Use of computer generated holograms for alignment of complex null correctors

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ABSTRACT

Large diameter, non-axisymmetric aspheric mirrors can be measured interferometrically using null correctors that employ computer generated holograms (CGHs). The testing of off axis segments for the new class of giant telescopes pose requirements that beyond the state of the art for CGHs alone. The long radius of curvature and the magnitude of the aspheric departure require other lenses and mirrors to be used along with the CGH. The alignment of these systems is very sensitive and the absolute accuracy of the alignment is critical to the system performance. We have developed techniques that use diffracted light from patterns on the CGH to accurately define the alignment of multi-element null correctors. We will present results from the null test of the 1.7-m New Solar Telescope primary mirror. The optical shape of this mirrors is an off-axis paraboloid from an f/0.7 parent.

Key words: optical alignment, computer generated hologram, null testing

1. INTRODUCTION

Computer Generated Holograms (CGH) have long been used in interferometric testing of aspheric surfaces.[1-3] With new families of giant telescopes with off-axis aspheric primaries,[4,5] the CGH alone is not enough to create the aspheric wavefront for null testing of these mirrors. The null correctors most likely consist of other refractive/reflective elements. How to align these elements to the tight tolerances typical to null correctors presents challenges. We faced this challenge when we designed the interferometric testing system for the primary mirror of the New Solar Telescope (NST) which is an off-axis segment of a paraboloid.[4] The null corrector is made up of a 0.5m fold sphere and a CGH. We developed techniques to accurately align both elements in the corrector and to roughly align the NST mirror to the testing wavefront. We used CGHs for all these alignments. Since CGHs can be fabricated with high precision using laser writers, e-beam machines, etc, they make ideal tools for aligning optics with demanding tolerances. These CGHs used for alignment purpose were fabricated on the same substrate as the testing CGH, which ensures high registration accuracies. In Section 2, we give a brief description of the NST null testing system. The alignment techniques that we developed are described in Section 3. The alignment of each element – the testing CGH, the fold sphere and the NST mirror is explained in detail.

2. THE NST NULL TESTING SYSTEM

Figure 1 shows the null testing system for the NST primary mirror. The NST primary is a 1.7m in diameter off-axis parabola with the parent radius of curvature of 7.7 meters and off-axis distance of 1.84 meters.[6,7] The null corrector is made up of a CGH and a 0.5m fold sphere. The 3-element compound lens creates spherical wavefront to illuminate the CGH.

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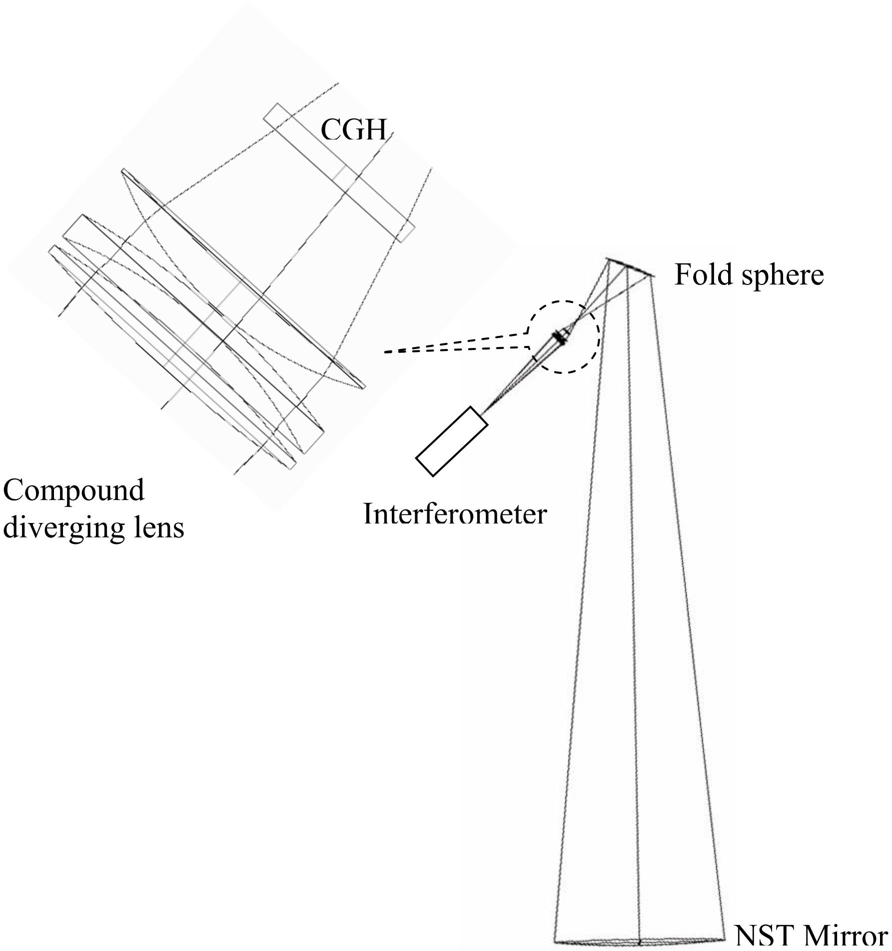


