Computer-Generated Hologram for optical testing – A review

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ABSTRACT

The computer generated hologram, or CGH, is the current de facto standard for accurate surface figure measurements of aspheres and freeforms. In this paper we will go over the history of the CGH technology development: from the birth of the holography to the invention of computer generated hologram; from early application of the CGH in testing aspheric surfaces to the development of precision fabrication techniques; from use of the CGH as null lens to more innovative applications testing and aligning optical systems. Dr. Wyant is a pioneer in the early development of the technology. His specific contributions will be introduced in detail. Efforts underway to expand the CGH use are also described.

Keywords: CGH, Computer Generated Hologram, optical testing, asphere, freeform

1. INTRODUCTION

Computer Generated Holograms are widely used for measuring surface figures of aspheres and freeforms. The CGH test is accurate, versatile, quick and powerful. This paper reviews the historic development of the technology. It started with the invention of holography by Denis Gabor, followed by the invention of the computer generated hologram by Adolf Lohman. Pioneering work on the CGH use in optical testing is reviewed including: Jim Wyant demonstrated the CGH application in optical testing; Steve Arnold and colleagues developed writing technology using ebeam machines; Alex Poleshchuk et al built a circular laser writers dedicated to writing the symmetric CGHs; Jim Burge invented many innovative uses of the CGH.

2. INVENTION OF HOLOGRPHY

In an effort to improve the resolution of the electron microscope, Denis Gabor proposed to record both the amplitude and phase of the image of an object, and then play back the image by illuminating the recorded image with the same or similar reference beam when recording the image. This gave birth to the field of holography. Figures 1 and 2 were taken from his original paper.

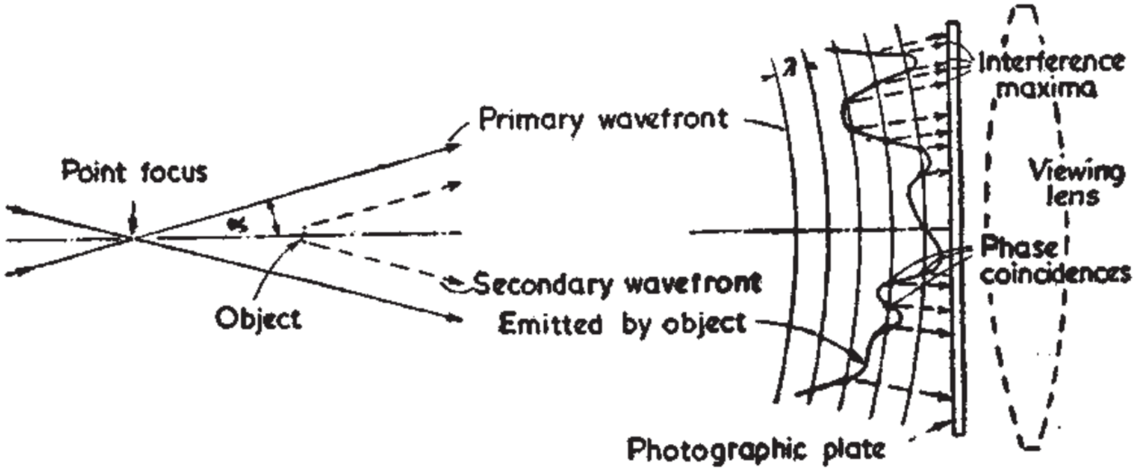

Figure 1. Interference between homocentric illuminating wave and the secondary wave emitted by a small object. (Taken from Gabor's original paper)

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Tribute to James C. Wyant: The Extraordinaire in Optical Metrology and Optics Education,
edited by Virendra N. Mahajan, Daewook Kim, Proc. of SPIE Vol. 11813, 118130K

