VACUUM SUPPORT FOR A LARGE INTERFEROMETRIC REFERENCE SURFACE

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OVERVIEW

This paper presents a vacuum support technique for a Fizeau type interferometer that uses a 1.1 m diameter reference surface. The interferometer uses Computer Generated Holograms (CGHs) for aspheric measurement, illumination optics and imaging optics. To reduce the effects of air turbulence and retrace error, the gap between the reference surface and Unit Under Test (UUT) is limited to 5 mm. The illumination optics consist of two lenses, one of which we call the test plate which includes the reference surface. The 1.1-m diameter illumination optics are quite heavy, 212 kg, and are prone to self-weight deflection problems. We solve this with a vacuum support of the test plate. A vacuum region is created between the two lenses in the illumination optics using a rubber seal. The upper lens of the illumination optics suffers extra deflection caused by vacuum. However, since this lens is in the common path of the interferometer this does not cause significant error in the interferogram.

In this paper, a simple experiment on a small surface and analyses on a large model are discussed. In the simple experiment the deflection of flat surfaces having 100mm in diameter and 2.7mm in thickness was measured by a Wyko 6000 interferometer. The region between the two flat surfaces was sealed by an O-ring and a needle was inserted into the O-ring so that the sealed region could be evacuated. This experiment shows correspondence of less than 10 % between the simulation and the experiment. A finite element model simulation of the vacuum support for the 1.1-m test plate is also presented. The nominal surface slope irregularity caused by gravity at the reference surface is 26.88 nm/cm RMS. When a differential pressure is equal to 2300 Pa, the deflection is minimized to 0.75 nm/cm RMS. Based on an optical simulation of the system, this deflection introduces only 8.0 nm RMS into the measurement error. Therefore the vacuum support can be useful for reducing the effect of gravity on the reference surface.

INTRODUCTION

Large convex and flat optics are accurately and efficiently measured using Fizeau interferometry, where the reference optic may be a meter or larger in diameter. The self-weight deflection of the reference optic must be considered. Any unknown shape change will cause an error in the measurement. Even a shape change that is well known will affect the measurement by increasing the dynamic range. It is possible to polish the inverse of the deflection into the optic so that the gravity effect is canceled, but this is difficult to do in practice.

M. B. Dubin et al. designed a Fizeau type interferometer to measure a secondary mirror for a telescope as shown in Figure 1[1].

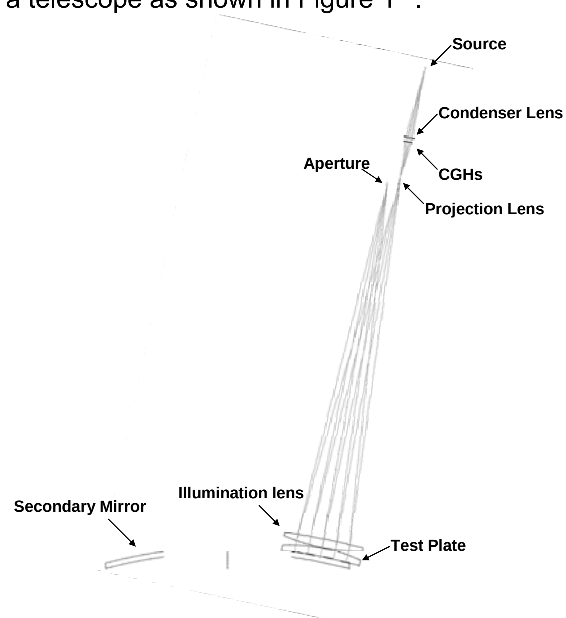


FIGURE 1. A Fizeau type interferometer having 1.1-m diameter reference surface measures a secondary mirror for a telescope.

In this case, the test plate including a reference surface would be bent because of the gravity. It becomes a problem, since the test plate itself would be flipped around after polishing the reference surface. Reducing the unexpected bending in the reference surface is required. For this purpose, evacuating air between the test plate and the illumination lens can be useful and effective for compensating the bending caused by the gravity.

REQUIREMENTS

Requirements for the vacuum support are listed in Table 1.

TABLE 1. Requirements and Verifications for the vacuum support.