Figure 1. Illustration of the NST null testing system.

3. USE OF CGH FOR ALIGNMENT

We used CGHs to align both elements of the null corrector – testing CGH and fold sphere, and the NST mirror. These alignment CGHs are all fabricated on the same substrate as the testing CGH. Figure 2 shows the scaled phase pattern plot and locations of all the CGHs on the substrate. The main testing CGH itself needs to be aligned with high precision relative to the interferometer optics. We designed a CGH to align it. It is more challenging to align the fold sphere. We used CGHs in combination with metering rods to align it. Also, we designed CGHs to create a cross hair and a clocking line to initially align the test optics to the test wavefront. Table 1 lists the spec of the substrate and Table 2 shows descriptions of each individual CGH.

Table 1. The spec of the CGH substrate and description of each CGH.

Material	Fused silica
Diameter	100mm
Thickness	9.5mm
Wedge	< 1 arc min
Transmission wavefront Quality	<1/20λ rms at 633nm

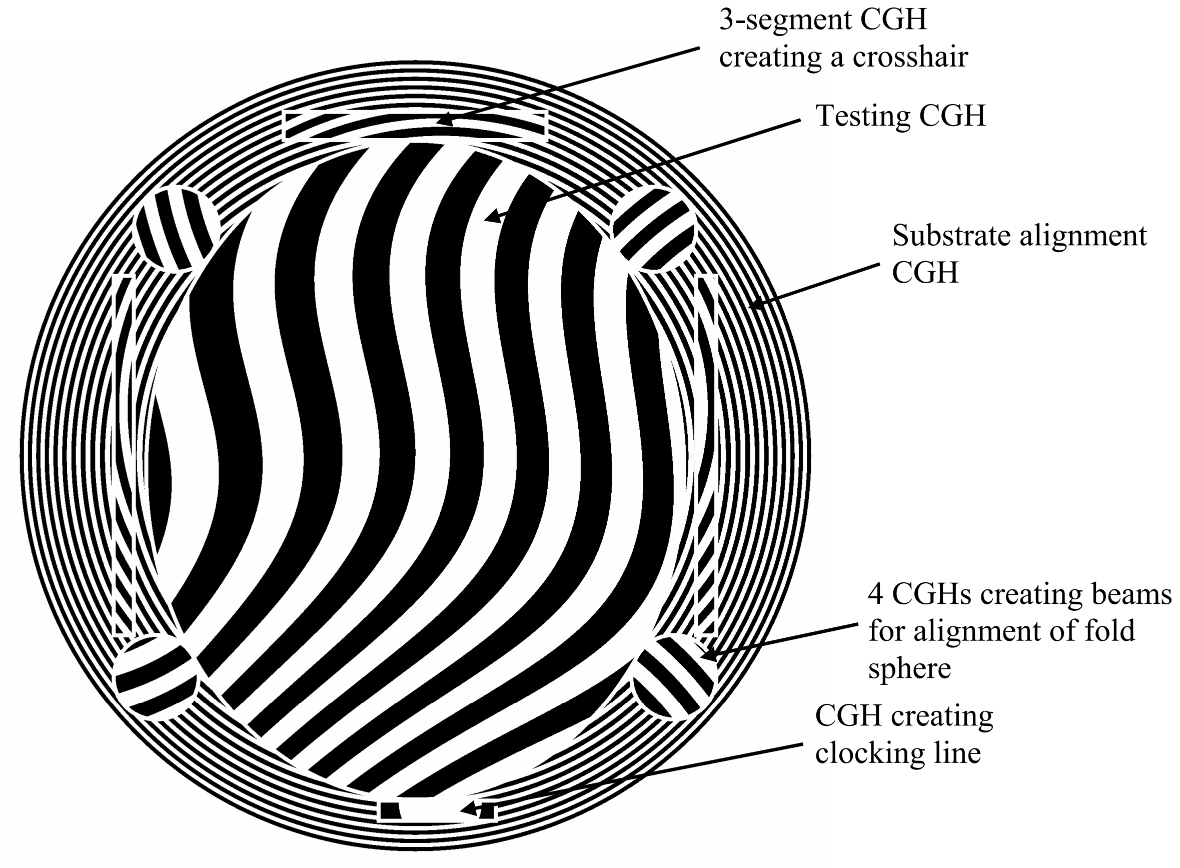


Figure 2. Fringe patterns of the testing CGH and all alignment CGHs fabricated on the same substrate with scale of 350waves/fringe.

Table 2. Description of the CGHs.

CGH	**Defined by**	**Order**	**Typical Fringe Spacing (µm)**
Main testing CGH	Grid phase	1	15-20
