Absolute calibration of null correctors using twin computer-generated holograms

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ABSTRACT

We present a method for a cascading null test using twin computer-generated holograms to calibrate errors in null correctors. This will allow us to test large aspheres an order of magnitude better than current limits. We discuss various sources of CGH errors and how to calibrate them. We also mention some ways to measure and calibrate the errors in the test optics.

1. INTRODUCTION

CGHs are very powerful optical elements because they can encode a wavefront of any desired shape. Thus, they are very useful in the null test of aspheres [1]. For high-accuracy testing of large aspheres, the errors in the CGH need to be carefully characterized [2]. Current limitations in testing have prevented tests of large aspheric mirrors to better than 8-10nm rms. This paper is divided into the following sections: 1.1 Definition of types of errors, 1.2 Twin-CGHs, 1.3 Transfer of errors from sphere to asphere, 2 Errors, 2.1 Calibrating CGH errors, 2.2 Calibrating test system errors, 2.3 Mapping distortions, 3 Cascading test, 4 Initial results, 5 Future work and 6 Conclusions.

1.1 Definition of types of errors

Calibration of null correctors must be done very carefully. Burge [3] has shown how CGHs may be used to certify null correctors. A detailed error analysis must be made of such a test. Errors from such a test can be divided into 2 categories: 1. High frequency errors, and 2. Low frequency errors. Furthermore, the low frequency errors can be divided into axisymmetric and non-axisymmetric parts as shown in figure 1.

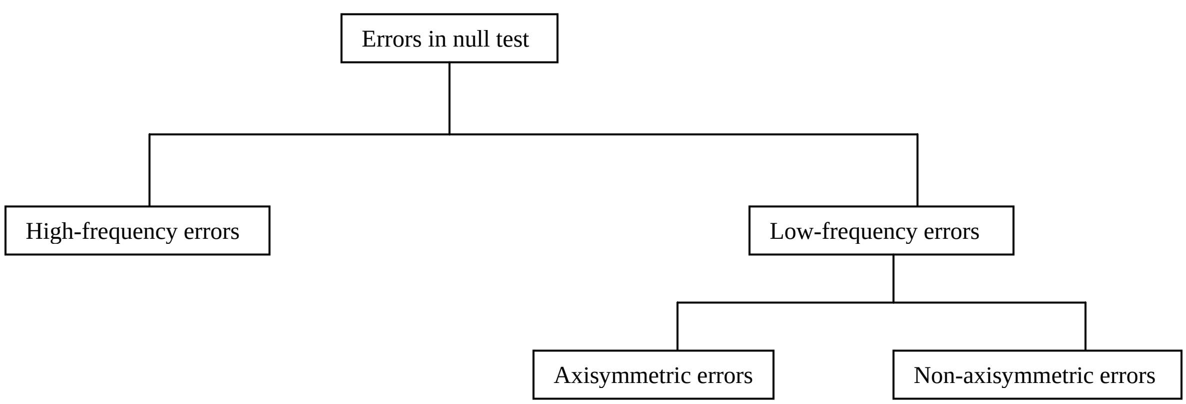

Figure 1. Above is a flowchart of the different types of errors in a test and calibration of a null lens.

It isn't fully clear what the dividing line between high-frequency and low-frequency errors are and that is part of our investigations.

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1.2 Twin-CGHs

A method for absolute interferometric testing of axially symmetric aspheres has been devised by Reichelt et al [4]. This method involves the use of a specially designed CGH that reconstructs both the aspherical and spherical auxiliary waves. Such a CGH is referred to as a twin-CGH. The twin-CGH is segmented into 4 quadrants as shown in figure 2. The spherical and aspherical patterns are encoded onto the CGH simultaneously, and thus the errors in the spherical pattern can be transferred to the aspherical pattern directly (see figure 3). The errors in the spherical pattern are measured absolutely [5].