	Requirement		Verification
1.	Difference between simulation and experiment	< 20 %	Test
2.	Supported by the edge face	NA	Inspection
3.	Surface slope irregularity	< 10 nm/cm RMS	Analysis
4.	Resonant Frequency	> 30 Hz	Analysis
5.	Stability - Power - w/o Power	 20 [nm] 3 [nm]	Analysis

The second requirement of "Supported by the edge" means that the test plate should be supported along the outer circumference, because there is not enough space under the test plate.

EXPERIMENT

Experimental Setup

This section validates the first requirement of difference between simulation and experiment is less than 20 % by a simple experiment.

Two flat surfaces made by Valley Design Corp. were used for this experiment. The flat surfaces were made from Borofloat, 100 mm in diameter, 2.69 mm in thickness, standard polished finish, and 60/40 scratch/dig. The surface flatness was measured by Unilamp made by Midwest Scientific Co. There were about 10 fringes on the flat surfaces.

A schematic of the vacuum system is shown in Figure 2 and the actual system is shown in Figure 3. The needle inserted into the O-ring connects to the vacuum system consisted of a vacuum pump, a reservoir, a leak valve, and a pressure gage.

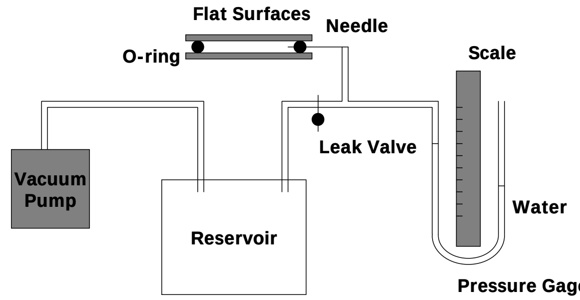


FIGURE 2. A schematic vacuum system for the simple experiments.

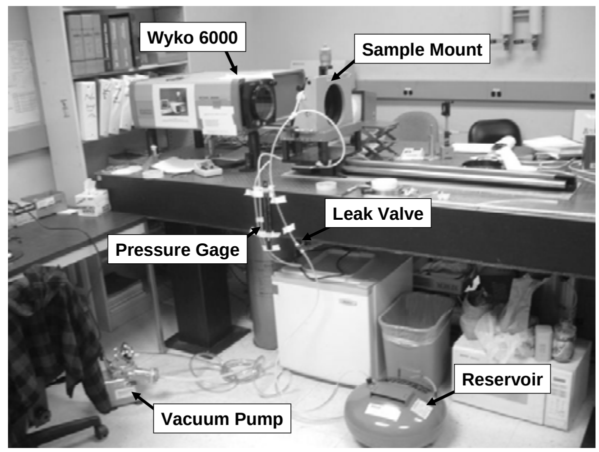


FIGURE 3. The actual vacuum system for the simple experiments.

The pressure gage consists of just a tube filled with water and a scale so that a sensitive vacuum level measurement can be achieved in low cost. In this experiment, a sensitivity required in the pressure gage was relatively tight because a little pressure change can affect the interferogram easily. Also, the pressure should be measured relative to atmosphere or ambient pressure. Then, a water height gage was chosen. Since 1 atmosphere is equivalent to 10.3 m in water height, the height of 101.7 mm is changed in 1000 Pa.

The flat and simply supported surface deflection caused by uniform loading can be calculated by using the following equation.

$$\delta_{\max}(P) = C_D \left(\frac{P}{E}\right) \frac{r^4}{h^3} \left(1-\nu^2\right) \cos\theta$$

δ_{max} is the maximum surface deflection, C_D is the deflection constant, P is the pressure, E is the elastic modulus, r is the radius of the evacuated area, h is the thickness of the flat surface, v is the Poisson's ratio, and θ is the angle between the optical axis and local vertical. In this experiment, C_D = 0.828 (Edge simply supported) for the O-ring, E = 64 GPa, v = 0.2 for Borofloat glass, r = 43.125 mm, h = 2.69 mm, and θ = 0. When P = 1000 Pa, the maximum deflection δ_{max} becomes 2.21 μm. 2.21 μm is enough to obtain reasonable accuracy with the interferometer. Thus our target of vacuum level for the system was 1000 Pa.

The flat surfaces were set in front of Wyko 6000 interferometer as shown in Figure 4.

