Efficient testing of off-axis aspheres with test plates and computer-generated holograms

J. H. Burge
Optical Sciences Center, University of Arizona, Tucson, AZ 85721
jim.burge@optics.arizona.edu
520-621-8182

ABSTRACT

Off axis aspheric surfaces, such as individual segments for a telescope mirror, and surfaces that do not have any optical axis are traditionally difficult to test. In addition to difficulties controlling the aspheric shape, mirror segments have tight on radius of curvature and optical axis position. This paper presents a new method of measuring these surfaces that uses a test plate with a spherical reference surface, in combination with a small computer generated hologram to compensate the aspheric departure. The example for measuring 1.8-m segments of a 10-m primary mirror is given.

Keywords: Interferometry, Aspheres, Optical testing, Computer generated holograms

1. INTRODUCTION

General aspheric surfaces can be measured using spherical test plates with computer generated holograms. Convex secondary mirrors are measured using concave test plates that have the CGH written directly onto the concave spherical reference of the test plate.[1] A different approach is considered here for measuring general aspheric parts that are concave or convex and may be off axis or may not have an axis. Rather than fabricate the hologram onto the reference surface of the test plate, a small hologram is used elsewhere in the system to correct the aspheric departure of the light reflected from the part under test. This allows a null test with the light from a well-known sphere as the reference. This test has several important advantages over other techniques, including the following:

- High accuracy: Using holograms fabricated by electron beam lithography, this test can achieve accuracy of $\lambda/100$ for large, steep, off axis aspheres.
- Low cost: This test requires only one highly accurate surface – the reference spherical surface of the test plate. The other optics and the holograms need only be made to standard shop tolerances.
- Easy to implement: The reference surface is nearly coincident with the mirror surface, so the other optics do not directly affect the measurement. The path could be folded with a relatively low quality flat mirror, and the requirements for vibration suppression and quiet air conditions are minimal. The absence of measurement noise due to vibration and seeing allows extremely efficient optical testing.
- Allows accurate radius measurement: The measurement of the radius of curvature is limited only by the ability to measure the small gap between the optic and the test plate.
- Allows accurate determination of axis location: Features on the hologram can be used to allow absolute lateral alignment of the asphere in the test.

Part of the SPIE Conference on Optical Manufacturing and Testing III
Denver, Colorado • July 1999
SPIE Vol. 3782 • 0277-786X/99/$10.00

The test also has several drawbacks which must be considered:

- It has never been implemented, so it must be studied carefully before it can be tested and implemented.
- It requires a full-aperture test plate made of good transmissive material, which is costly for large optics.
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2. DESIGN CONCEPT

The test can be thought of as an extension of the CGH test plate interferometry used for secondary mirrors.[1] The CGH test plate uses a full aperture spherical reference surface which has a CGH actually written *onto the spherical surface*. This causes the reference wave to have the same shape as the wavefront reflected from an ideal test asphere. The interference between these wavefronts allows a measurement of surface errors that is accurate to $\lambda/100$.

