Fabrication and testing of 1.4-m convex off-axis aspheric optical surfaces

J. H. Burge, S. Benjamin, D. Caywood, C. Noble, M. Novak, C. Oh, R. Parks, B. Smith, P. Su, M. Valente, C. Zhao

College of Optical Sciences
University of Arizona
Tucson, AZ 85721

ABSTRACT

New developments in fabrication and testing techniques at the College of Optical Sciences, University of Arizona have allowed successful completion of 1.4-m diameter convex off-axis aspherics. The optics with up to 300 µm aspheric departure were finished using a new method of computer controlled polishing and measured with two new optical tests: the Swingarm Optical CMM (SOC) and a Fizeau interferometer using a spherical reference surface and CGH correction. This paper shows the methods and equipment used for manufacturing these surfaces.

Keywords: Optical fabrication, aspheres, optical testing, large optics

1. INTRODUCTION

Fabrication of large optical surfaces is difficult because of the complicated tooling needed for all stages of handling, manufacturing, and measuring. Aspheric surfaces are especially difficult because the polishing tools need to conform to a non-spherical shape, and the measurement cannot rely on the symmetry provided by spherical shapes. Off-axis aspheres cannot even use the axisymmetry of more common aspheric shapes, which are figures of revolution. The unique difficulty for convex surfaces arises from the difficulty performing optical tests – reflection from a concave surface causes light to converge, allowing the test system to be smaller than the optic being measures. Reflection from a convex surface causes the light to diverge, requiring auxiliary optics that are larger then the surface being measured. We present the successful completion of such surfaces that are large (1.4 meters in diameter), non-symmetric aspheres (off axis portions of a paraboloid or OAP, having up to 300 µm aspheric departure), and convex (requiring new optical test methods).

This paper summarizes the manufacturing for these OAPs, emphasizing the techniques developed at University of Arizona that are novel and interesting on their own. The polishing of the aspherical surfaces was performed with a new class of computer controlled polishing machines that use the swing arm geometry to provide robust motion control. The measurement of the optical surface was performed using two methods:

- Swing arm Optical CMM SOC: A new machine was constructed that provide two-dimensional shape information from a series of scans that use swing arm geometry and utilize an interferometric, non-contact measurement. These measurements are accurate to ~6 nm rms. [1]
- Fizeau interferometry with a spherical reference and CGH correction: Interferometric surface measurements were performed using a Fizeau test that looks through the solid glass OAP and compares the aspherical surface with a concave spherical reference surface. A computer generated hologram (CGH) is used to compensate the difference between these. The measurements are accurate to < 4 nm rms.

The comparison between the two measurements provides confidence that the completed optical surfaces and the test methods achieve accuracy well below 10 nm rms.

James H. Burge: jburge@optics.arizona.edu, 520-621-8182

Optical Manufacturing and Testing VIII, edited by James H. Burge, Oliver W. Fähnle, Ray Williamson, Proc. of SPIE Vol. 7426, 74260L · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.828513

2. MANUFACTURING

2.1 Initial work on the substrates

The optical surfaces were fabricated onto solid Zerodur™ glass blanks, which were nominally 1.4 meters in diameter and 175 mm thick. The initial shaping and surface preparation was not performed at the University of Arizona and is not discussed here. The steps prior to finishing are:

1. Initial shaping of the blank with diamond tools. The glass blanks were provided as plano-plano cylinders with the outer edge fine generated.
2. Polishing the back. The flat back surface was polished to an inspection level finish to allow the optical test to view through this surface.
3. Initial shaping of the aspheric surface. The convex surface was initially cut with diamond tools. The aspheric shape was ground and polished out using feedback from a coordinate measuring machine.
4. Diamond generating datum features. The datum features used to locate the ultimate registration of the optical surfaces were cut into the glass.

2.2 Support

The OAPs were supported near the edge via three invar pads bonded to the flat back surface. The 6 µm self weight deflection, shown in Figure 1, does not affect performance. The OAPs are always measured and used with the optical surface face up on this support. We add three tangents arms to constrain the optic, but we are careful to adjust the support so these take no load during metrology.