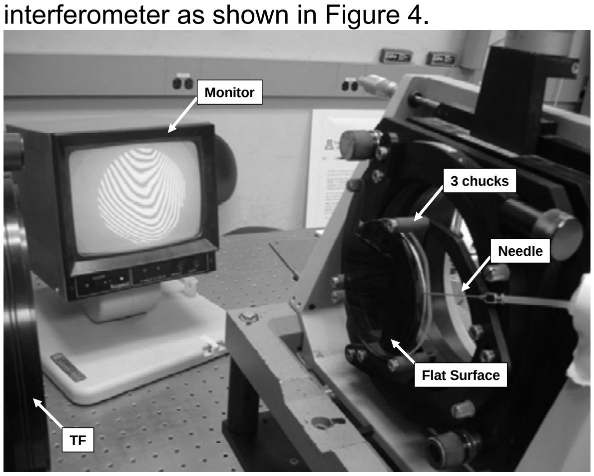


FIGURE 4. Flat surface is mounted in front of the interferometer.

A region between two flat surfaces was sealed by an O-ring similar to E. Everhart's method[2]. A needle was inserted into the O-ring so that the sealed region could be evacuated. The diameter of the O-ring was 86.25 mm and the thickness was 5.6 mm, and the diameter of the needle is 1.06 mm. The O-ring and the two flat surfaces were glued by RTV157 to prevent leaking from the small cavity between them. The back surface of the flat surface measured by an interferometer was coated by #33 Liquid made by Universal Shellac & Supply company, Inc. to avoid a reflection from the back surface affecting the interferogram.

Experimental Results

Figure 5 shows the relationship between pressure and Power term (Zernike 4th term (Z4)) for both the experimental data and simulation data. The experimental data is shown in solid line with error bars and simulation data is shown in dashed line. The relationship between pressure and Power term (Z4) is linear with as ratio of 5.82E-4 μm/Pa in the experiment and 5.87E-4 μm/Pa in the simulation. In the experimental data, the solid line connects the average points calculated by 3 same pressures. Also, each data points have error bars calculated from the 3 same pressures. Figure 5 shows the excellent correspondence between the experimental data and the simulation data in this region. The maximum difference between experiment and simulation is 9.6 % at 275 Pa. As G. Lemaitre mentioned, ρ^4 term (Zernike 11th term (Z11)) was also appeared as shown in Figure 6[3]. The maximum difference between experiment and simulation is 9.9 % at 275 Pa. This experiment shows correspondence of less than 10 % between a simulation and an experiment, which meets the requirement of 20 %.

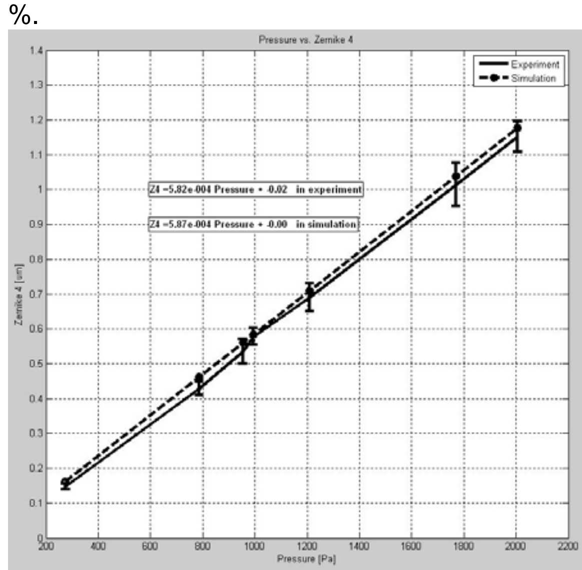


FIGURE 5. Pressure vs. Zernike 4th term.

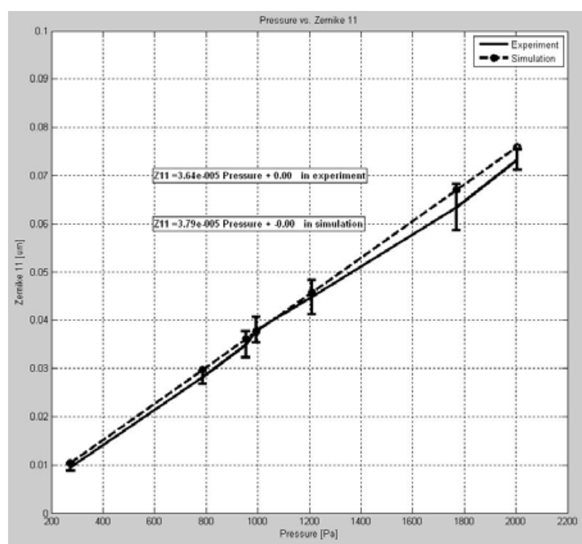


FIGURE 6. Pressure vs. Zernike 11th term.