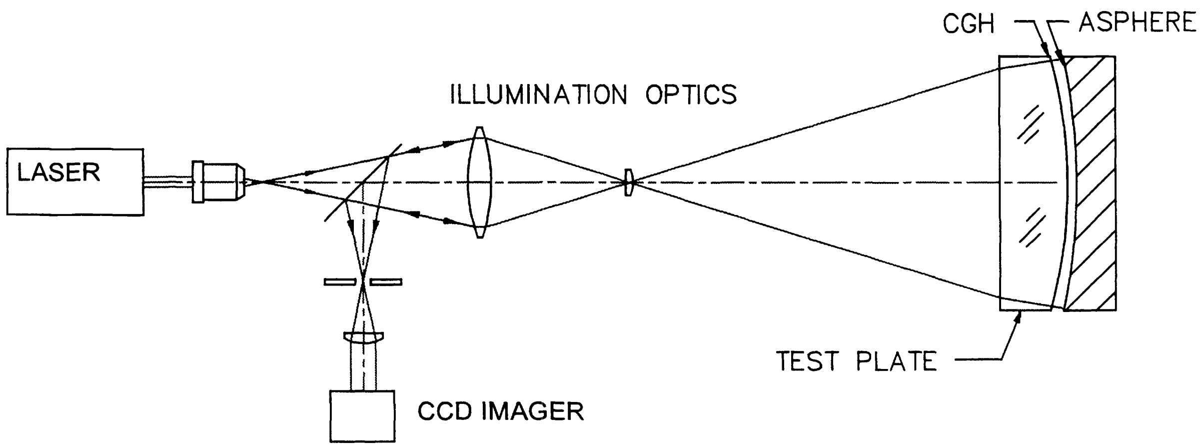

Figure 1. Layout for measuring concave aspheres with a CGH test plate. The new testing method presented in this paper does ***not*** use a hologram on the test plate. Instead, a hologram placed in the illumination optical system projects the hologram to the test surface.

The CGH test plate would actually be excellent for measuring the off axis parts, but there exist no facilities to fabricate non-axisymmetric holograms onto large curves substrates. The hardware implemented at the University of Arizona, and the hologram fabrication equipment are limited to measuring parts with rotational symmetry.[2]

The next best thing to the CGH test plate would be a spherical test plate that has the CGH projected to it. This is exactly the configuration developed here. The basic geometry is shown below in Figure 2. The important feature of this design is the CGH, which pre-distorts the test wavefront so after reflecting off the aspheric mirror segment, it matches the spherical reference wavefront. Both reference and test beams go through the CGH and the test plate together, so the refractive index variations and surface figures of the CGH substrate are not important. The test wavefront uses the first order of diffraction and the reference wave uses the 0-order. The fact that the wavefronts are coincident at the CGH is important because it allows the CGH to be written on a standard lithography substrate and it allows the test plate to be made from a non-precision transmission grade glass, like Zerodur.

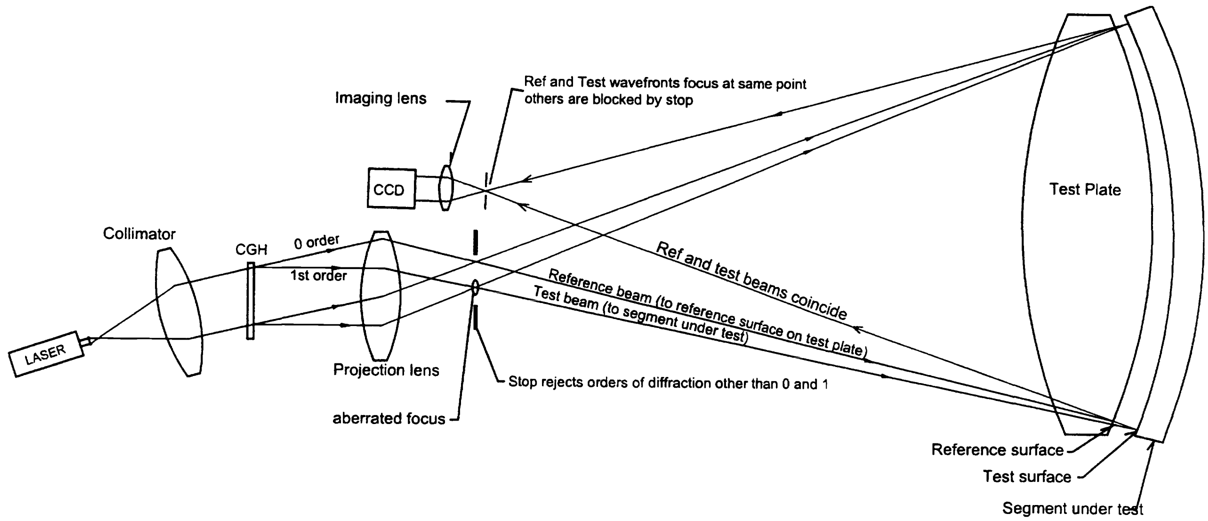

Figure 2. Layout of CGH test where hologram is imaged to test surface. The first and zero orders from the CGH are projected using the projection lens so that a good image of the CGH is formed on the test part. The hologram is designed so the 1st-order light reflected from the segment will exactly match the 0-order light reflected from the test plate. The other reflections are blocked. An imaging lens is used to focus the interferogram onto a CCD array.