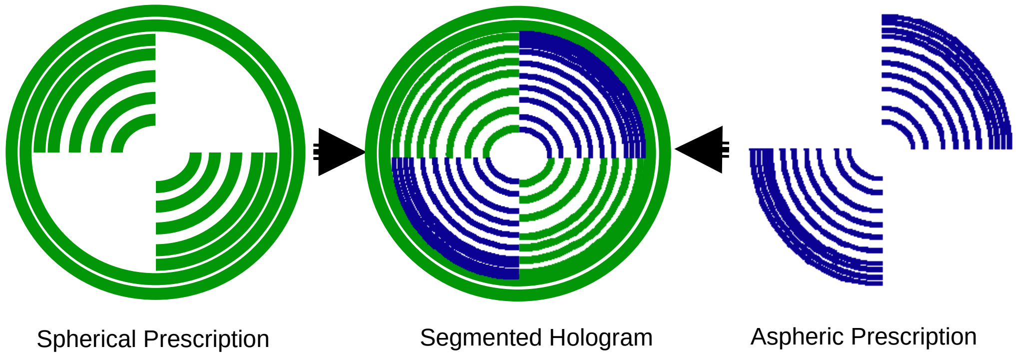


Figure 2. The twin-CGH is segmented into 4 quadrants as shown above.

1.3 Transfer of errors from sphere to asphere

Knowledge of the errors from the spherical quadrants of the CGH can be transferred in a straightforward manner to the errors in the aspherical quadrants as shown in figure 3.

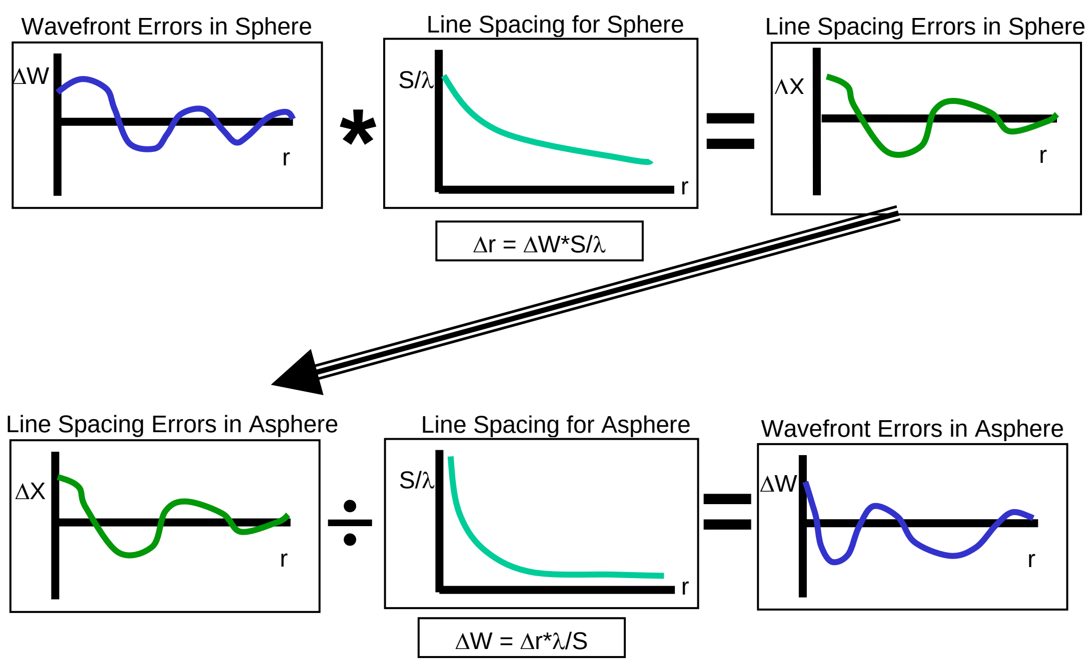


Figure 3. The transfer of knowledge of errors in the spherical quadrants to the aspherical quadrants will allow us to calibrate the aspheric wavefronts accurately.