doi: 10.1117/12.2568339

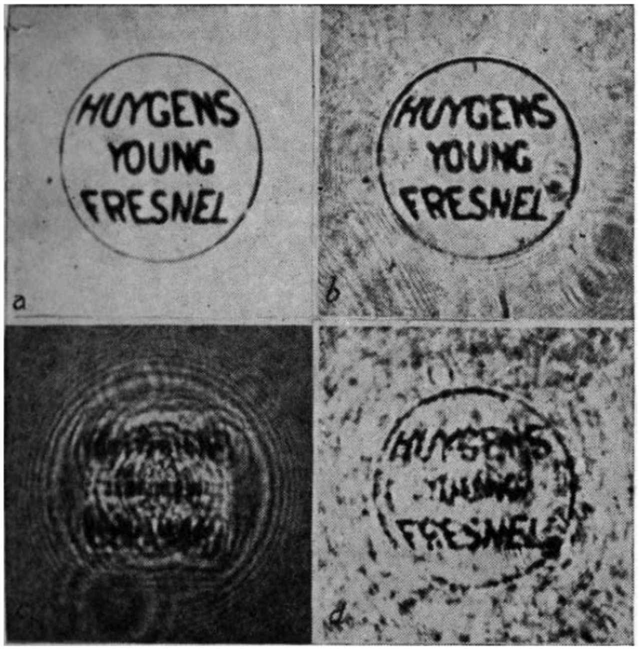


Figure 2. (a) Original micrograph, 1.4mm diameter. (b) Micrograph, directly photographed through the same optical system which is used for the reconstruction (d). AP. 0.04. (c) interference diagram, obtained by projecting the micrograph on a photographic plate with a beam diverging from a point focus. The letters have become illegible by diffraction. (d) Reconstruction of the original by optical synthesis from the diagram on the left. To be compared with (b). The letters have again become legible (Taken from Gabor's original paper)

3. INVENTION OF COMPUTER GENERATED HOLOGRAM

With advent of computers, Adolf Lohmann realized that an object does not have to exist to record a hologram; you can calculate the light field from the object and then plot the "hologram." To plot both the amplitude and phase of a light field, he proposed an encoding scheme called "detour phase". He defined a unit recoding area as a cell which has an opening, the size and position of which represent the amplitude and phase, respectively. The scheme is illustrated in Figure 3. An early CGH pattern and the re-constructed image is shown in Figure 4.

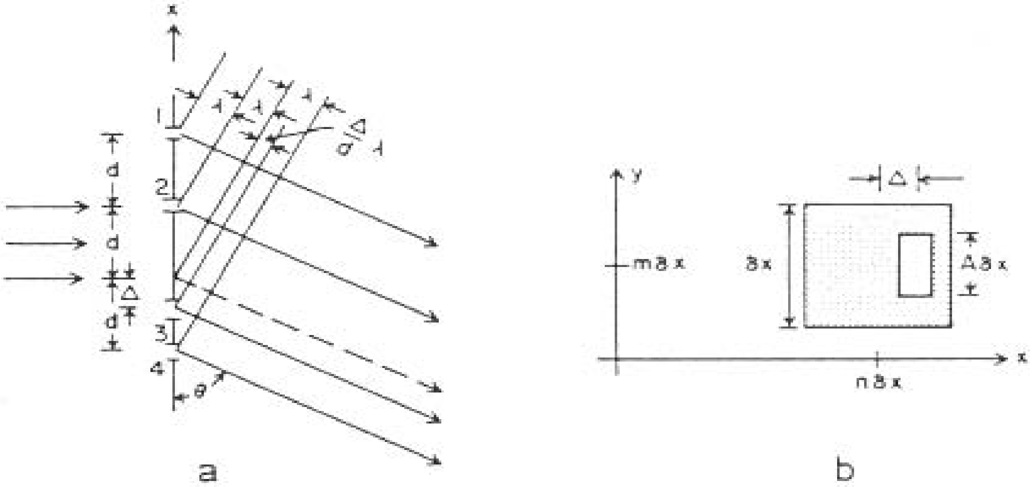
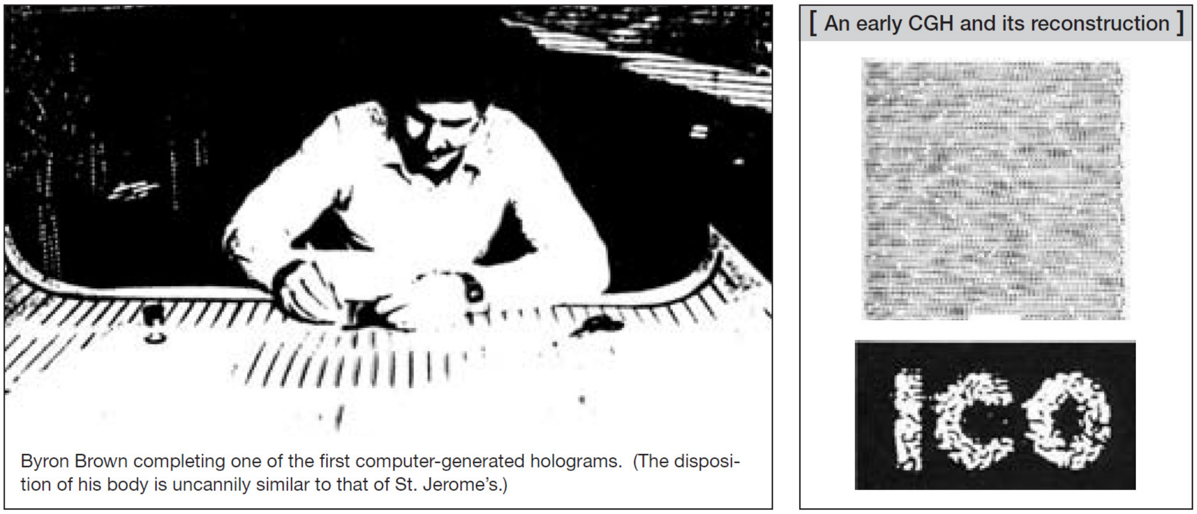