As described above, only the first and zero orders of diffraction are used. All other orders are stopped out, as are the 0^{th}-order reflection from the test plate and the 1^{st}-order reflection off the segment. A chart showing the use of the different orders of diffraction is given below.

Table 1. Where the orders of diffraction go.

	Reflected from	Final destination
Zero order from CGH	Test plate	**Reference beam**
	Asphere	Blocked at imaging lens
First order from CGH	Asphere	**Test beam**
	Test plate	Blocked at imaging lens
All other orders	-----------	Blocked at projection lens

Phase shifting interferometry can be used for this test. The phase shift can be accomplished by pushing the test plate with PZTs. This is currently being done with test plates up to 1.8- meters for measuring convex mirrors at the University of Arizona.[3] High-resolution CCD cameras, frame grabbers, and software are commercially available that will allow rapid, high resolution measurements

The test achieves high accuracy using computer-generated holograms written using electron beam lithography, which is used for manufacturing integrated circuits. For nominal line space of 20 μm, holograms with pattern accuracy of 0.125 μm will give 0.006 λ accuracy in the wavefront, or 0.003 λ in the surface. The reference and test beams separate at the hologram, so they do not travel through the projection lens together. This means that the quality of this lens must be high. Note that the lens does not have to perfect, it must be well known.

High contrast interferograms are naturally obtained using holograms made as chrome patterns with 50% duty cycle. Diffraction efficiencies are 25% for 0 order and 10% for the 1^{st} order beam. For testing the asphere as a bare glass surface, interferograms have 90% contrast. This is reduced to 60% for measuring surfaces with reflective coatings.

3. SYSTEM DESIGN FOR SEGMENTS FROM A 10-M PRIMARY MIRROR

The new CGH test was designed and studied as a possibility for measuring the 1.8-m segments for the 10-m Gran Telescopio Canarias (Grantecan). The CGH test has some advantages for supporting the segment fabrication. A single test plate and projection system can be built and aligned. Tests of the different segments can be made by changing only the CGH and making no other alignments. Also, this test naturally controls the position of the segment asphere relative to the parent. Radius of curvature matching is made to 0.1 mm by simply controlling the 5 mm gap between the test plate and the segment. The principal disadvantage of this test is the cost of the large test plate.

Other candidate tests for these segments need to deal with the long focal length. Center of curvature testing with a null lens requires the interferometer to be 33 meters from the optic. Autocollimation using a flat mirror requires a 16.5 m interferometric path, with two reflections from the segment. While possible, the geometry of these tests is difficult and the ability to control optical axis position and radius of curvature to better than 1 mm is limited.

3.1 DESIGN OF TEST PLATE

The test plate for the Grantecan test was chosen to be bi-convex with to minimize the viewing distance and fabrication costs. The viewing distance of 15.8 m was set because the spherical aberration from the bi-convex test plate starts to become significant at shorter distances. Also, by using the same radius of curvature on both sides, fabrication costs are reduced.

The radius of the test plate was chosen to give optimal amount of focus in the holograms. To keep the system common for all segments, the tilt in the segment, relative to the test plate was held as a constant. The test plate radius was chosen to minimize this slope, which minimizes the average hologram ruling frequency, thus the sensitivity to errors.