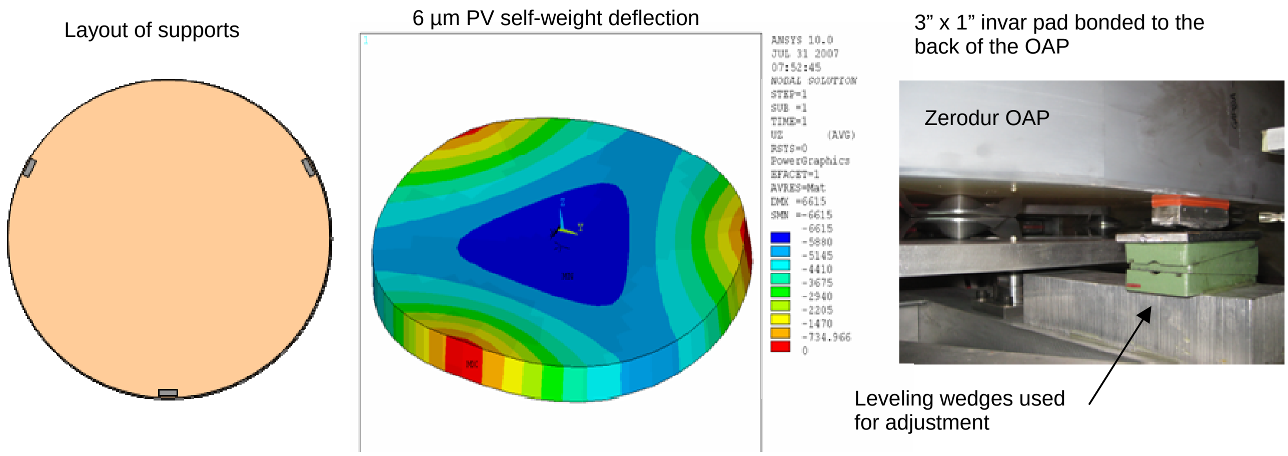

Fig. 1. The OAPs are supported at three points near the edge. The support locations are defined by three 25 x 75 mm plates bonded to the flat back of the optic. As the parts are always measured and used with this same support, the 6 µm self-weight deflection is not important.

2.3 Polishing

The final polishing and figuring were performed using 1.8-m capacity computer controlled optical surfacing machines designed and built at the University of Arizona. These unique machines utilize the swingarm geometry discussed later in this paper to provide the necessary degrees of control to position the polishing head on the optical surface. This advantageous geometry allows safe, robust operation because the natural geometry drives the lap in an arc over the surface, requiring no additional control for vertical translation or tilt of the lap. There is no degree of freedom under active control that is capable of driving the polishing spindle into the surface.

The polishing provides the ability to drive with independent controls for lap orbit and lap rotation. This control allows the polishing strokes themselves to be optimized for smoothing (passively removing errors that are small compared to the size of the lap) and directed figuring (correcting the figure by spending more time or energy on the high regions.)[2] A variety of laps were used to balance removal rate, natural smoothing, and surface finish. The final finish of the aspheric surfaces was approximately 12 Å rms.