Figure 3. Illustration of the "detour phase" encoding scheme (Taken from Lohmann's original paper)



Byron Brown completing one of the first computer-generated holograms. (The disposition of his body is uncannily similar to that of St. Jerome's.)

[An early CGH and its reconstruction]

Figure 4. An early CGH and its reconstruction (Taken from Lohmann's OPN article)

4. APPLICATION OF THE CGH IN OPTICAL TESTING

Pastor studied hologram interferometry for testing aspheric surfaces. He first proposed replacing the hologram with a computer generated one in hologram interferometry. In early 70's, MacGovern and Wyant demonstrated perhaps the earliest use of the CGH in an interferometric test of an asphere. Fercher and his colleagues examined the CGH use in optical testing at about the same time.

4.1 CGH test configuration

In Wyant's landmark paper, he investigated using the CGH in a Twymann-Green setup for testing an aspheric surface. He developed the theory and validated it with experiments. The advantage of this setup is that the CGH is in the common path of the reference and test beam such that the thickness variation across the film the CGH was recorded on does not affect the measurement accuracy. As the beams pass through the CGH only once, it is easy to filter out the unwanted diffraction orders with a spatial filter at the Fourier plane. He proved that, with the spatial filtering, the wavefront generated by the hologram represent the true continuous target wavefront.

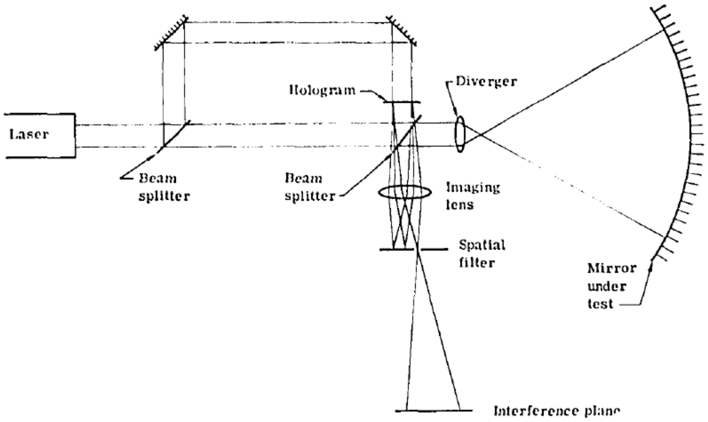


Figure 5. A CGH test configuration proposed by Wyant (taken from his original paper) where the CGH is placed in the viewing arm.

For large aspheric departure, to avoid the re-trace error, Wyant proposed to place the CGH in the testing arm, using it as a null lens. This becomes the most popular test configuration nowadays.