ANASYSIS

Design Concept

Figure 7 shows a design concept for the 1.1-m diameter test plate. Three 2-axis flexures support the test plate laterally, and three hard contacts support the test plate axially. The 2-axis flexure is connected to the test plate via Invar parts. The Invar parts are intermediate parts to prevent stress caused by a difference of thermal expansion coefficients of the test plate and the flexures. The three hard contacts are located on the flange of the test plate. This flexure system allows the test plate to be compliant in lateral direction and stiff in axial direction. In addition, the hard contacts are used to measure the pressure required to support the test plate with load cells.

As Figure 7 shows, the test plate is supported along the outer circumference, because there is not enough space under the test plate. This meets the second requirement.

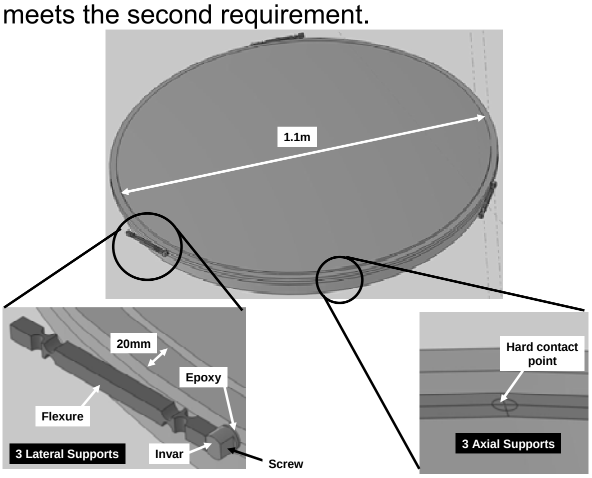


FIGURE 7. The test plate is supported by three flexures and three hard contacts along to outer circumferential.

Figure 8 shows a schematic of the hard contact. The test plate has the flange around the edge surface, which has 20 mm in radial direction and 20 mm in axial direction. There are three load cells, part number LLB300 made by Futek Advanced Sensor Technology Inc. The maximum load capacity is 500 lbs. (227 kg) and nonlinearity is 0.5 %. These three load cells are located under the flange of the test plate to measure the actual lens weight. When the test plate is supported by vacuum, the lens's weight is changed based on the pressure level. Since it is difficult to measure in-situ vacuum pressure precisely, the load cells are used instead of a pressure gauge. Also, by measuring the lens's weight at three different points, non-uniformity of a sealing, such as tilt, will be known.

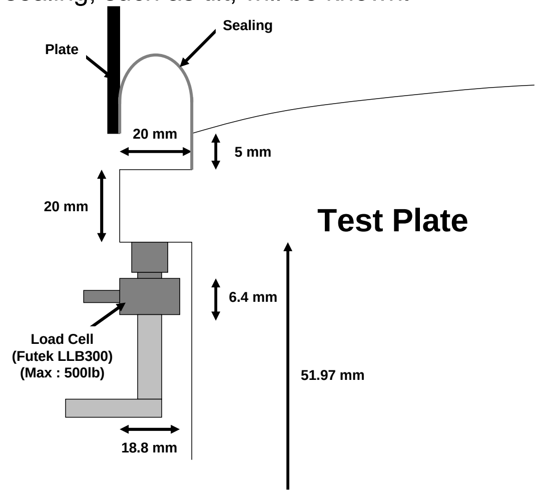


FIGURE 8. A schematic of Hard contact and Load cell.

Surface Slope Irregularity

A relationship between pressure and surface slope irregularity of the test plate was simulated including a seal. This means that gravity, pressure on the reference surface of the test plate, and force on edge of the test plate caused by vacuum were applied to the simulation of surface slope irregularity. A cross section diagram regarding the sealing effect is shown in Figure 9.