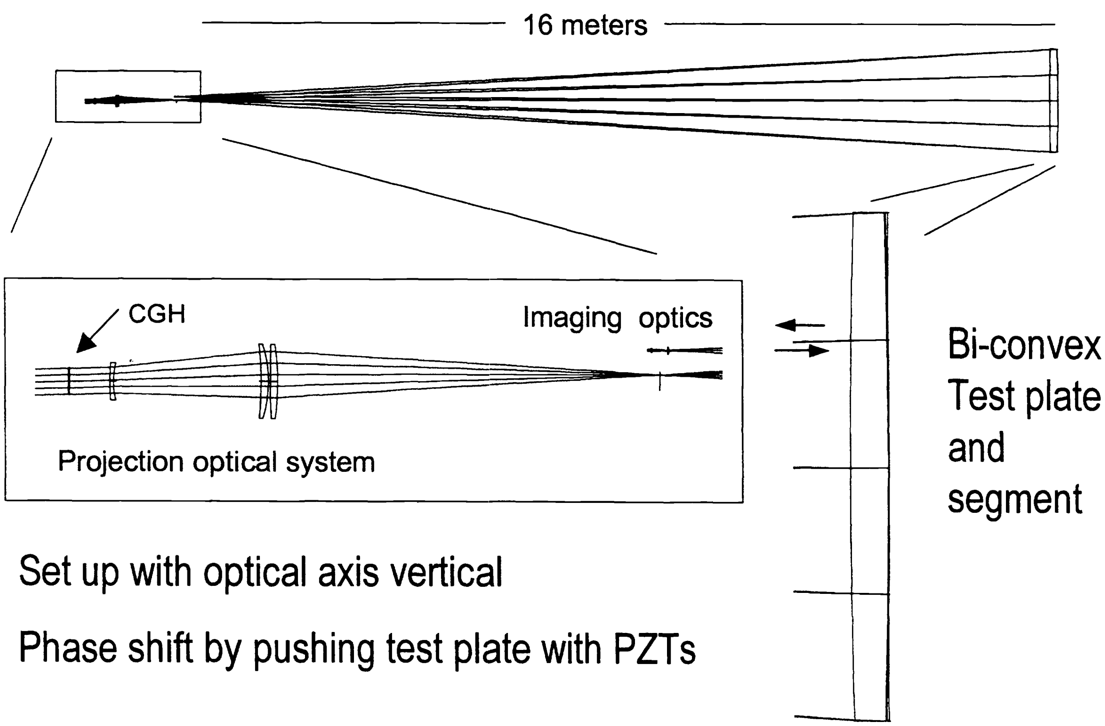

Figure 3. Layout of CGH test for Grantecan mirror segment

3.2 DESIGN OF PROJECTION LENS

The projection lens transmits the two orders of diffraction from the hologram (0 and 1 order) such that no other orders propagate. These lenses are critical to this test because accurate compensation of the aspheric departure of the segments requires the holograms to be projected to the test surface. A three-element set of lenses was designed to project the wavefronts from the hologram to the test plate. These lenses were actually designed backwards, i.e. they were designed to image the test mirror onto the CGH. The basic constraints on these lenses are:

1. Image scale of 70 mm at CGH for 1880-mm mirror segment. This came from the preliminary design with the concerns of sensitivity to fabrication errors and cost for the holograms.
2. Effective entrance pupil for imaging lenses 50 mm diameter, located 15885 from test plate. The image quality was defined to be better than 0.2 waves over the entire pupil.
3. The image was constrained to be telecentric – with the ray bundle that is defined by the 50-mm pupil hitting at normal incidence to the CGH plane. This allows to CGH to be illuminated with collimated light, which eases manufacturing difficulties over requiring a specific wavefront for illumination. This will also insure that the 1^{st} order of diffraction is nominally at normal incidence to the CGH and that the image created by this will be centered in the projection lenses.

The projection lens uses three BK7 lens elements that must be manufactured and assembled to high accuracy. The lenses do not need to be perfect, only well known with only low-order errors. Unlike the large test plate, the two beams do not travel through these lenses together. So the surface figure and internal quality of these elements is very important.

3.3 DESIGN OF HOLOGRAMS

The size of the holograms was chosen as 70 mm diameter. This size fits well with existing fabrication equipment. For performance and accuracy, larger holograms are always better. However, there is little cost benefit to going smaller and the cost increases quickly for going larger.

The only free variables for the hologram designs are the power in the pattern, which is determined by the radius of curvature of the test plate, and the tilt in the patterns, which always has a minimum required amount to separate the orders of diffraction.