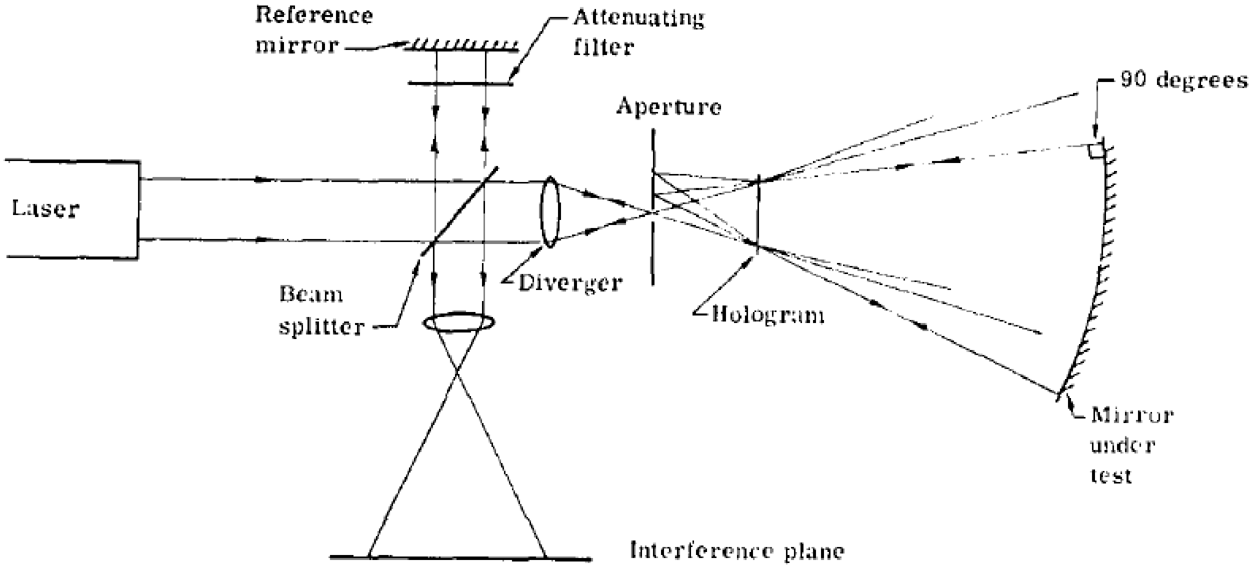


Figure 6. Test configuration proposed by Wyant where CGH is used as a null lens, taken from his original paper..

In a following paper, Jim Wyant further investigated the error sources of the CGH test and verified it with the experiment results. He realized the CGH pattern is just a binary representation of the real interferogram formed by the ideal object and reference wavefront, therefore, he departed away from Lohmann's and Lee's encoding scheme. All the CGHs now used in testing aspheres/freeforms are generated this way.

4.2 CGH fabrication

Early CGHs were plotted with digital plotter, and then photo-reduced onto film. In today's standard, the digital plotters back then had very limited plotting resolution – the plotter Wyant used to make his hologram had 6000 pen positions over 760mm. The photo-reduction process introduces error as well. Also, it took days to fabricate a CGH from plotting to photo-reduction to film development. Early CGH use is therefore limited by these factors.

Leung, et al investigated writing CGHs with e-beams. The state of the art e-beam machine has resolution of ~5 nm compared to ~0.1 mm plotter resolution in the old days. Direct writing of the CGH shortens the fabrication time from days to hours, and also reduces the number of error sources and allows the use of high quality glass substrate. These capabilities enable practical use of CGH metrology for aspheric and freeform surfaces.

Specialized laser writing machines have been built to manufacture diffractive optics. Alexander Poleshchuk and his colleagues at the Institute of Automation and Electrometry of Russian Academy of Sciences built a circular laser writer specifically optimized for manufacturing axisymmetric diffractive optics. The laser writing head moves in radial position while the substrate rotates on a precision rotary table. It writes ring patterns on substrates up to 240mm in diameter and 20mm thick. The laser spot is 0.8μm in diameter and the linear motion is controlled to 20 nm accuracy. Jim Burge at University of Arizona built a large laser writer to manufacture patterns on curved surfaces up to 1.8m in diameter for measuring large convex secondary mirrors. A similar but smaller version was built by Lu at Changchun Institute of Optics and Precision Mechanics. These machines enable large CGHs for specialized applications, but today's CGHs are primarily written with the e-beam or laser writers developed for making photomasks for the semiconductor industry.