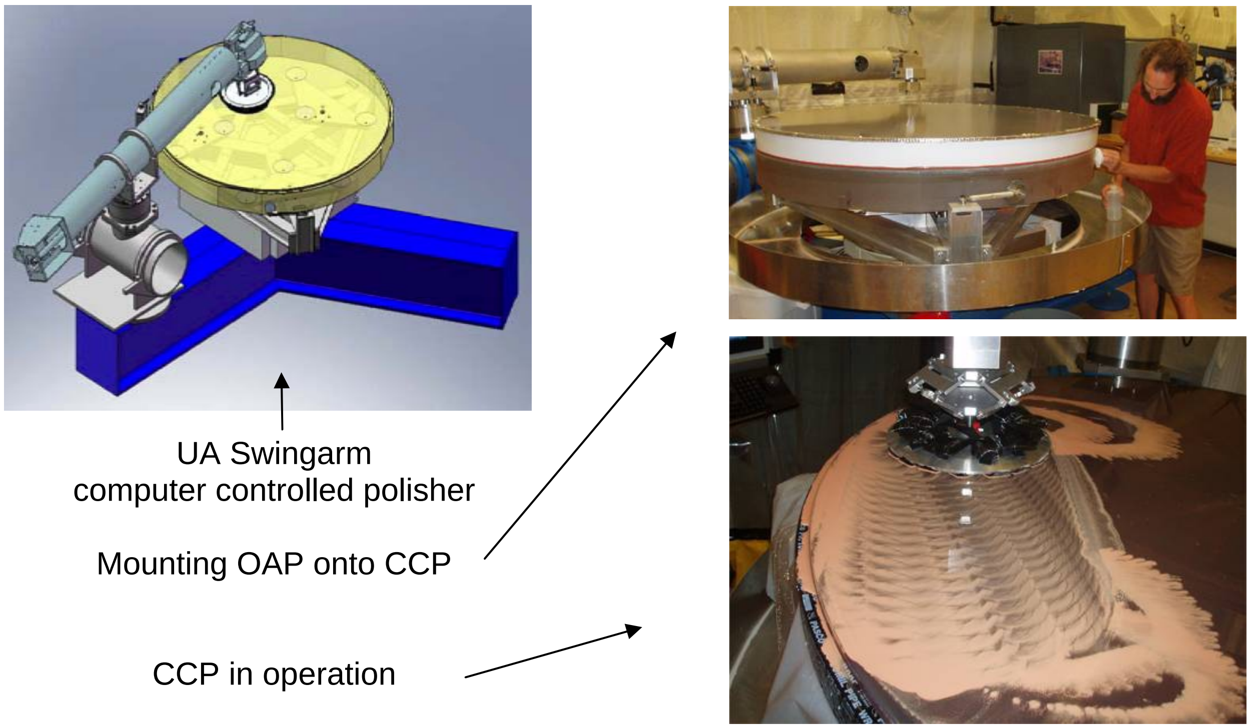

Fig. 2. The computer controlled polishers at the University of Arizona use the swing arm geometry to control the position of the polishing head. A combination of swinging the arm rotation and rotating the table provides control to position the lap anywhere on the optical surface. The polishing laps are driven in both orbit and rotation to provide directed removal and smoothing, as designed by computer optimization.

The figuring was performed quite rapidly, as seen with the convergence plot in Figure 3. The final figuring of this part was performed in 6 calendar weeks using a total of 150 hours on the machine. This particular surface had one small feature from initial aspherizing that was tracked in addition to the overall figure. The final figure for this part was ~ 30 nm rms overall, and ~8 nm rms after removing low order terms.

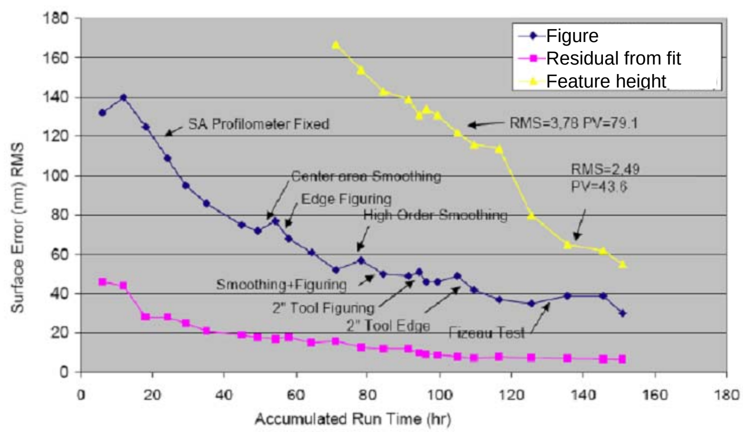

Fig. 3. The figuring was completed using 150 machine hours in about 6 weeks. The plot shows magnitude of a particular feature, the overall figure, and a residual after removing low order terms.