2. ERRORS

2.1 Calibrating CGH errors

There are several methods of measuring and calibrating CGH errors. It is important to be able to separate figure errors and pattern errors of the CGH. Pattern errors are caused due to etching depth, duty cycle and pattern distortion variations from ideal [6]. Figure errors in the CGH substrate are the most critical errors for phase reconstruction.

Recent experiments on CGHs with different duty cycles and etching depths have given us a better idea of how these variations influence wavefront errors. A parametric model has been developed by Ping Zhou et al (to be published) that relates CGH fabrication errors with wavefront errors.

2.2 Calibrating test system errors

Removal of errors in the test optics is critical to our being able to make measurements to better than lambda/1000. These errors can be divided into rotationally symmetric and non-rotationally symmetric errors [7]. Non-rotationally symmetric errors may be removed by rotating either the test part or the reference part to N equally spaced positions.

Another convenient method to calibrate errors in the interferometer involves using a ball [8]. A ball is placed such that its center is at the center of curvature of the reference sphere. By rotating the ball to several positions and by averaging the measurements, the errors in the reference sphere can be determined.

2.3 Mapping distortions

There are mapping distortions caused by the mapping of the asphere position onto the CGH plane [9]. For a CGH at paraxial focus, the rays map from the mirror to the CGH according to

$$x(r) \cong \frac{-Kr^3}{2R^2},$$

and the wavefront created by the CGH can be approximated as

$$OPD = -\frac{3Kr^4}{8R^3},$$

where r = radial asphere position
R = paraxial radius of curvature of asphere
K = conic constant of asphere
x(r) = ray intercept position on CGH corresponding to r on asphere

The above formulas are truncated terms in a power series, and for accurate calibration of these errors more terms may need to be used.

We plan on using the methods mentioned above to carefully calibrate the errors of our test system.

3. CASCADING TEST

To test large aspheres to a high degree of accuracy (better than lambda/1000) we have devised a cascading null test. We will first calibrate the errors of the twin-CGH absolutely. Using these calibration results we will use the twin-CGH to test the null corrector. Once the errors in the null corrector are calibrated, we can use it to test the asphere.

There are at least 2 reasons why a cascading null test is essential for the success of our measurements. A CGH may be used as a null lens directly. However, due to the inherent nature of writing a CGH, high-frequency errors may be present in the pattern. This will result in our being unable to separate high frequency errors in the aspheric mirror from those in the CGH. Secondly, aspheres of a large diameter have large aspheric departures from the best fitting sphere. This results in very large mapping errors from the CGH to the test mirror.

A test stand is being assembled to enable us to measure the twin-CGH and the null corrector. The twin-CGH is 220mm in diameter with a wavefront radius of curvature (RoC) of 7600mm for the aspherical quadrants and wavefront RoC of 350mm for the spherical quadrants. The aspherical quadrants of the twin-CGH simulate a mirror with a diameter of 4.5 meters and a focal ratio of f/0.85.

4. INITIAL RESULTS

The large, 220mm diameter, CGHs have been fabricated. Below is a picture of the fringe pattern of the substrate for one of the CGHs. Also shown is a photograph of the fabricated CGH.