Substrate alignment CGH	Zernike fringe phase	3	6
CGH creating cross hair	Zernike fringe phase	3	6
CGH creating clocking line	Zernike fringe phase	1	24
CGHs for alignment of fold sphere	Zernike fringe phase	3	10

3.1 Alignment of the testing CGH

The Testing CGH itself as part of the null lens needs to be accurately aligned to the illuminating wavefront.[6,7] We designed a patch of CGH outside of the testing CGH to retroreflect the illuminating wavefront. The interferometer gives us the interference fringes between the reflected wavefront and the reference wavefront. When the CGH is in its nominal position, we get a null fringe. The substrate has three degrees of freedom of adjustment. By adjusting the axial position of the CGH substrate, we remove the power fringes; by adjusting the tilt, we remove the tilt fringes. Note that we did not control the clocking of the CGH substrate. The clocking of the testing CGH is not important since the illuminating wavefront is axi-symmetric, although the testing CGH is not. Whatever the testing CGH's orientation turns out to be, it determines the symmetry axis of the testing wavefront.

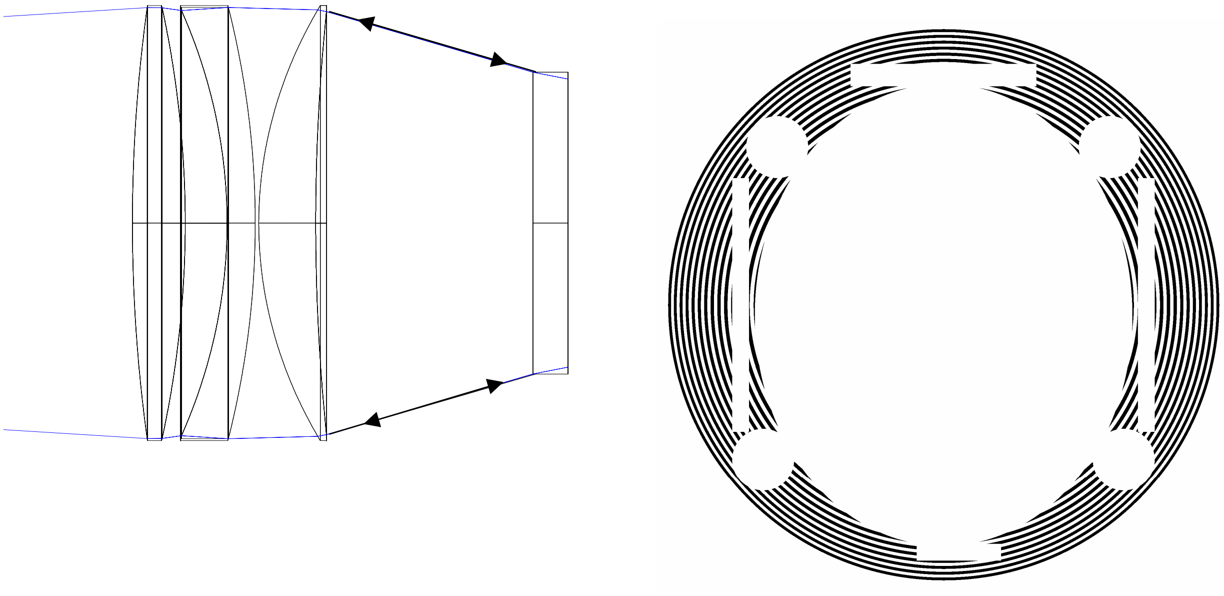

(a) (b)

Figure 3. Design of the CGH for alignment of the testing CGH. (a) The CGH retroreflects the illuminating spherical wavefront. (b) Scaled plot of the phase pattern of the CGH.

