushed with a PZT to allow phase shifting interferometry. The interference pattern showed nearly perfect contrast allowing low-noise measurements. The mirror was measured to have a shape error of 44 nm rms, most of which was due to a quarter wave of astigmatism. The azimuthal component of the hologram error was determined by a rotation test to be 3 nm rms. The comparison of the CGH test results with an independent measurement using a Hindle test, shown below in Figs. 16 and 17, demonstrates excellent agreement.

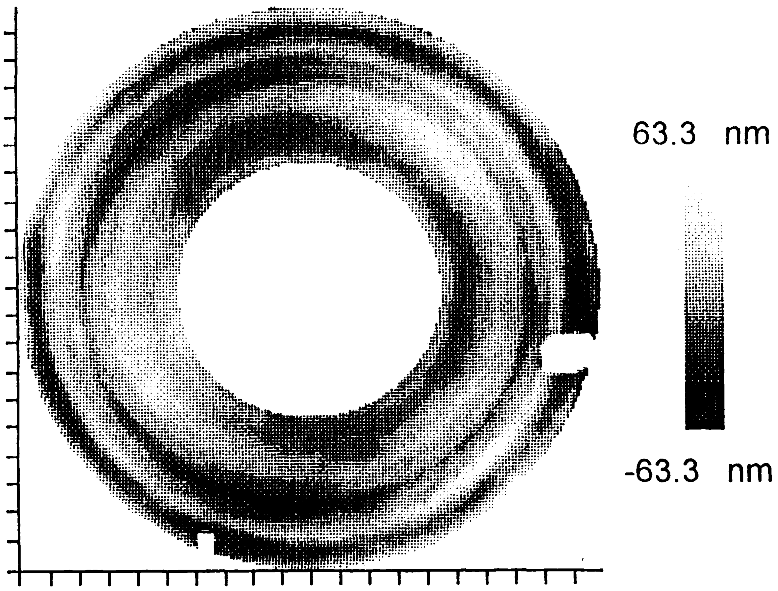


Figure 16. Phase map showing figure of the secondary mirror as measured by a holographic test plate. The surface has 19.5 nm rms variation after 35 nm rms astigmatism has been removed.

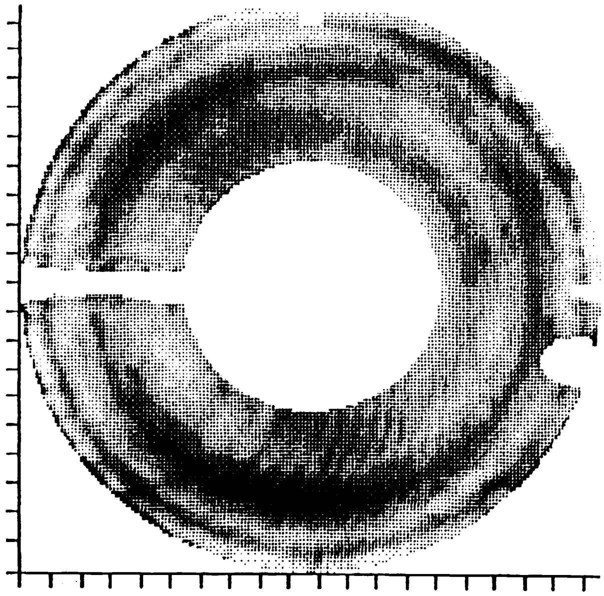


Figure 17. Map of the secondary from the Hindle test. This surface map, which closely matches that in Fig. 16, has 20.9 nm rms variation after 41 nm rms astigmatism has been subtracted.

The CGH test is highly accurate because it uses concave spherical reference surfaces and it uses holograms with large spacing. An error analysis is summarized in Table 1 for the measurement of the most difficult convex asphere planned, the *f*/4 wide field secondary for the Large Binocular Telescope. The CGH test plate will measure this mirror, which has 340 μm departure from the best-fit sphere, with 6 nm rms accuracy. The conic constant will be measured with ±0.0001 accuracy. The test of this mirror requires a hologram with over 5000 rings that are spaced an average of 100 μm apart.

Table 1. Error budget for CGH test of LBT *f*/4 secondary

	Surface figure (nm rms)	Conic constant (ppm)
Hologram writing errors	4.0	47
Test plate surface	3.0	10
Etching and coating errors	3.5	10
Errors in use of test plate	0.2	78
RSS	6.1	92

5. FABRICATION OF HOLOGRAMS

Most holograms for optical testing are fabricated using e-beam or optical writing machines optimized for integrated circuit production. These machines typically use precise x-y motion of the substrates and fine control of a focused beam to write patterns into thin photoresist films. Modern e-beam writers are mature products that are accurate to 100 nm over 150 mm substrates. However, the equipment is optimized for writing x-y features onto standard size substrates and is inefficient at writing holograms. The continuous bands or rings required by holograms must be fractured into a basis set of polygons that the machine can accommodate.[21] The curved lines are accurately approximated using small polygons, which requires large volumes of data. This drives up the cost and time to write the patterns. Also, very few writing machines are built to accept the thick, non-standard substrates that are required for many CGH applications.

Circular patterns are optimally fabricated using polar coordinate writing machines. The writers expose rings by rotating the substrate under a fixed laser or electron 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. The fabrication of zone plates by rotating the optic and writing one ring at a time has been performed by several groups on flat substrates to high accuracy.[22,23,24] Also, high-efficiency diffractive optics for infrared applications have been made using single point diamond-turning lathes.