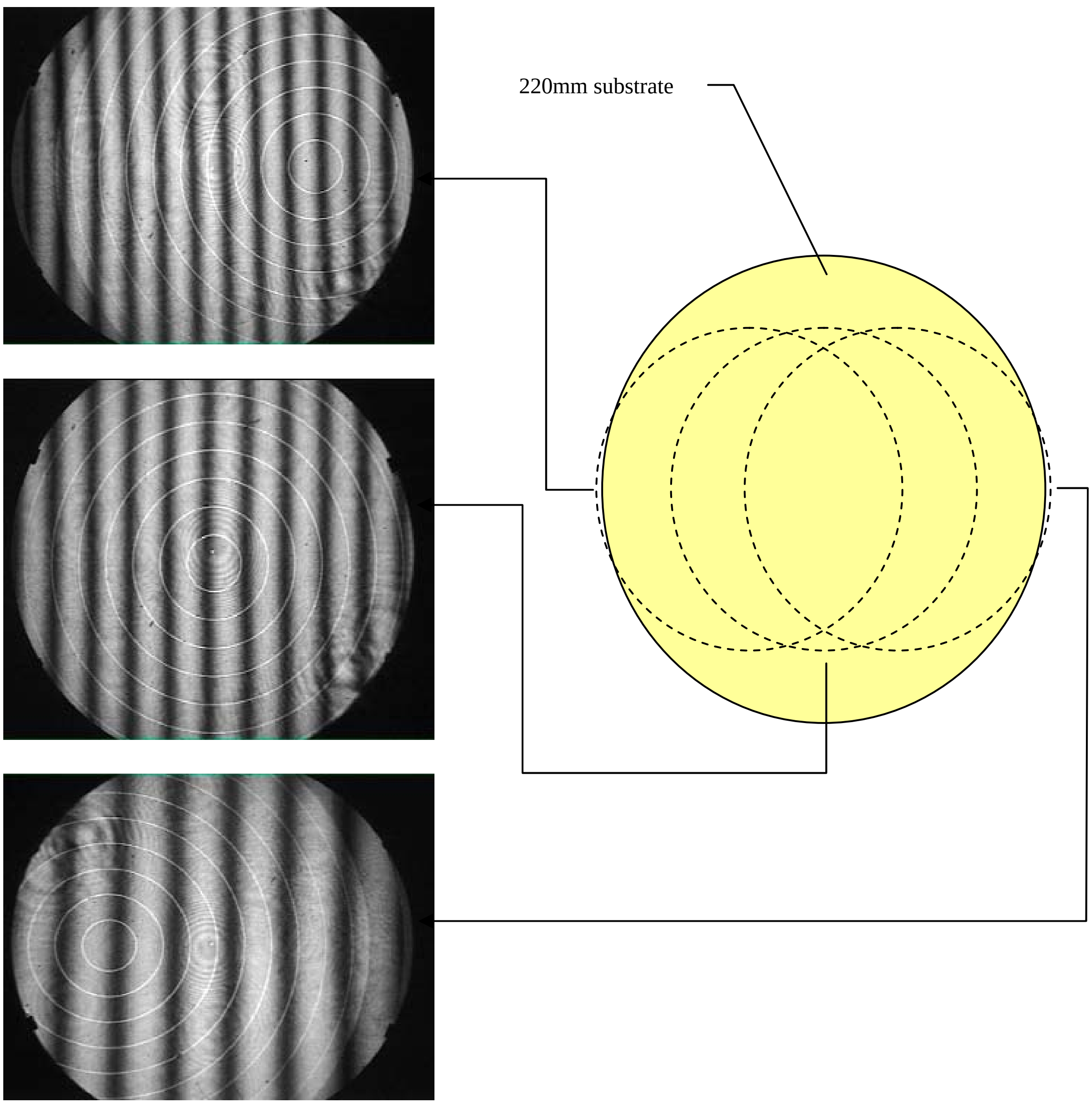


Figure 4: Interferograms (on reflection, 150mm field) of 220mm substrates and locations of interferograms on substrate