3.2 Alignment of the fold sphere

The 0.5m fold sphere needs to be aligned within 10µm in axial position and 10µm tilt at the edge. We used the main testing CGH's 0th order focus as one reference, and created 4 other references on the fold sphere with CGHs (see Figure 2 for the phase patterns and locations of the 4 CGHs), we then used metering rods to control the distances between the 0th order focus and the four references on the fold sphere. The 0th order wavefront is ideally spherical. We put a tooling ball at the focus, by nulling out the reflection fringes, the center of curvature of the ball is aligned to the 0th order focus. Four tooling balls are mounted at the fold sphere. The balls lateral positions can be adjusted. They keep contact with the surface of the sphere as their lateral positions are being adjusted. The 4 CGHs direct converging beams to focus on the center of curvature of the balls. The CGHs are fabricated in high accuracy such that the 4 beams are accurately known. We align the balls to these beams so that their lateral positions are accurately known, so are the nominal distances between them and the tooling at the 0th order focus. The alignment sequence is as follows:

1. Align the ball at the 0th order focus to null out the reflection fringes. Roughly align the 4 balls on the sphere to retroreflect the beams directed on them by the CGHs.
2. Put in place the metering rods. Adjust the fold sphere and record the change in length of the four metering rods. The influence function of each adjustment degree of freedom of the sphere on the lengths of the metering rods can then be determined. Take down the metering rods.
3. Accurately align the balls on the sphere so that the beams directed on them by the CGHs are retroreflected.
4. Put on the metering rods. Adjust the fold sphere according to the readings of the metering rods and the influence functions of three adjustment degree of freedom.
5. Repeat Steps 3-4 until the metering rods lengths converge to within their tolerances.