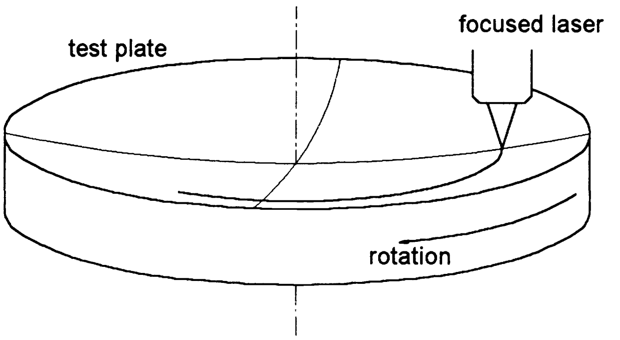


Figure 18. General geometry for optically writing ring patterns onto curved test plates. A focused laser beam is positioned radially and one ring at a time is exposed on the rotating optic.

Some limitations imposed by conventional manufacturing techniques are avoided by using a different fabrication method -- thermochemical writing using laser-induced oxidation of a metal film.[25, 26, 27, 28] The thermochemical technique avoids the difficulties of applying and controlling photoresist by writing the image directly onto a chrome film with a laser beam. The main steps of hologram fabrication are shown on Fig. 19. A thin coat of chrome, typically 50 - 80 nm thick, is deposited onto the glass substrate. The laser exposes the chrome by heating it, which oxidizes a layer at the surface. After this oxide latent image is created, the optic is immersed into a caustic bath of $NaOH + K_3Fe(CN)_6$ that dissolves the bare chrome much more quickly than the chrome oxide. A pattern of chrome remains where the laser had exposed the surface and created the oxide layer. This effect allows the direct generation of patterns with spatial resolution better than 1000 line/mm onto bare chrome films.[29]

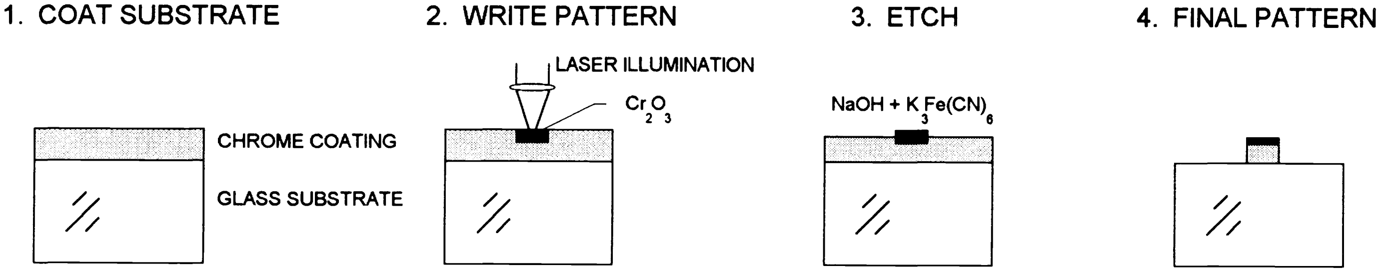


Figure 19. Pattern generation using laser induced oxidation.

The thermochemical writing technique is optimal for fabricating the large holograms onto curved surfaces required for CGH test plate measurements of convex aspheres. The holograms for these test plates are in a unique domain where micron-scale errors are allowed, but the writer must work on large diameter, steeply curved surfaces. Control of line width is not critical because it only affects the amplitude of the light. The ring center position, defined to be halfway between the two edges, must be held to a few microns because it affects the phase of the light. Hologram errors of 1 μm rms and 5 μm P-V degrade the surface measurement accuracy by 3 nm rms and 20 nm P-V for the most difficult secondary mirror planned, the 120 cm LBT $f/4$.

A large computer-controlled laser writer was built for writing the holograms for testing secondary mirrors for astronomical telescopes. The writer uses a 1 W argon laser at 488 nm to expose rings into thin chrome coatings on optics rotating at speeds up to 10 rpm. The machine writes with 1 μm accuracy onto curved substrates, up to 1.8-m in diameter, and as fast as $f/1$. An acousto-optic modulator rapidly scans the 8 μm focused spot radially to write rings as wide as 100 μm wide in a single rotation. The intensity of the writing beam is monitored with an internal photodiode and is controlled to 1% with the acousto-optic modulator. An image of the writing beam is projected onto a CCD array to allow feedback control of the scan width and the center position. The video image is digitized and processed to determine the edge positions, which correspond to the inner and outer edges of the exposed ring. This information is fed back to the control of the acousto-optic modulator to compensate errors in the system. To write onto curved surfaces, the machine uses horizontal and vertical linear stages, giving radial and axial motion of the writing head. Position control is maintained using an athermal machine design, laser interferometers, and a high quality rotary air spindle.

The holograms for certifying null correctors have been written using a new version of the laser writing system built at the Institute of Automation and Electrometry (IAE) in Novosibirsk, Russia.[30] The circular laser writing system is capable of writing 250-mm diameter holograms with accuracy 100 nm. This machine rotates the substrates at 600 rpm and uses a linear air bearing with interferometers to position the writing beam radially to 100 nm. This machine also writes general patterns that do not have circular symmetry using coordinate transformation software, a high-quality angular encoder, and rapid beam switching.

6. CONCLUSION

Interferometry using computer-generated holograms has been proven to give accurate and reliable measurements of aspheric surfaces. The holograms are readily fabricated using equipment from the microelectronics industry and using special hologram writing machines that take full advantage of the circular symmetry.

The holographic null lens test and the CGH test plate were developed to meet the extreme challenges for measuring large telescope mirrors. These techniques are definitely *not* limited to large optics. Virtually any null corrector can be certified with a CGH. The CGH test plate technique can be used to measure any asphere -- convex or concave; large or small. Equipment and fabrication technologies are in place for making the holograms for both of these tests.

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