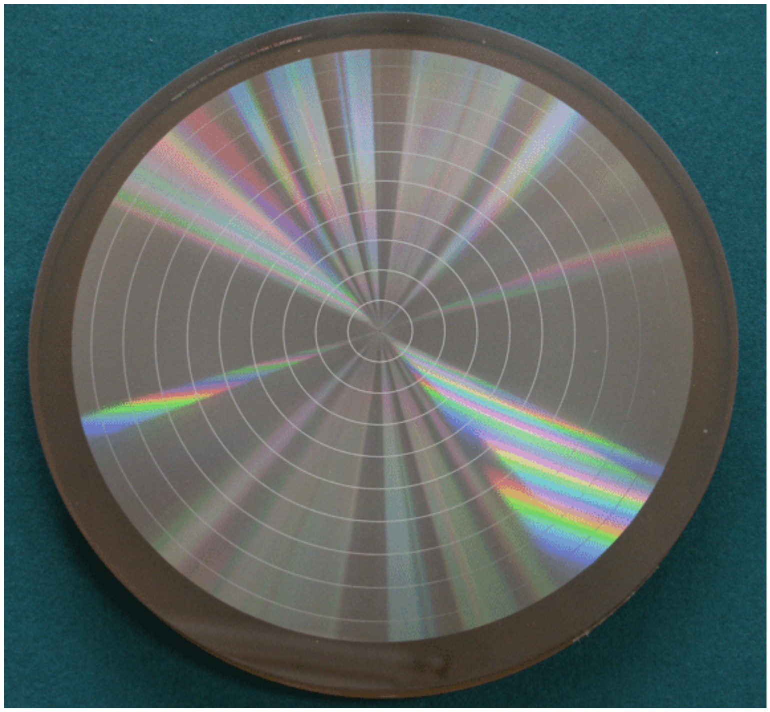
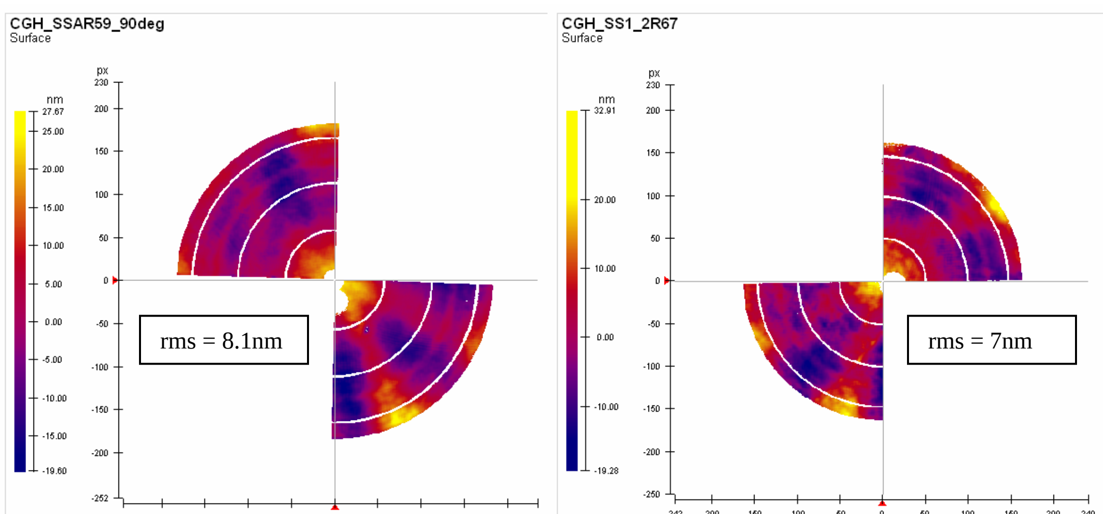