The basic steps for CGH design and manufacture have not changed from those described by Steve Arnold in 1985, shown below. The desired phase function is created using ray trace software. Several software steps calculate the pattern geometry and convert this into a set of polygons in the machine language for the writing machine. After writing, and developing the pattern can be left as chrome-on-glass which diffracts transmitted light by amplitude modulation, or the pattern can be etched into the surface to get higher efficiency using phase modulation

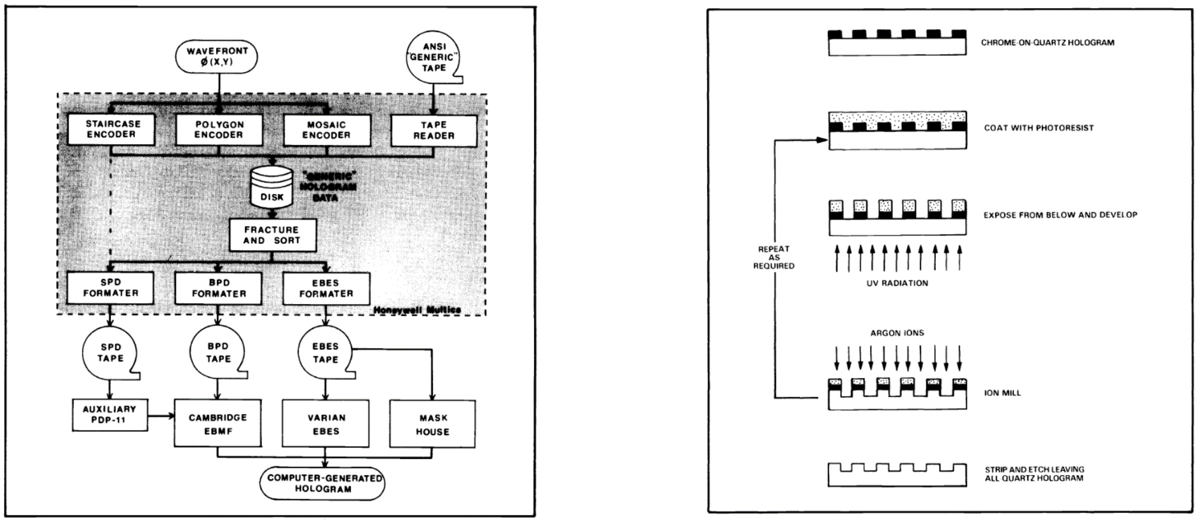


Figure 7. Process of writing CGH with ebeam machine (taken from Arnold's 1985 Optical Engineering paper.)

5. INNOVATIVE USE OF THE CGH – AN EXAMPLE

After the basic principles of the CGH metrology were established and highly accurate and efficient fabrication technology was developed, innovative application of CGH metrology has solved challenging problems. In this section, we present an example test demonstrating the power of the CGHs in overcoming practical metrology challenges.

The Thirty Meter Telescope (TMT) primary mirror consists of nearly 500 segments with 82 different aspheric shapes. Their radii of curvatures need be tightly controlled so the ensemble can act like a single 30 meter mirror. To measure all the segments in a production setting presents challenging requirements. A Fizeau interferometer invented by Burge was built to test the segments. The interferometer consists of a source module, a multiplexed CGH (one for each type of segments), a projection lens and a 1.5m test plate, as illustrated in Figure 8.