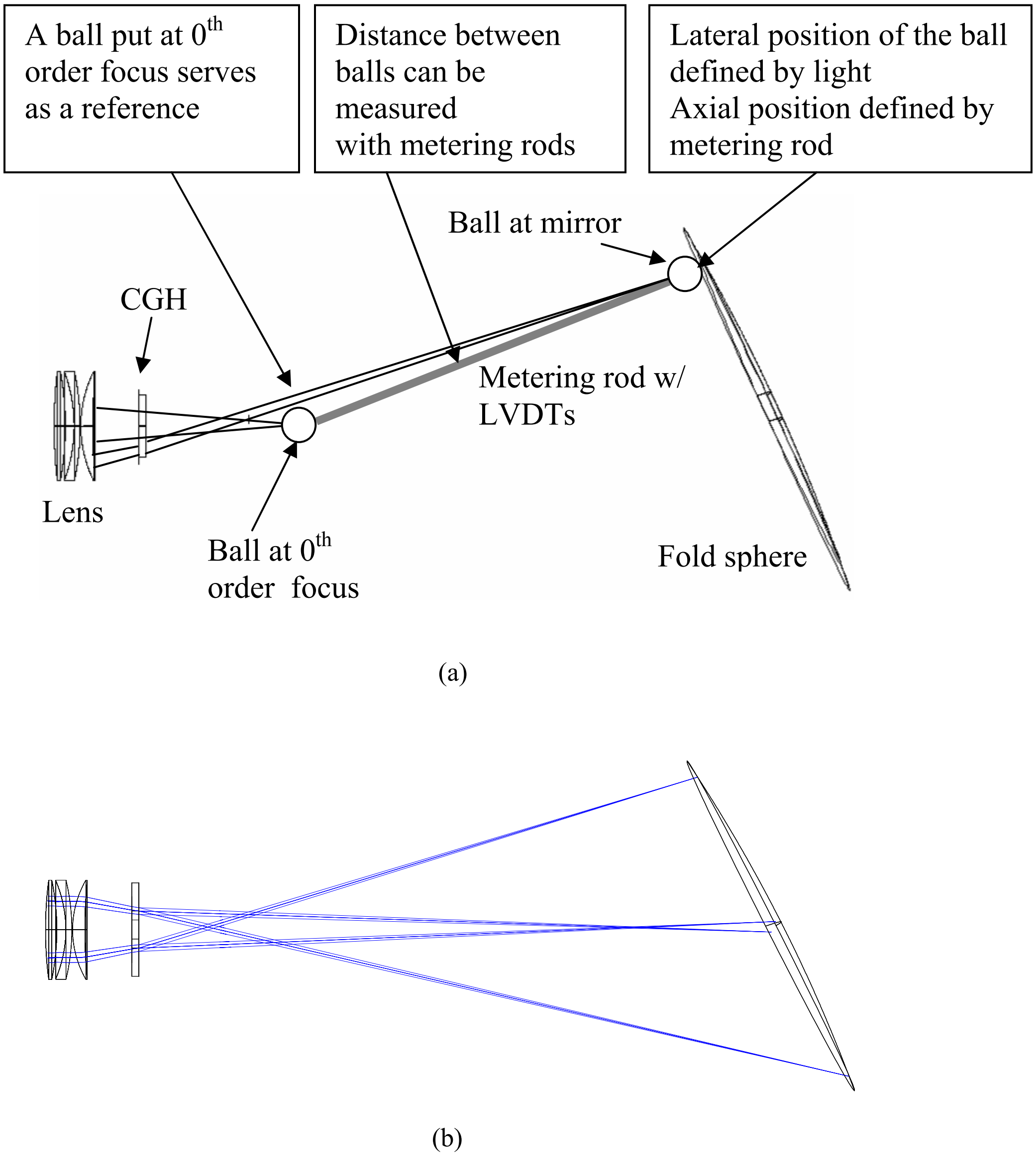
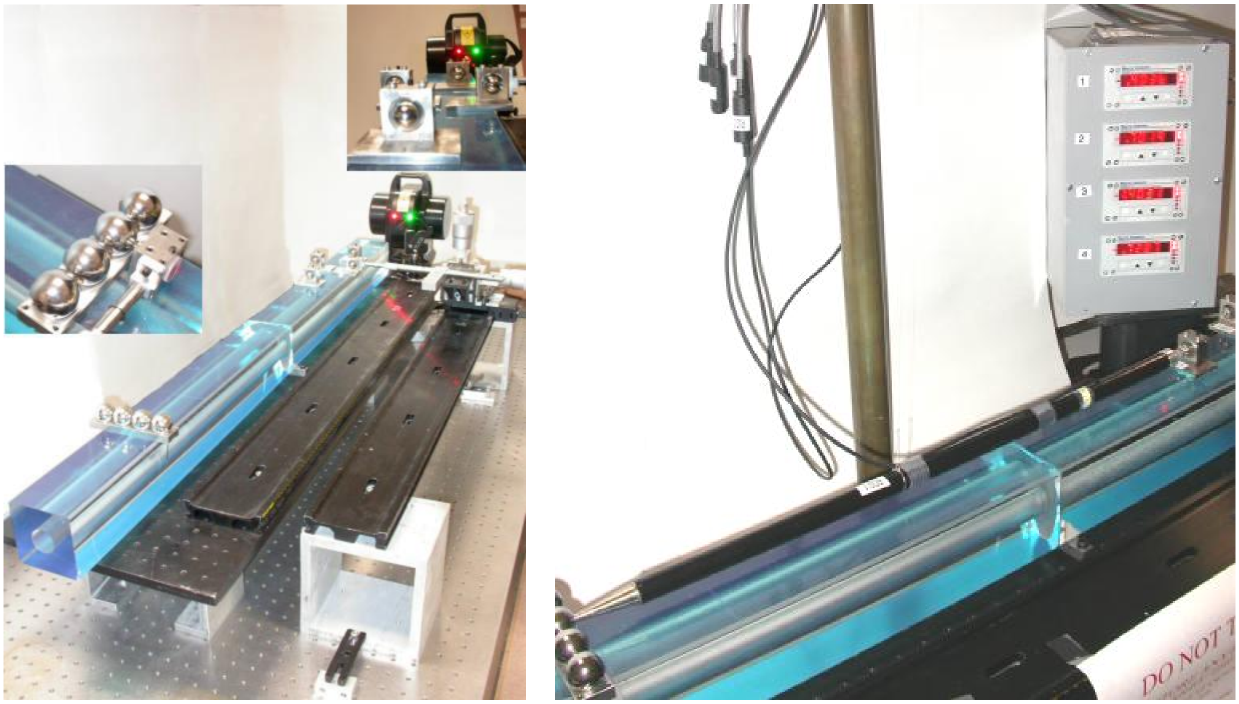


Figure 4. (a) Illustration of the alignment mechanism for the fold sphere. (b) Four CGHs are designed and fabricated to create four reference beams to help align the fold sphere. See Figure 2 for the phase patterns of these CGHs.

