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USE OF COMPUTER-GENERATED HOLOGRAMS IN OPTICAL TESTING

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14.1 GLOSSARY

CGH	computer-generated hologram
M	linear, lateral magnification
N	diffracted order number
n	integers
P	number of distortion-free resolution points
r	radius
S	maximum wavefront slope (waves/radius)
$x, \Delta x$	distance
$\Delta\theta$	rotational angle error
$\Delta\phi$	wavefront phase error
θ	rotational angle
λ	wavelength
$\phi(\ )$	wavefront phase described by hologram

14.2 INTRODUCTION

Holography is extremely useful for the testing of optical components and systems. If a master optical component or optical system is available, a hologram can be made of the wavefront produced by the component or system and this stored wavefront can be used to perform null tests of similar optical systems. If a master optical system is not available for making a hologram, a synthetic or a computer-generated hologram (CGH) can be made to provide the reference wavefront.[1–8] When an aspheric optical element with a large departure from a sphere is tested, a CGH can be combined with null optics to perform a null test.

There are several ways of thinking about CGHs. For the testing of aspheric surfaces, it is easiest to think of a CGH as a binary representation of the ideal interferogram that would be produced by interfering the reference wavefront with the wavefront produced by a perfect sphere. In the making of the CGH the entire interferometer should be ray traced to determine the so-called perfect aspheric wavefront at the hologram plane. This ray trace is essential because the aspheric wavefront will change as it propagates, and the interferometer components may change the shape of the perfect aspheric wavefront.

Figure 1 shows an example of a CGH. Since the amplitude of the aspheric wavefront is constant across the wavefront, best results are obtained if the lines making up the hologram have approximately one-half the spacing of the lines (i.e., fringe spacing) at the location of the lines. Thus, the line width will vary across the hologram. The major difference between the binary synthetic hologram

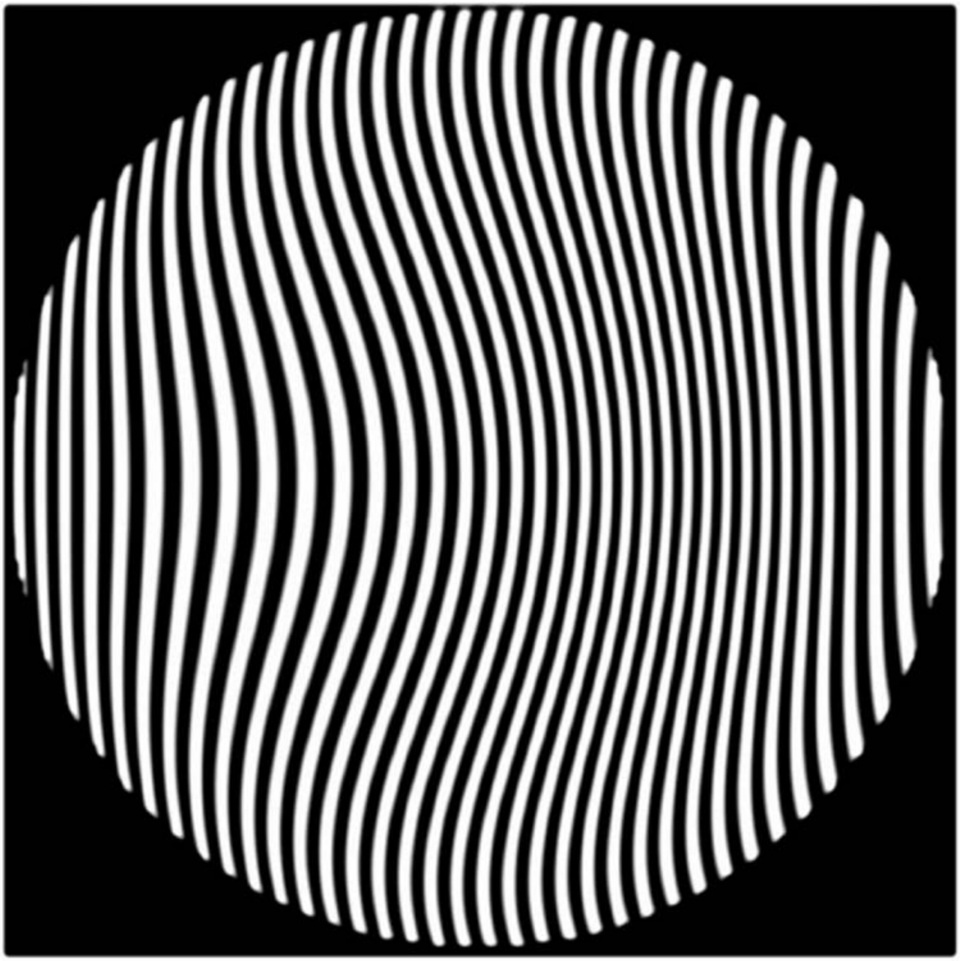


FIGURE 1 Sample computer-generated hologram (CGH).