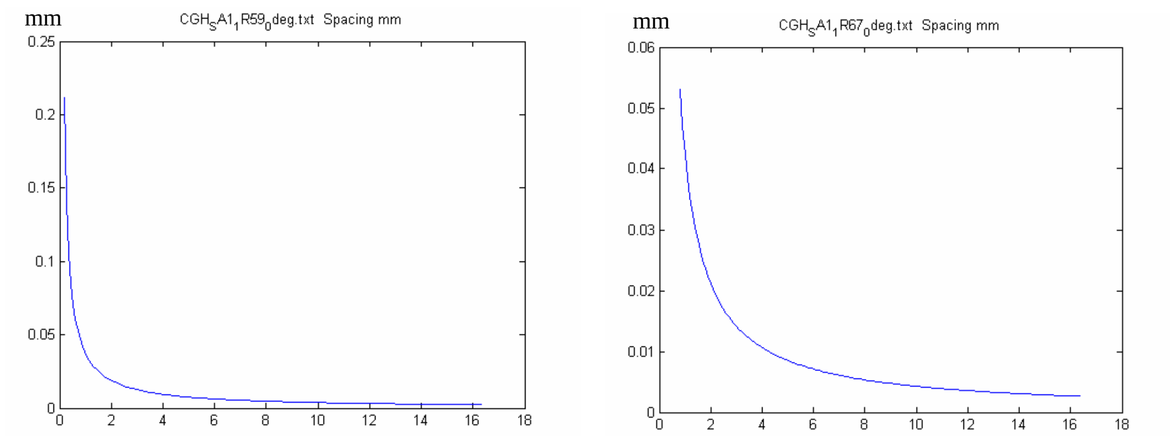
Figure 5: Photograph of fabricated CGH

2 prototype twin-CGHs were fabricated and the quadrants with the spherical prescription were tested. These twin-CGHs are 35mm in diameter, with a wavefront RoC of about 60mm. The wavefronts from the spherical quadrants of the 2 CGHs tested are shown in figure 6. Below the wavefront map corresponding to each CGH is the line spacing error and the resulting wavefront error. As shown in figure 6, the CGH line spacing is obtained from the test wavefronts. The line spacing error is then calculated. The CGH surface error is obtained from the line spacing error.

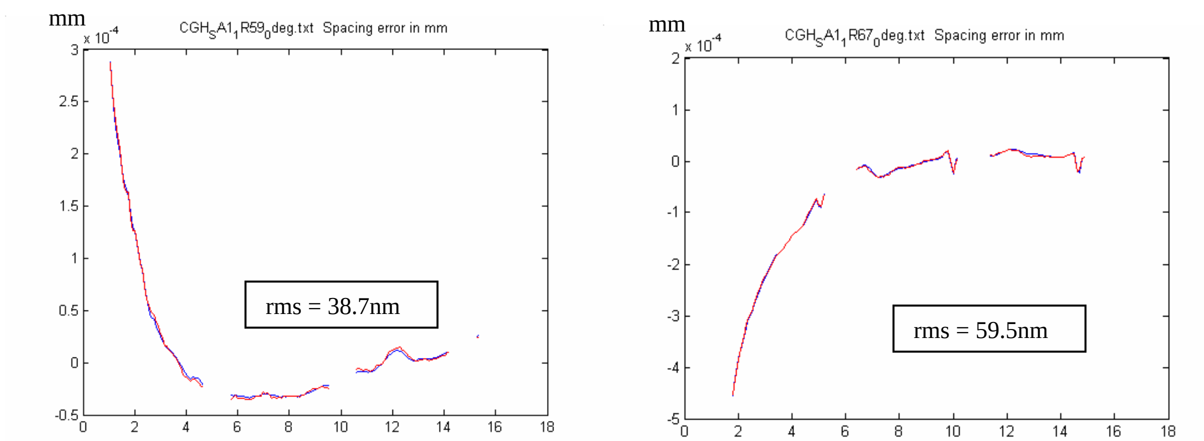
The overall errors from the 2 CGHs match to about 10nm root mean square (rms), which will result in the wavefront errors matching to better than 2nm rms. These results are plotted in figure 7. This gives us confidence that we can calibrate the twin-CGH errors and the null corrector errors to a high degree of accuracy.