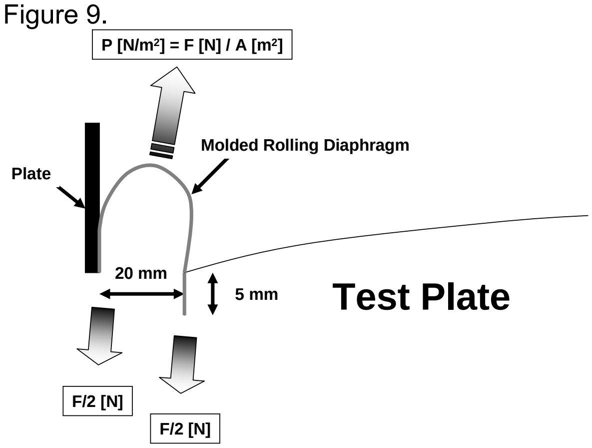


FIGURE 9. A schematic of Sealing effect.

The evacuated area is sealed by a plate and a molded rolling diaphragm. Since the plate can be considered as a rigid part, it is not bent by vacuum. But, the molded rolling diaphragm is bent by vacuum as shown in Figure 9. The reason why the shape of the sealing material is like an inverse of "U" is to allow the test plate move laterally and axially. Above pressure caused by vacuum creates below forces in

Figure 9. A force on the test plate is half of the force caused by vacuum basically. Because of choosing the molded rolling diaphragm, the force on the test plate is almost parallel to the optical axis. The difference between the surface slope irregularity with the force on the test plate and without the force is only 0.13 nm/cm RMS at 2300 Pa. Then, the amount and direction of the force on the test plate does not affect the surface slope irregularity.

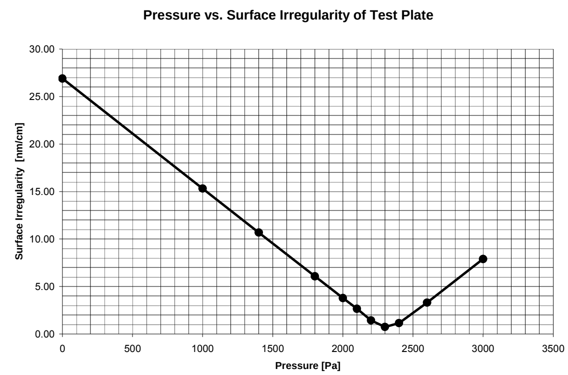
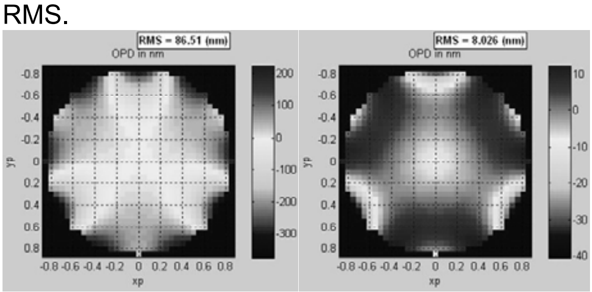


FIGURE 10. Pressure vs. Surface slope irregularity.

Figure 10 shows the relationship between pressure and surface slope irregularity when the sealing effect is considered. When the area between the test plate and the illumination lens is evacuated to 2300 Pa, the surface slope irregularity is minimized to 0.75 nm/cm RMS. When pressure is equal to 2300 Pa, the force on the test plate caused by the sealing is 80.3 N.

Figure 11 shows the interferograms of the system without the vacuum support and with the vacuum support. The vacuum support can reduce an error from 86.5 nm RMS to 8.0 nm RMS.



Without Vacuum Support

With Vacuum Support

FIGURE 11. Interferograms of the system without the vacuum support and with the vacuum support.

When the test plate has a decenter of 100 um, the area of the sealing material, which should be taken into account to calculate the force on the test plate, changes. This means that the force on the test plate also changes about 0.4 N. However, the change of the surface slope irregularity is only 0.02 nm/cm RMS in the case of 0.4 N, then the decenter of the test plate does not affect the surface slope irregularity.

Next, moments caused by flexure supporting the test plate laterally was considered. This effect is not dependent from vacuum level. When the flexures are attached to the test plate or other mechanical components, there are appropriate tolerances. Since these tolerances make the flexures bend and distort, then these bending and distortion create moment on the attached surface of the test plate.
In the case of the flexure shown in Figure 7, a tolerance of 96 um causes a torque of 0.2 N-m. When a flexure has a torque of 0.2 N-m, the simulated deflection is shown in Figure 12.