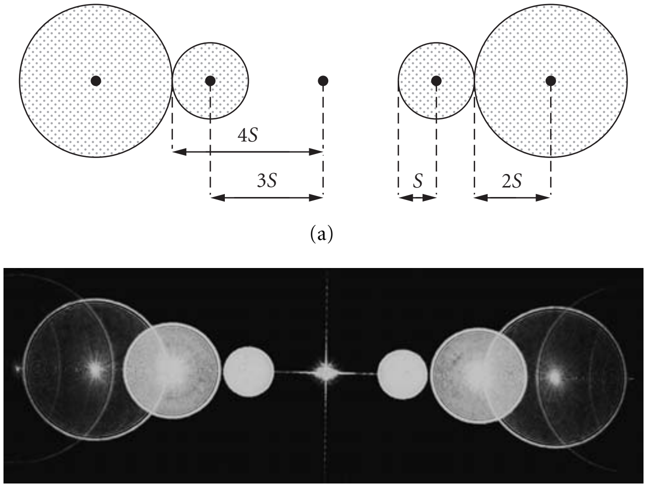
and the real grayscale hologram that would be produced by interfering a reference wavefront and the aspheric wavefront is that additional diffraction orders are produced. These additional diffraction orders can be eliminated by spatial filtering.

14.3 PLOTTING CGHs

The largest problem in making CGHs is the plotting. The accuracy of the plot determines the accuracy of the wavefront. It is easier to see the plotting accuracy by comparing a binary synthetic hologram with an interferogram. In an interferogram, a wavefront error of $1/n$ waves causes a fringe to deviate from the ideal position by $1/n$ the fringe spacing. The same is true for CGHs. A plotting error of $1/n$ the fringe spacing will cause an error in the produced aspheric wavefront of $1/n$ wave. As an example, assume the error in drawing a line is 0.1 μm and the fringe spacing is 20 μm, then the wavefront produced by the CGH will have an error in units of wave of 0.1/20, or 1/200 wave.

To minimize wavefront error due to the plotter, the fringe spacing in the CGH should be as large as possible. The minimum fringe spacing is set by the slope difference between the aspheric wavefront and the reference wavefront used in the making of the synthetic hologram. While it is not mandatory, the interferogram is cleaner if the slope difference is large enough to separate the diffraction orders so spatial filtering can be used to select out only the first order. Figure 2 shows a photograph of the diffracted orders. As shown in Fig. 2, to ensure no overlapping of the first and second orders in the Fourier plane, the tilt angle of the reference beam needs to be greater than three times the maximum slope of the aberrated wave.[9] This means that, in general, the maximum slope difference between the reference and test beams is four times the maximum slope of the test beam. Thus, the error produced by plotter distortion is proportional to the slope of the aspheric wavefront being produced.

Many plotters have been used to plot holograms, but the best holograms are now made using either laser-beam recorders or more commonly electron-beam (e-beam) recorders of the type used for producing masks in the semiconductor industry.[10] The e-beam recorders write onto photoresist



(a)

(b)

FIGURE 2 Diffracted orders in Fourier plane of CGH: (*a*) drawing and (*b*) photograph.

deposited on an optical-quality glass plate and currently produce the highest-quality CGHs. Typical e-beam recorders will write areas larger than 100 mm × 100 mm with positional accuracies of less than 100 nm.[11]

If needed, plotter distortion can be measured and calibrated out in the making of the hologram.[12,13] The easiest way of determining plotter distortion is to draw straight lines and then treat this plot as a diffraction grating. If the computer-generated grating is illuminated with two plane waves, and the $-N$ order of beam 1 is interfaced with the $+N$ order of beam 2, the resulting interferogram gives us the plotter distortion. If the lines drawn by the plotter are spaced a distance Δx, a fringe error in the interferogram corresponds to a distortion error of $\Delta x/2N$ in the plot.