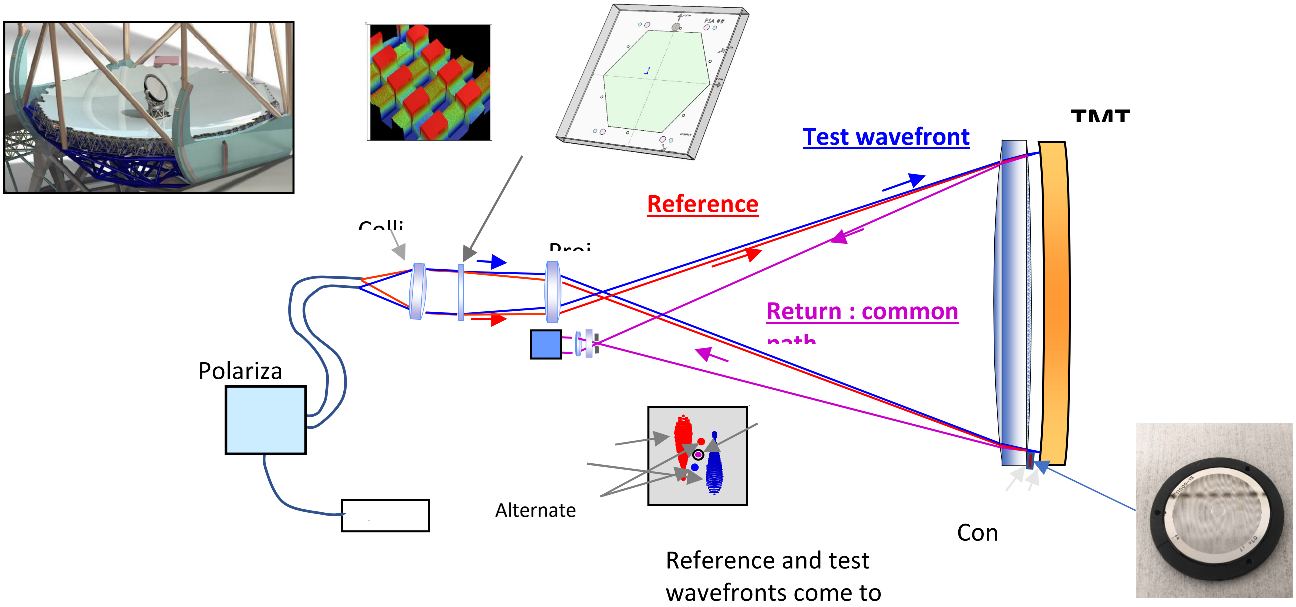


Figure 8. Testing TMT primary segments with a custom Fizeau interferometer.

The innovation featured in this Fizeau interferometer include:

1. Each type of segment has its own 3” x 3” CGH that can be easily and accurately inserted into the system using kinematics. The CGH uses multiple patterns including two overlapped patterns that are double etched to provide the reference and testing wavefronts. Other patterns aiding the alignments are included as well.
2. A full-sized test plate, supported 13 meters from the CGH system is common for all the segments.
3. Alignment of the test is achieved using phase fiducial targets – which are reflective CGHs – accurately bonded to the back of the test plate. This system demonstrated 5µm resolution and 25µm alignment accuracy in a manufacturing environment.
4. The system incorporates a pixelated phase sensor from 4D Technologies to perform instantaneous phase shift interferometry, making the test insensitive to vibration.

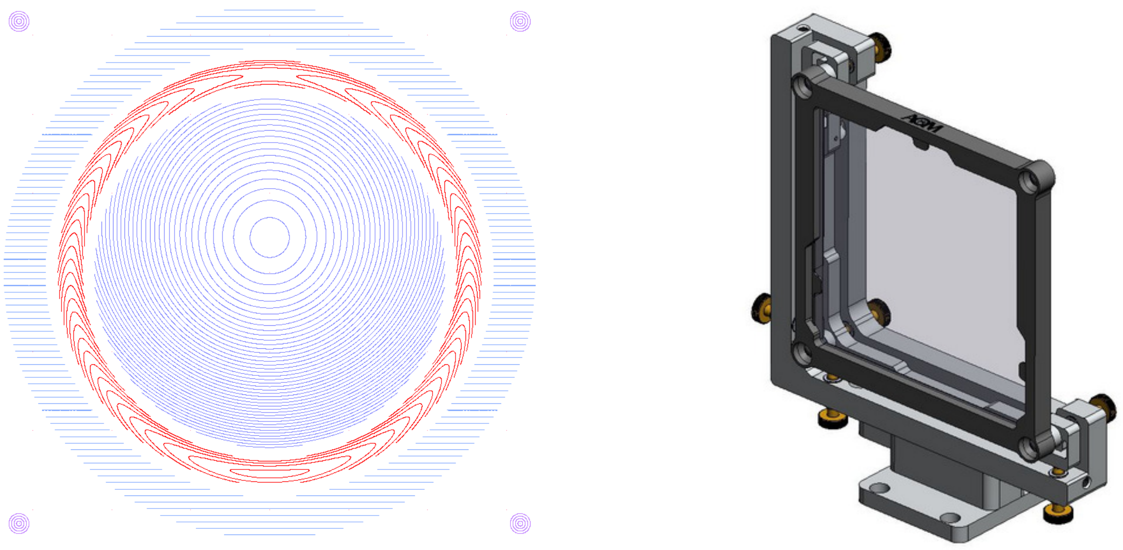
This system was set up at Arizona Optical Systems for a prototype 1.3-m TMT mirror segment, demonstrating complete alignment within a few minutes, achieving measurement repeatability of 1 nm rms.