The hologram design places requirements on the projection lenses. Obviously the size of the hologram determines the magnification of the system. The imaging becomes more difficult with increasing magnification. Also the holograms themselves define the rays that will go through the projection lens, thus they define the effective pupil over which the system must be corrected.

The holograms themselves are designed using a custom macro in Zemax. The system is simulated as a multi-configuration, with the test beam defined in one configuration and the reference beam in the other. The phase difference between these is simulated and the CGH phase function is optimized so the two beams match.

3.4 CONTROL OF DIFFRACTION ORDERS

It is imperative that only two beams are passed to the focal plane. The CGH test uses two apertures to isolate the desired orders. First of all, an aperture is placed at the output of the projection lens. This passes only the 0 and 1^{st} diffraction order. (The CGH design must insure that these are fully separated and isolated from other orders.) These two beams will each reflect from the test plate and from the reference surface, resulting in 4 returns to the imaging system. An aperture at the imaging system passes only the two desired beams. Figure 4 below shows isolation of the 0 and 1^{st} order from the projection system. Figure 5 shows isolation of the desired orders at the imaging system.

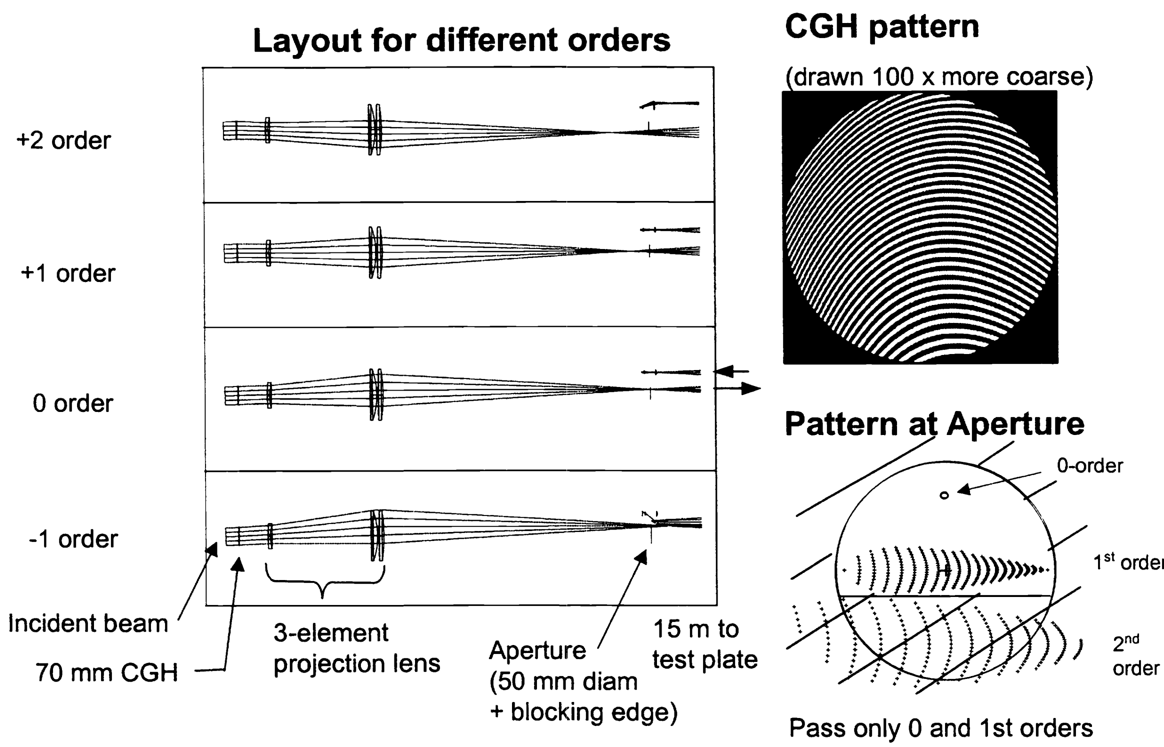

Figure 4. Layout for test of most severe Grantecan segment. Multiple orders of diffraction from the CGH are shown. The aperture at the focus of the projection system passes only the 0 and 1st diffracted orders.