14.4 INTERFEROMETERS USING COMPUTER-GENERATED HOLOGRAMS

Many different experimental setups can be used for the holographic testing of optical elements. Figure 3 shows one common setup. The setup must be ray traced so the aberration in the hologram plane is known. While in theory there are many locations where the hologram can be placed, it is convenient to place the hologram in a plane conjugate to the asphere under test so the intensity across the image of the asphere is uniform. The longitudinal positional sensitivity for the hologram is reduced if the hologram is made in a region where the beams are collimated. Another advantage of this setup is that both the test and the reference beams pass through the hologram so errors resulting from hologram substrate thickness variations are eliminated without requiring the hologram be made on a good optical flat.

Another common setup for using a CGH to test aspheres is shown in Fig. 4.[14] The largest advantage of this setup is that it works well with commercial Fizeau interferometers. The only addition to the commercial interferometer is a mount to hold the CGH between the transmission sphere and the optics under test. Since the light is diffracted by the CGH twice, the CGH must be a phase

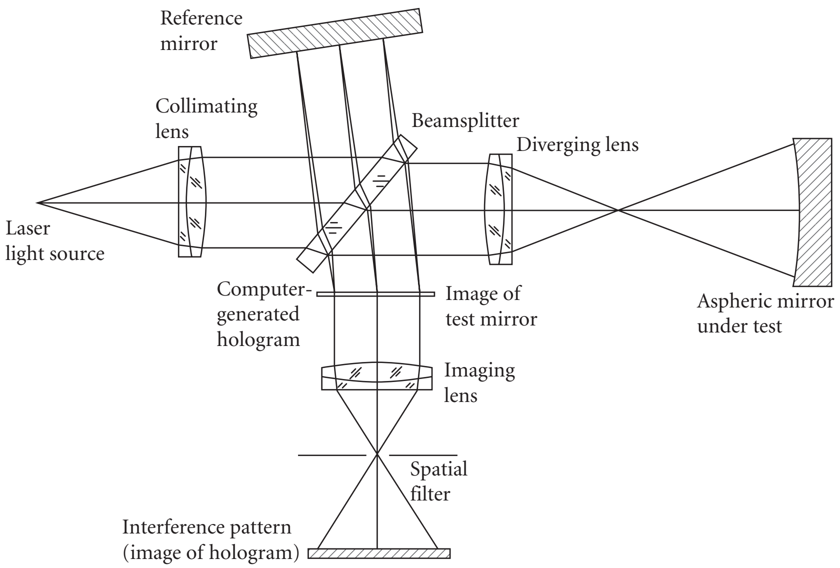


FIGURE 3 Interferometer setup using CGHs to test aspheric wavefronts.

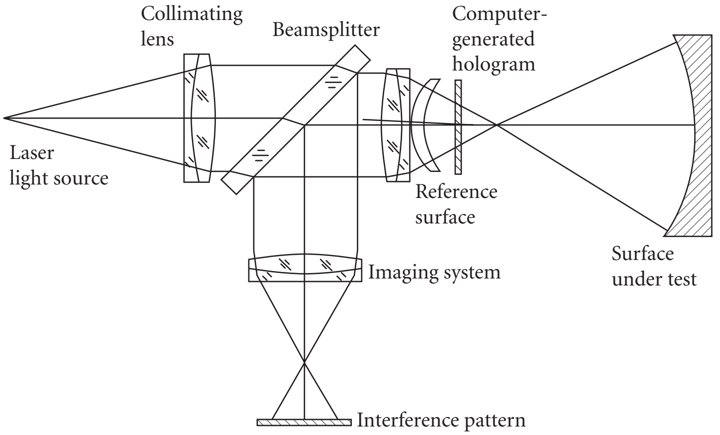


FIGURE 4 Use of CGH with Fizeau interferometer.

hologram so the diffraction efficiency is good, and since only the test beam is transmitted through the CGH, the substrate must either be high quality or thickness variations in the substrate must be measured and subtracted from the test results.