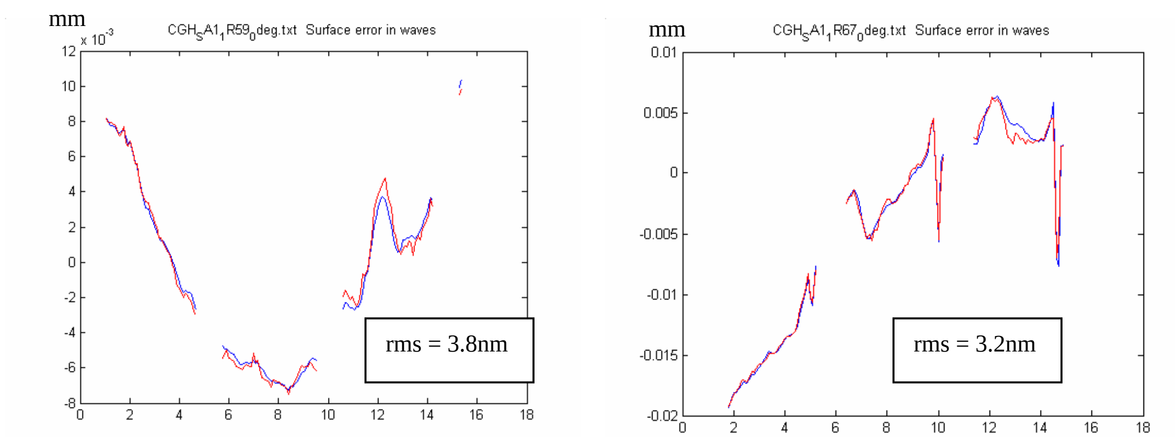
Surface map (in nm)



Line spacing: y-axis is line spacing; x-axis is radial position on CGH in mm.



Line spacing error: y-axis is line spacing error; x-axis is radial position on CGH in mm.



Surface error: y-axis is CGH surface error; x-axis is radial position on CGH in mm.

Figure 6: The CGH surface map, line spacing, line spacing error and the surface error are shown above.

The wavefront errors are calculated and shown in figure 5 below.

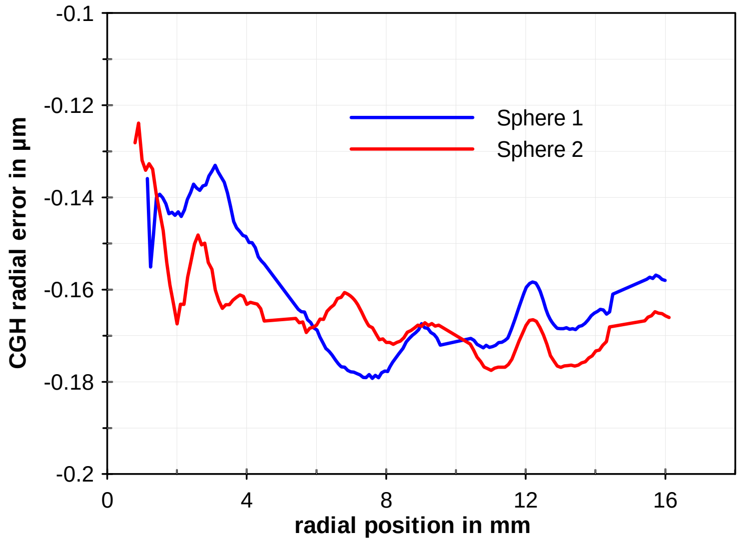


Figure 7: CGH wavefront errors are plotted above. Sphere 1 and Sphere 2 refer to each CGH. Only the quadrants with spherical prescription were tested.

5. FUTURE WORK

The test stand needs to be assembled and the large twin-CGHs need to be tested. The aspheric quadrants of the twin-CGH will simulate a large asphere. This will be tested using the null corrector. Carefully keeping track of all our test errors, we should be able to test large aspheres (~4m in diameter) to better than lambda/1000.

6. CONCLUSIONS

We have described a cascading null test for large aspheres. This type of test is particularly useful for measuring large aspheres with large aspheric departures from the ideal best-fit sphere. In fact, our scheme is essential in being able to test such aspheres to better than lambda/1000. This will further the limits of aspheric testing.

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