6. FUTURE OF CGH METROLOGY

Use of Computer Generated Hologram in optical testing was pioneered by Wyant and others. The technology is now mature and ready for prime time. We expect it to become more widely used as increasing numbers of aspheres and freeforms are produced. New designs, manufacturing methods, and software are making CGH metrology more accessible by decreasing cost and lead times and by making it easy and quick to align the test and process the data.

6.1 Setting up the test made easy

Computer Generated Holograms from Arizona Optical Metrology are mounted in cells with magnetic kinematic interfaces to the supporting stage, making assembly literally a snap. The alignment to the interferometer is made quick and easy using light reflected back into the interferometer by a hologram that is outside the region of the main hologram.



(a) (b)

Figure 9. (a) a CGH pattern layout showing multiple patterns are multiplexed on the CGH to aid the alignment of the CGH and the test surface; (b) the CGH bonded in frame mounted on a 6-axis stage.

The alignment of the optic under test is made easy and repeatable by utilizing additional patterns on the same CGH substrate. Light from these patterns is used to guide the position of optomechanical references, which are in turn used to set the alignment of the test. Figure 10 illustrates the concept of a metrology platform which is accurately aligned to the CGH using such dedicated alignment patterns. The optic is placed accurately onto kinematic features on the metrology platform that mate with the datum features on the optic.

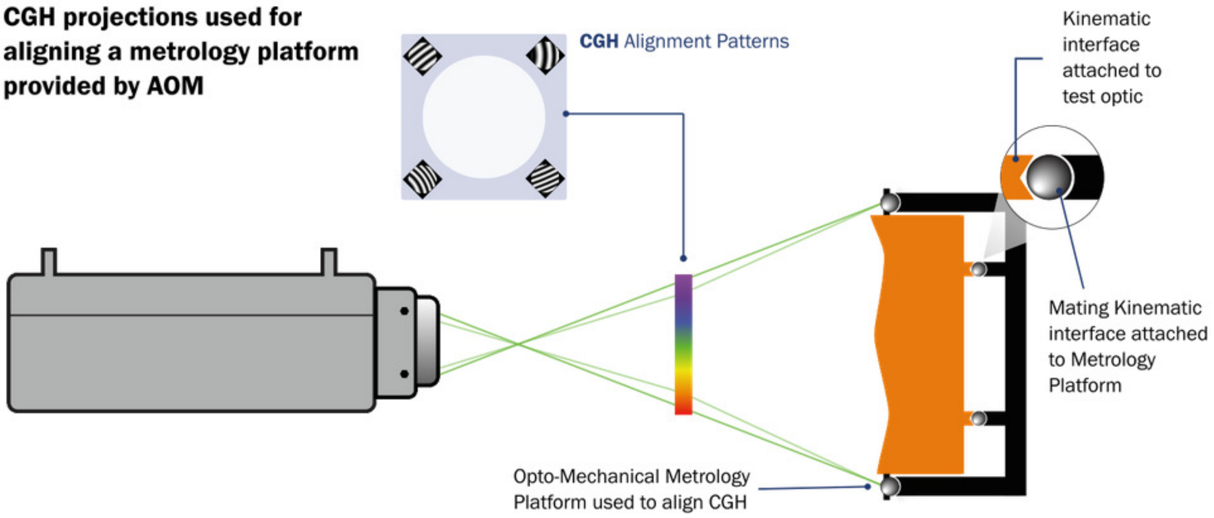


Figure 10. Metrology plat form for holding test surface where mechanical references are attached.

6.2 Data processing made easy

Interferometric CGH testing of aspheric and freeform surfaces requires special data processing. The alignment error of the surface under test causes unique wavefront signature that should be separated from the measurement of the form errors. For example, in the CGH test of a conic surface, lateral alignment error of the surface introduces coma in the wavefront that is not error in the surface, therefore, should be removed as an alignment term. More complex freeform surfaces have more complex alignment terms. Another special issue with the CGH tests comes from the mapping distortion due to the geometry of the test. This is accommodated by remapping or "morphing" the data. The *CGHplus* software from AOM is supplied with CGHs to perform these processing steps as well as creating reports of the as-built accuracy.