Figure 5 shows a setup for testing convex surfaces. In this case an on-axis CGH is used and the CGH is made on the concave reference surface.[15] The light waves are perpendicular to the concave reference surface and then after diffraction they become perpendicular to the surface under test. The CGH pattern may be drawn exposing photoresist, ablating a metallic coating, or by creating a thin oxidation layer by heating a metal coating with a focused laser beam.[16]

CGHs can also be combined with partial null optics to test much more complicated aspherics than can be practically tested with either a CGH or null optics. This combination gives the real power of computer-generated holograms.[17]

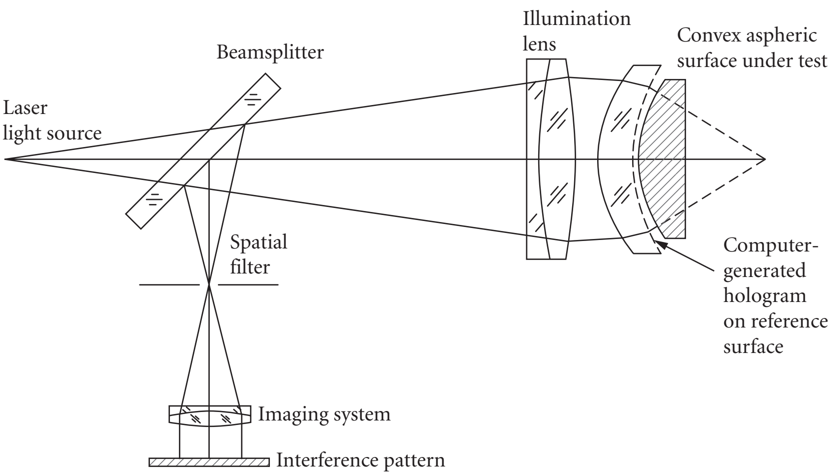


FIGURE 5 Using CGH to test convex surface.

14.5 ACCURACY LIMITATIONS

The largest source of error is the error due to plotter distortion as discussed previously. The other large sources of error are improper positioning of the hologram in the interferometer, and incorrect hologram size.

Any translation or rotation of the hologram produces error.[2] If the hologram is made conjugate to the exit pupil of the master optical system, the exit pupil of the system under test must coincide with the hologram. If the test wavefront in the hologram plane is described by the function $\phi(x, y)$, a displacement of the hologram a distance Δx in the x direction produces an error

$$\Delta\phi(x, y) \approx \frac{\partial\phi(x, y)}{\partial x}\Delta x \tag{1}$$

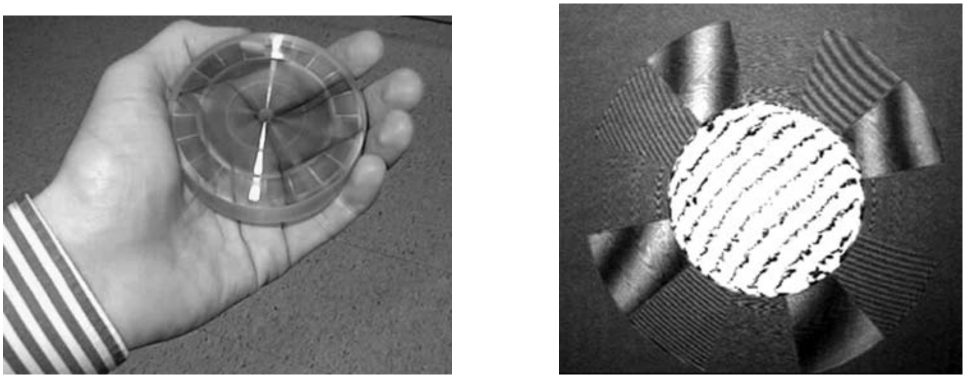
where $\partial\phi/\partial x$ is the slope of the wavefront in the x direction. Similarly, for a wavefront described by $\phi(r, \theta)$, the rotational error $\Delta\theta$ is given by

$$\Delta\phi(r, \theta) \approx \frac{\partial\phi(r, \theta)}{\partial\theta}\Delta\theta \tag{2}$$

Another source of error is incorrect hologram size. If the aberrated test wavefront in the plane of the hologram is given by $\phi(r, \theta)$, a hologram of incorrect size will be given by $\phi(r/M, \theta)$, where M is a magnification factor. The error due to incorrect hologram size will be given by the difference $\phi(r/M, \theta) - \phi(r, \theta)$, and can be written in terms of a Taylor expansion as

$$\begin{aligned}\phi\left(\frac{r}{M}, \theta\right) - \phi(r, \theta) &= \phi\left[r + \left(\frac{1}{M} - 1\right)r, \theta\right] - \phi(r, \theta)\\ &= \left[\frac{\partial\phi(r, \theta)}{\partial r}\right]\left(\frac{1}{M} - 1\right)r + \cdots\end{aligned} \tag{3}$$

where terms higher than first order can be neglected if M is sufficiently close to 1, and a small region is examined. Note that this error is similar to a radial shear. When the CGH is plotted, alignment aids, which can help in obtaining the proper hologram size, can be drawn on the hologram plot. Figure 6 shows a CGH where the hologram is made in the center of the substrate and alignment aids are placed on the outer portion of the CGH.[11] Not only can the alignment aids help in putting the CGH in the proper position, but they can be used to help position the optics being tested. Figure 7



(a) (b)

FIGURE 6 Use of CGH for alignment: (*a*) note structure in CGH and (*b*) interferogram produced with this CGH.