The interference pattern is imaged onto a CCD camera using a two-element lens. The remaining unwanted orders are easily isolated with the aperture of the imaging system, as shown in Fig. 5. The components in the Grantecan test are summarized below in Table 2.

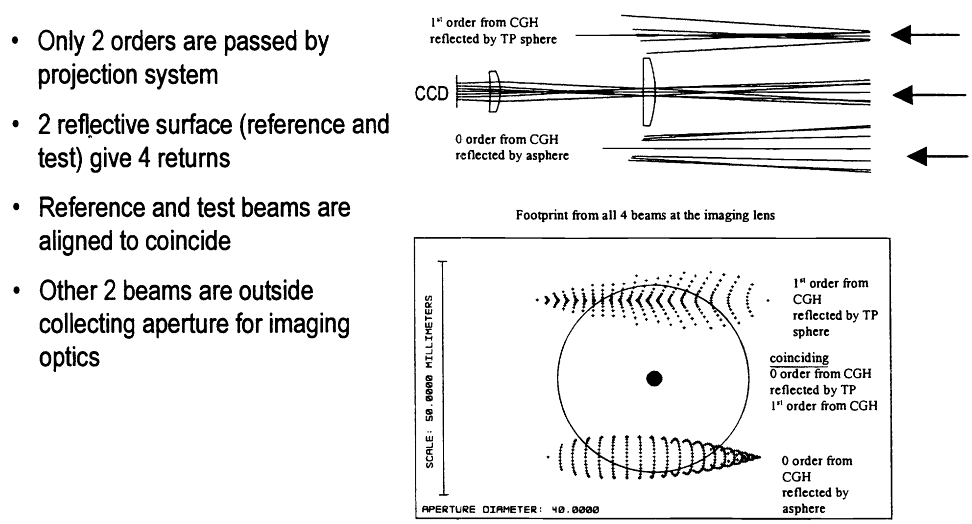

Figure 5. Isolation of unwanted reflections and orders of diffraction.

Table 2. Optical system summary for CGH test of Grantecan segments.

Component	Function	Brief description
Computer generated holograms	• Provide wavefront correction for aspheric departure of mirror segments • Use sufficient tilt to allow isolation of diffraction orders 0 and 1 • Different CGH for each segment	• 70-mm diameter, chrome patterns on 100-mm fused silica substrates. • Nominally 20 μm line spacings • 50% duty cycle (line width = line gaps = half of period).
Projection optics	• Project image of CGH onto segment • Pass only diffraction orders 0 and 1 • Same system and alignment for all tests	• 1.6-m long, with 3 BK7 elements • Lens diameter -- 20 cm for 2 lenses, 10 cm for third. • 1.2-m EFL, magnifies CGH 26.8 times. • Fully corrected for 70 mm CGH over 50-mm pupil.
Test plate	• Provide reflected wavefront from convex surface as a reference. • Transmit test wavefront • Minimize viewing distance	• Bi-convex, R1 = R2 = 33200 • 1.92 meter diameter, made of Zerodur • 15 cm center thickness (12.2 cm edge thick) • weighs ~ 1000 kg • Located 15.88 m from projection and imaging systems
Imaging optics	• Create a good image of the test part onto a CCD array. • Pass only the reference and test beams - block others	• 58 mm long with 2 BK7 elements, 20 and 12 mm diameter. • Creates 4.8-mm image of 1880-mm part for 2/3" format. • 6-mm stop, allows slope errors of $\pm$0.2 mrad. • Allows 1000 resolution elements across interferogram. • Distortion of image 0.1% or < 1 mm at segment.

4. CONTROL OF ASPHERE ALIGNMENT

The CGH is accurately fabricated and is precisely imaged onto the mirror with the projection optics. The position of the asphere can then be determined using fiducial marks on the hologram that are projected to the test plate. The positions of these images is then measured with a CCD camera. Cross patterns can be written outside the diameter of the hologram, so they will be imaged outside of the real mirror. (See Figs. 6 and 7.) For Grantecan testing, the FWHM of these images will be around 300 μm at the mirror, so the center can be found easily to 100 μm per fiducial.