The metering rods are made of low thermal expansion carbon fiber tubes. One end is attached with a spherical tip made of invar to hold onto the ball at the 0th order focus. The other end is attached with a LVDT[8] which is calibrated such that it gives accurate reading of length change. The metering rods were calibrated with a laser tracker[9] working in mainly distance measuring mode. And the calibration stage was made with low thermal expansion ULE blocks. All these ensures the metering rods' readings have accuracy better than 3µm. Figure 5 shows the metering rods and the calibration bench. When the metering rods are in action, they are supported by strings attached to the test tower so that little load is felt by the balls. Figure 6. shows that metering rods are being used in actual alignment process.



(a) (b)

Figure 5. (a) Using laser tracker to calibrate the metering rod calibration bench which is made of ULE block. (b) Calibrate the metering rod with LVDT at one end.

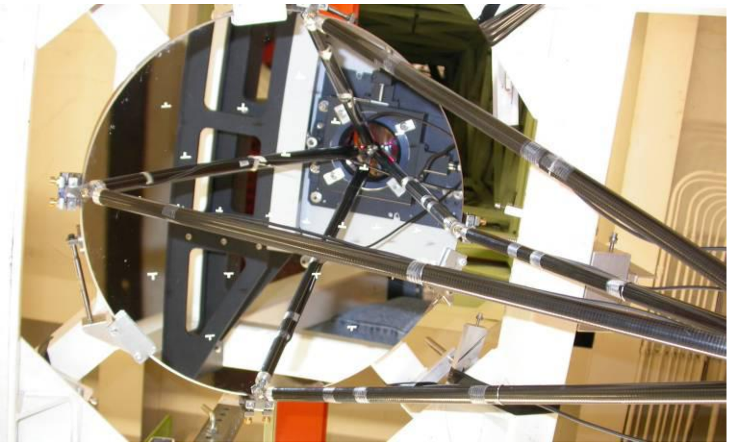


Figure 6. Aligning the fold sphere with metering rods.

To align the balls on the fold sphere to retroreflect the incident beams, we built a device which composes of a beam splitter and a CCD (see Figure 7). We look at two reflection spots on the CCD – one is from the rear surface of the beam splitter and the other is from the ball itself. Any tilt of the beam splitter relative to the incident beam will deflect the beam which causes the lateral shift of the ball. By looking at the reflection from the rear surface of the beam splitter we can align the beam splitter so that the beam is normal incident. By matching the reflection from the ball to the same spot as the reflection from the beam splitter's rear surface, we effectively align the balls to retroreflect the incident beams.

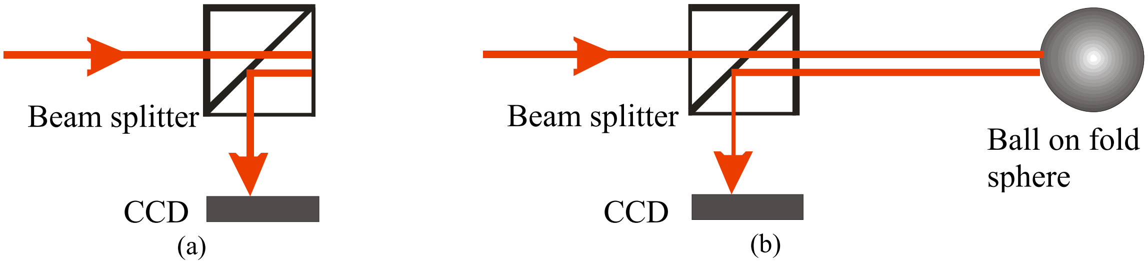


Figure 7. The principle of the device for aligning the ball to retroreflect the incident beam. (a) Illustrates how to align the beam splitter to the incident beam. (b) Align the ball by overlapping the reflection from the ball with the reflection from the beam splitter's rear surface.