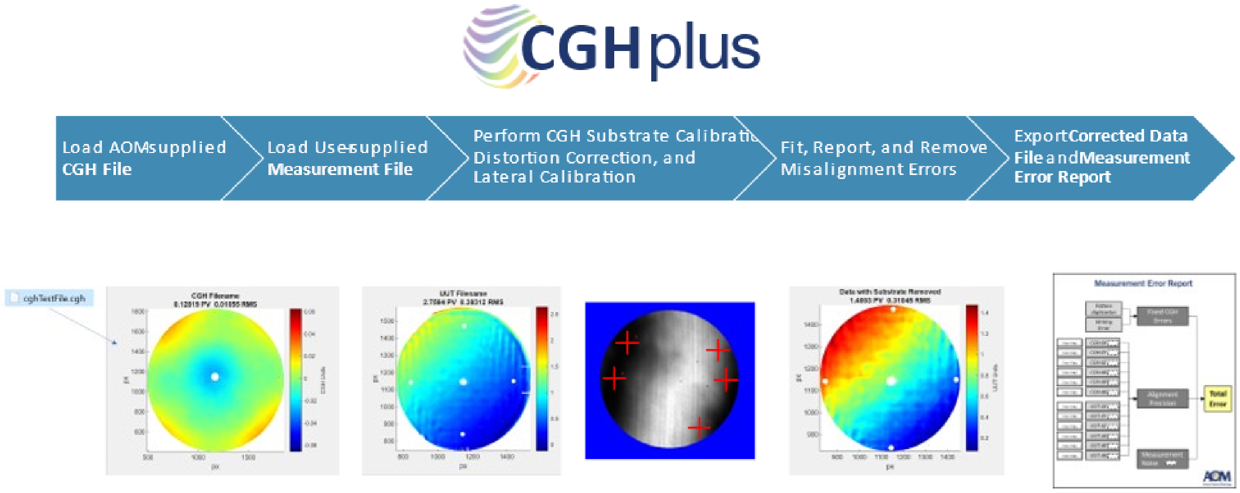


Figure 11. Data processing sequence in CGH plus software.

6.3 Benefitting from economies of scale

The standard CGH size has been set by the 6”x6” photomask standard. AOM now offers smaller CGHs and mounting hardware at considerably lower cost than the full sized hologram. As production rates for these CGHs increase, the costs will continue to come down.

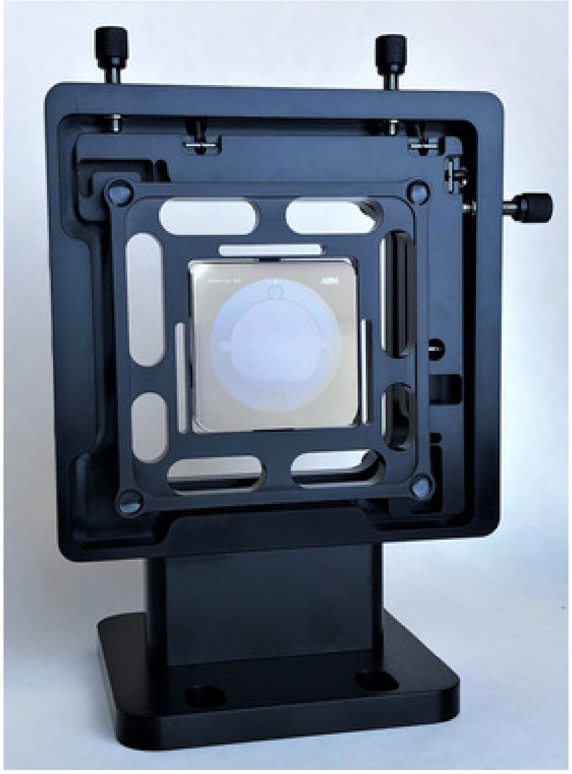


Figure 10. A 2”x2” CGH mounted on a 6-axis stage.

6.4 Short lead time

AOM has implemented a design/fabrication process that significantly reduces the lead time. The standard delivery time is 4-5 weeks. It is shortened to 2 weeks with expedition.

7. SUMMARY

We reviewed history of the development of CGH application in optical testing. With the trail blazing work of the pioneers, the CGH technology is ready for the prime time. With the development efforts underway, we expect the CGH metrology to be adopted much more widely in the near future.

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