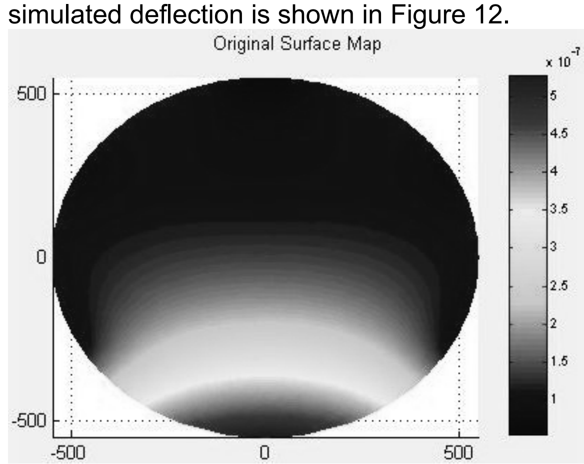


FIGURE 12. Simulated deflection is shown when a flexure has a torque of 0.2 N-m.

The surface slope irregularity is 2.71 nm/cm RMS. Since the surface slope irregularity can be summed up by root sum square (RSS), the surface slope irregularity with three tolerated flexure becomes 4.69 nm/cm. When the original surface slope irregularity of 0.75 nm/cm RMS is considered, the total RSS becomes 4.75 nm/cm RMS, which met the requirement of 10 nm/cm RMS.

Resonant Frequency

The 1st resonant frequency of this system was 242.1 Hz, which meets the requirement of 30 Hz. For bonding the test plate and invar joints, Epoxy of Scotch-Weld EC-2216 made by 3M was used. But stiffness of Epoxy does not affect the resonant frequency, because the system uses hard contacts and then the dominant term defining a resonant frequency is stiffness and mass of the test plate itself.

Stability

The Load Cell has a Non-Linearity of 0.5 % for an output signal. When 2300 Pa is applied to the test plate, the stability of the system is 11.5 Pa.

The difference between the deflection patterns of 2300 [Pa] and 2311.5 [Pa] was simulated via Power term (Z4) and the other terms without Piston (Z1), Tilt (Z2 and Z3), and Power term (Z4). Since Power term (Z4) at 2300 [Pa] was 11.37 [nm] and Power terms (Z4) at 2311.5 [Pa] was 9.03 [nm], then the Power terms difference between 2300 [Pa] and 2311.5 [Pa] was 2.34 [nm], which meets the requirement of 20 [nm]. Since the other terms without Piston (Z1), Tilt (Z2 and Z3), and Power term (Z4) at 2300 [Pa] was 8.16 [nm] and the other terms at 2311.5 [Pa] was 8.54 [nm], then the other terms difference between 2300 [Pa] and 2311.5 [Pa] was 0.38 [nm], which meets the requirement of 3 [nm].

CONCLUSION

The simple experiment and analyses for a vacuum support were studied. The maximum difference between experimental data and simulation data was 9.6 [%] in Power term (Z4) and 9.9 [%] in ρ^4 term (Z11) at 275 [Pa], which met a requirement of 20 [%]. Then, it was validated that simulation about deflection caused by vacuum corresponded with experimental data. The simulated surface slope irregularity was 0.75 nm/cm RMS. When the flexures have a moment, the RSS of the surface slope irregularity including the original 0.75 nm/cm and moment effect was 4.75 nm/cm RMS, which met the requirement of 10 nm/cm RMS. The simulated resonant frequency was 242.1 [Hz], which met a requirement of more than 30 [Hz]. For stability, the Power term (Z4) stability was 2.34 [nm], which meets the requirement of 20 [nm], and the stability of the other terms without Piston (Z1), Tilt (Z2 and Z3), and Power term (Z4) was 0.38 [nm], which meets the requirement of 3 [nm]. Therefore, all requirements are met by the experimental results and analyses and the vacuum support can be useful for reducing errors in the reference surface.

REFERENCES

[1] Dubin M.B., Su P., Burge J.H. Fizeau interferometer with spherical reference and CGH correction for measuring large convex aspheres. Proc. SPIE. 7426; 2009; OS-1-10.

[2] Eeverhart E. Making Corrector Plates by Schmidt's Vacuum Method. Applied Optics. 1966; Vol. 5; Issue 5; 713-715.

[3] Lemaitre G. New Procedure for Making Schmidt Corrector Plates. Applied Optics. 1972; Vol. 11; Issue 7; 1630-1636.