3.3 Alignment of NST mirror to the testing wavefront

When the testing system is aligned and mounted on the test tower, we need to move the test mirror to the right place to get the return beam into the interferometer and obtain fringes. Since the test mirror is 6.5m away from the testing system, we need some references to aid the process. Again we used CGH to create the needed reference. We designed CGHs to focus the laser beam onto two designated points on the NST mirror. Since we have no space to make the entire pattern of the CGHs, nor do we have to, we made the patterns in small apertures as shown in Figure 8(c). This way we still have enough power in the focus spots, and the diffraction effect of the limited aperture creates a cross hair and a clocking line instead of sharp spots, which is easily visible, therefore more advantages for our purpose of alignment. We placed the test mirror according to the positions of the cross hair and clocking line. From there, we can adjust its position to get fringes.

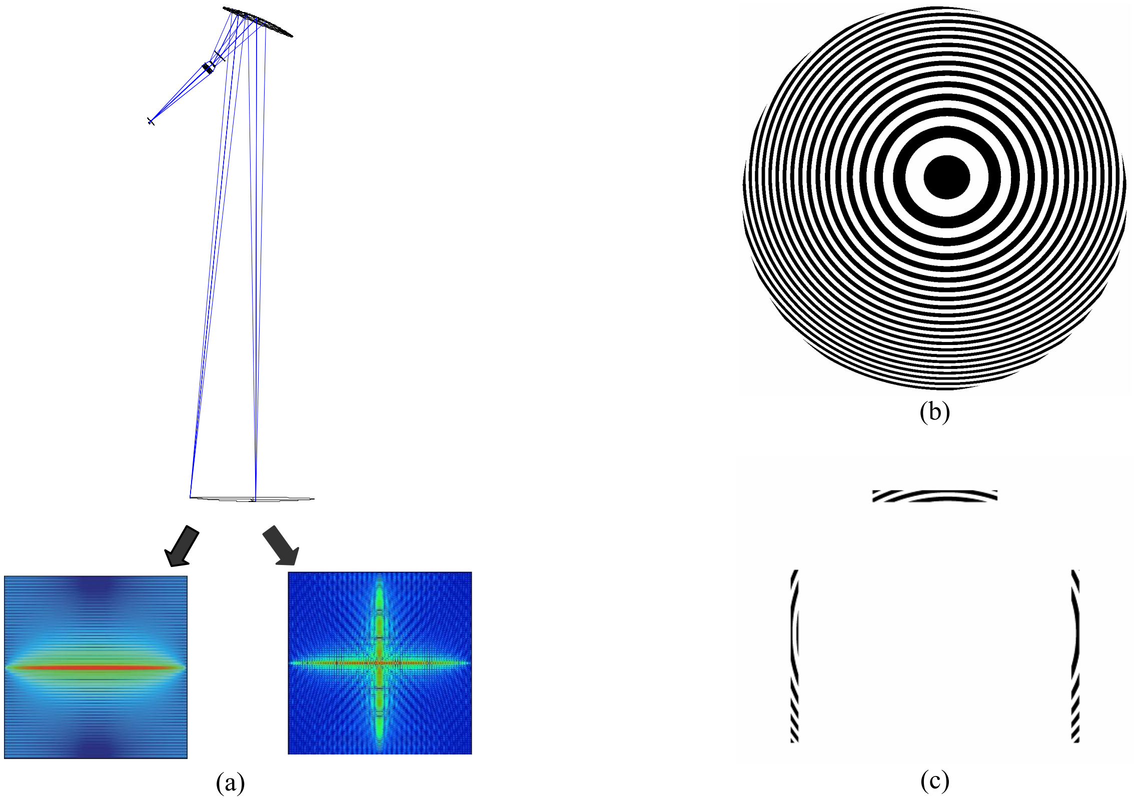


Figure 8. CGHs are designed to project a cross hair and a clocking line to help align the test mirror to the testing wavefront. (a) Plot of the system layout and pictures of the produced marks. (b) The phase pattern of the CGH focusing light onto the location of the cross hair. (c) The actual CGH fabricated to create the cross hair. The phase pattern of the CGH for creating the clocking line is designed similarly. Only it is fabricated in a bar-type aperture as shown in Figure 2 and the diffraction effect makes it a line.

The references created with this technique can be used not only for rough alignment of the test mirror, but also for precision alignment when a CCD camera is employed to determine their accurate locations.

4. SUMMARY

CGHs that are accurately fabricated on a precision substrate can be used in general optical alignment. In this paper, we presented several techniques using CGHs to align null corrector optics and the test optic. These techniques have been used in aligning the testing system for the primary mirror of the New Solar Telescope and they will be used again in the alignment of testing system for the primary segments of the Giant Magellen Telescope.[10]

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