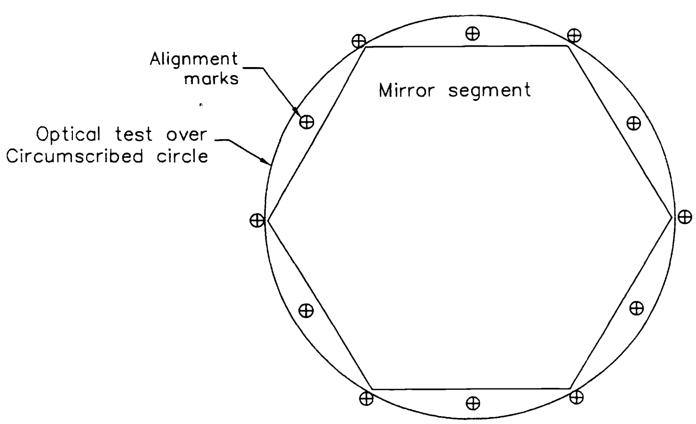

Figure 6. Alignment marks on the CGH will project accurately to the test surface. Since these will be written at the same time as the hologram, they will be positioned with 0.125 μm accuracy.

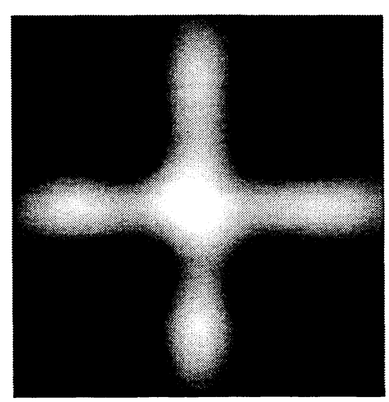

Figure 7. Simulated image of the fiducial for Grantecan testing. The cross is about 2 mm in its major dimensions. The FWHM of the lobes is about 300 μm.

The alignment fiducials provide another important feature. The CGH is imaged to the asphere, but the absolute scale of this image is important for accuracy and difficult to control. By measuring the relative positions of the fiducial images, the scale can be determine to about 20 ppm. The spacing between the projection optics and the test plate is then adjusted to maintain the desired scale.

5. SUMMARY OF TOLERANCES FOR GRANTECAN TESTING

A complete analysis of the test indicates that it can achieve excellent accuracy for controlling both the figure of the segment and for defining the position and orientation of the optical surface relative to the parent. The results for figure errors, in terms of reflected wavefront tat the telescope, are summarized below in Table 3. The assumptions and analysis to support the error budgets are also summarized below.

Table 3. Wavefront error budget for figure errors of the most extreme Grantecan segment.

Effect	**Magnitude**	**Wavefront** λ **rms**
CGH fabrication errors	0.125 μm	0.0063
projection optics	Tolerances	0.0059
test plate inhomogeneity	±0.15 mrad	0.0128
test plate illumination surface	2 fringes/cm	0.0013
alignment to fiducials - coupled through scale effect	6@ 0.1 mm	0.0014
reference surface figure	0.05 λ/cm	0.0146
Root Sum Squared		**0.0213**

5.1 COMPUTER GENERATED HOLOGRAM ACCURACY

The CGH's can be readily fabricated using e-beam lithography, maintaining 0.125 μm accuracy. With nominal period of 20 μm, the effect of the hologram errors on the wavefront is 0.125/20 or 0.0063 λ rms. Other errors in the CGH are negligible. Both wavefronts go through the CGH together, so surface figure and refractive index variations do not affect the test. The CGH design is easily made to be accurate to << 0.1 μm, so it does not affect the accuracy.

5.2 PROJECTION OPTICS

The effect of the tolerances for the projection optics was determined by direct simulation. The analysis included:

- For each lens, 2 radii of curvature, thickness, wedge, index, inhomogeneity
- Surface figures of $\lambda/8$ for each lens
- Lens spacing, tilt, decenter for mounting

Each term was perturbed the appropriate amount, then the system alignment using the fiducials was simulated. The wavefront errors were determined by direct comparison of the reference and test wavefronts. Segment position and radius errors were separated from figure errors.