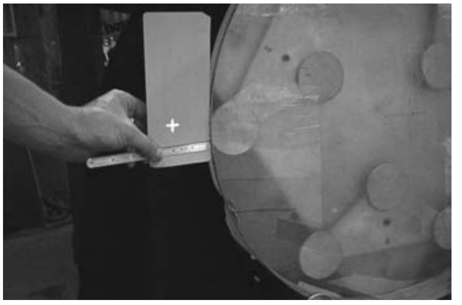


FIGURE 7 Use of crosshair produced by CGH to aid in the alignment of an off-axis parabola mirror.

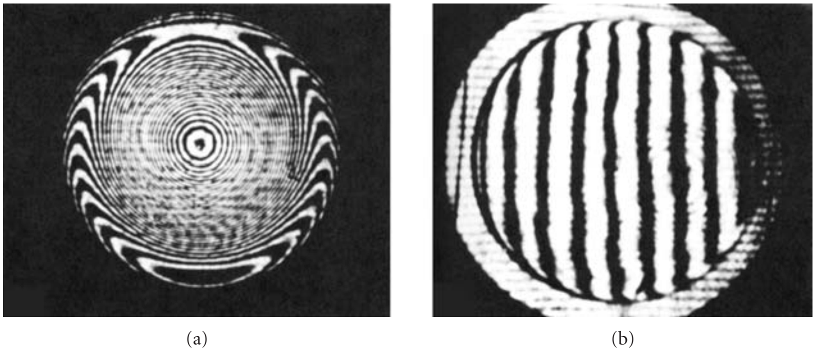
shows a crosshair produced by a CGH that aids in the alignment of an off-axis parabolic mirror. The same CGH used to produce the crosshair produces the aspheric wavefront required to provide a null test of the off-axis parabola.[11]

14.6 EXPERIMENTAL RESULTS

Figure 8 shows the results of using the setup shown in Fig. 3 to measure a 10-cm-diameter F/2 parabola using a CGH generated with an e-beam recorder. The fringes obtained in a Twyman-Green interferometer using a helium-neon source without the CGH present are shown in Fig. 8*a*. After the CGH is placed in the interferometer, a much less complicated interferogram is obtained as shown in Fig. 8*b*. The CGH corrects for about 80 fringes of spherical aberration, and makes the test much easier to perform.

To illustrate the potential of a combined CGH/null-lens test, results for a CGH/null-lens test of the primary mirror of an eccentric Cassegrain system with a departure of approximately 455 waves (at 514.5 nm) and a maximum slope of approximately 1500 waves per radius are shown.[17] The mirror was a 69-cm diameter off-axis segment whose center lies 81 cm from the axis of symmetry of the parent aspheric surface. The null optics was a Maksutov sphere (as illustrated in Fig. 9), which reduces the departure and slope of the aspheric wavefront from 910 to 45 waves, and 300 to 70 waves per radius, respectively. A hologram was then used to remove the remaining asphericity.

Figure 10*a* shows interferograms of the mirror under test obtained using the CGH Maksutov test. Figure 10*b* shows the results when the same test was performed using a rather expensive refractive



(a) (b)

FIGURE 8 Results obtained testing a 10-cm-diameter F/2 parabola: (*a*) without using CGH and (*b*) using CGH made using an e-beam recorder.