5.3 TEST PLATE

The test is not exactly common path through the test plate, so the measurement is susceptible to errors from refractive index variations and errors in the illumination surface. It is possible to measure these errors and calibrate them out of the test, but the analysis here assumes no such backout is performed.

The refractive index variations were analyzed by simulating sinusoidal phase ripples in the test plate corresponding to ±0.15 mrad deviation (~2.5 fringes/cm). This is very conservative – typical Zerodur is much better than this. A complete simulation was made of each segment, showing an average wavefront error of 0.010 λ rms, and 0.013 λ rms for the most extreme segment.

This process was repeated for the illumination surface of the test plate. For surface errors corresponding to 2 fringes/cm when test plated, the test wavefront accuracy was simulated to be 0.0013 λ rms for the worst segment.

5.4 FIDUCIAL ALIGNMENT

The scale of the projected CGH is important to the test. This is determined using the fiducial images, which are 300 μm FWHM at the test plate. Finding the position of six of these, with 0.1 mm accuracy per fiducial, determines the scale to $0.041mm = \frac{0.1mm}{\sqrt{6}}$. Over 1.9 meters, this corresponds to 21 ppm. This was simulated directly to determine the effect on wavefront and segment position.

5.5 REFERENCE SURFACE FIGURE

The spherical reference surface of the test plate is used as the reference for the asphere measurement. This surface does not need to be perfect, only accurately know because errors in the surface can be removed from the asphere test in the data reduction. However, the accuracy of backing out these errors is limited by the mapping between the tests of the test plate and the asphere. The error is approximately the product of the mapping error and the slope of the surface.

The test plate is measured with a full aperture concave reference sphere. Like the test plate, figure errors in this surface are removed in data processing. So its slope errors also couple into the final accuracy. In addition, the interferometer used to measure the reference sphere will not be perfect and there will be some noise in the data.

Assuming the test plate and reference sphere are manufactured with P-V slope errors of 0.05 λ/cm, backing out the reference surface errors will contribute 0.0073 λ rms to the measurement of the aspheric surface.

6. ERROR BUDGET FOR SEGMENT ALIGNMENT

6.1 SEGMENT POSITION AND ALIGNMENT

The mirror segments have tight tolerances for the position of the optical axis and for the rotation of the segments. The same tolerancing procedure as above was followed to determine the accuracy of the test for these terms. A summary is given below in Table 4.

Table 4. Error budget for position and angle for the most extreme segment.

Effect	**Magnitude**	**Segment position Δx** mm	**Segment rotation $\Delta\theta$** Deg
CGH fabrication errors	0.125 um	0.003	0.0002
Projection optics	Tolerances	0.122	0.0080
Alignment to fiducials - coupled by scale effect	6@ 0.1 mm	0.106	0.0000
Alignment to fiducials - direct effect	6@ 0.1 mm	0.058	0.0060
Mechanical measurements	0.05 mm	0.050	0.0032
Root Sum Squared		**0.179**	**0.0105**

6.2 RADIUS OF CURVATURE MATCHING

The mirror segments also have tight tolerances for matching the radius of curvature from one segment to the next. The same tolerancing procedure as above was followed to determine the accuracy of the test for these terms. A summary is given below in Table 5.

Table 5. Error budget for radius of curvature matching for the most extreme segment

Effect	**Magnitude**	**ΔR, Radius of curvature matching** mm
projection optics	Tolerances	0.056
alignment to fiducials - coupled through scale effect	6@ 0.1 mm	0.024
mechanical measurements	0.05 mm	0.05
Root Sum Squared		**0.079**

7. CONCLUSION

A new type of CGH test is presented that has several advantages for measuring off axis aspheres. Once validated in the laboratory, this testing method promises an excellent technique for measuring a difficult class of aspheric surfaces.

ACKNOWLEDGMENTS

This work was funded by the Gran Telescopio Canarias project. Designs and data in this paper were developed by the author and do not represent GTC or other projects. Dave Anderson suggested the basic concept for this test in a personal communication.

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