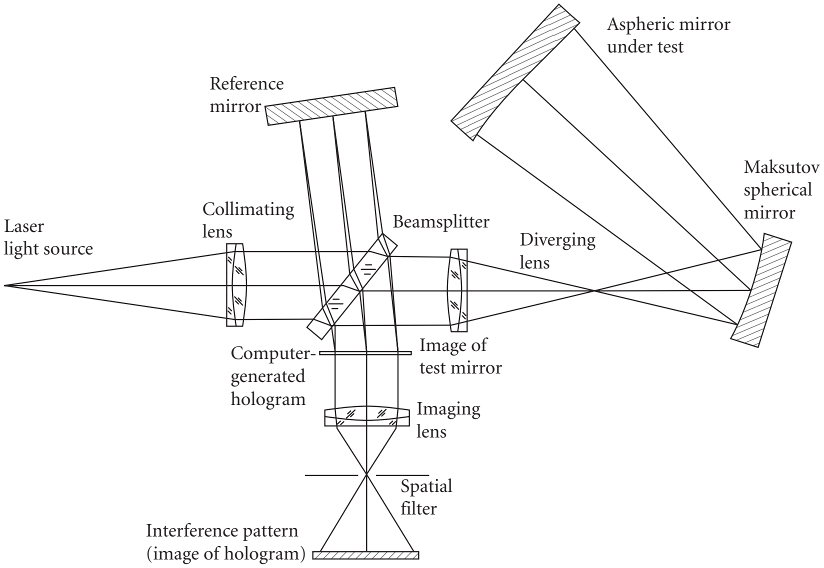
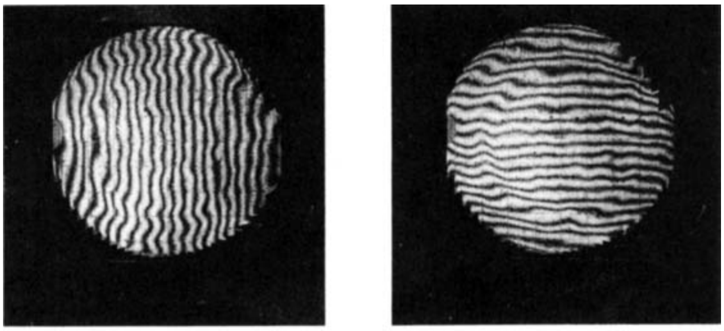
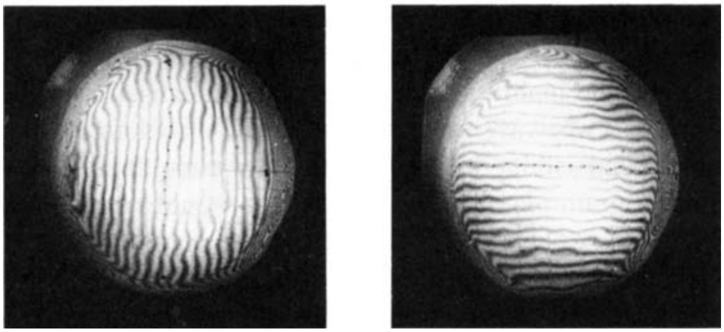


FIGURE 9 Setup to test the primary mirror of a Cassegrain telescope using a Maksutov sphere as a partial null and a CGH.



(a)



(b)

FIGURE 10 Results obtained using Fig. 9: (*a*) CGH-Maksutov test (λ = 514.5 nm) and (*b*) using null lens (λ = 632.8 nm).

null lens. When allowance is made for the fact that the interferogram obtained with the null lens has much more distortion than the CGH Maksutov interferogram, and for the difference in sensitivity (λ = 632.8 nm for the null-lens test and 514.5 nm for the CGH-Maksutov test), the results for the two tests are seen to be very similar. The "hills" and "valleys" on the mirror surface appear the same for both tests, as expected. The peak-to-valley surface error measured using the null lens was 0.46 waves (632.8 nm), while for the CGH-Maksutov test it was 0.39 waves (514.5 nm). The rms surface error measured was 0.06 waves (632.8 nm) for the null lens, while the CGH Maksutov test gave 0.07 wave (514.5 nm). These results certainly demonstrate that expensive null optics can be replaced by a combination of relatively inexpensive null optics and a CGH.

14.7 DISCUSSION

The difficult problem of testing aspheric surfaces, which are becoming increasingly popular in optical design, is made easier by the use of CGHs. The technology has reached the point that commercial interferometers using computer-generated holograms are now available. The main problem with testing aspheric optical elements is reducing the aberration sufficiently to ensure that light gets back through the interferometer. Combinations of simple null optics with a CGH to perform a test enable the measurement of a wide variety of optical surfaces. The making and use of a CGH are analogous to using an interferometer setup that yields a large number of interference fringes, and measuring the interferogram at a large number of data points. Difficulties involved in recording and analyzing a high-density interferogram and making a CGH are very similar. In both cases, a large number of data points are necessary, and the interferometer must be ray traced so that the aberrations due to the interferometer are well known. The advantage of the CGH technique is that once the CGH is made, it can be used for testing a single piece of optics many times or for testing several identical optical components. Additional alignment aids can be placed on the CGH to aid in the alignment of the CGH and the optics under test.

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