3. SURFACE METROLOGY WITH THE SWINGARM OPTICAL CMM

The optical surface was measured using a variation of the swingarm profilometer that has been used extensively at the University of Arizona.[3] For the measurement of the OAPs, we have improved performance, added a high performance optical probe, and developed the ability to create full surface scans. With these additions, we have dubbed the machine to be the SOC : Swingarm Optical CMM. The scan geometry and picture of the system are shown below in Figure 4, and a separate paper is given in this conference on the SOC.[1] The SOC was attached directly to a computer controlled polishing machine for this project.

The Swingarm Optical CMM uses advantageous geometry to provide measurements across the convex surface that limit the runout and tilt of the optical displacement probe. The arm rotates about a tilted axis that goes through the center of curvature of the optical surface, so the probe sees no runout or angle change with respect to a spherical surface. The total linear and angular displacements are only those from the aspheric departure.

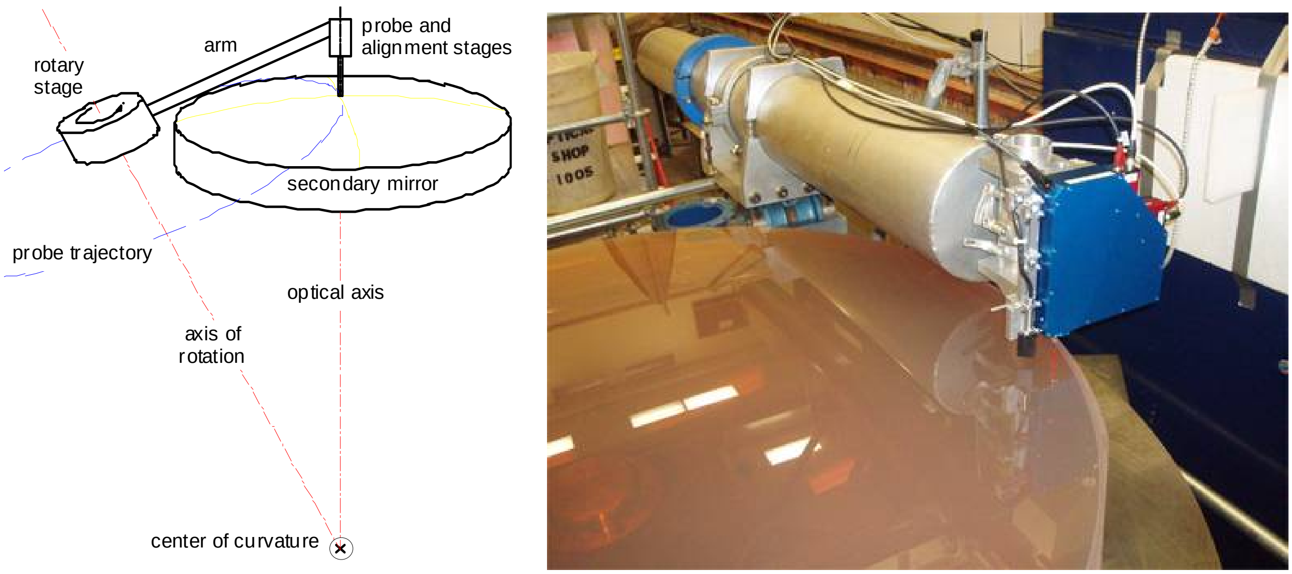

Fig. 4. The Swingarm Optical CMM uses advantageous geometry to provide measurements across the convex surface that limit the runout and tilt of the optical displacement probe. The SOC was attached directly to a computer controlled polishing machine for this project.

The performance of the SOC exceeded expectations. As shown in Figure 5, the individual scans proved to be repeatable to 6 nm rms after removing the lowest order alignment terms. For a single scan created by an average of 8 scans, the random error was only ~ 2 nm rms. The system did suffer ~35 nm rms repeatable error due to wobble in the arm bearing. The 23 nm rms odd (antisymmetric) portion of this was directly calibrated using symmetry of the measurements. The 25 nm rms even (symmetric) portion of this cannot be separated from axisymmetric errors in the surface being measured. This was calibrated using the Fizeau test discussed below.

The SOC uses multiple scans to provide data over the entire surface. For final measurements, 64 scans were taken at even intervals and combined using a maximum likelihood reconstruction to provide full surface maps. This procedure is illustrated in Figure 6.

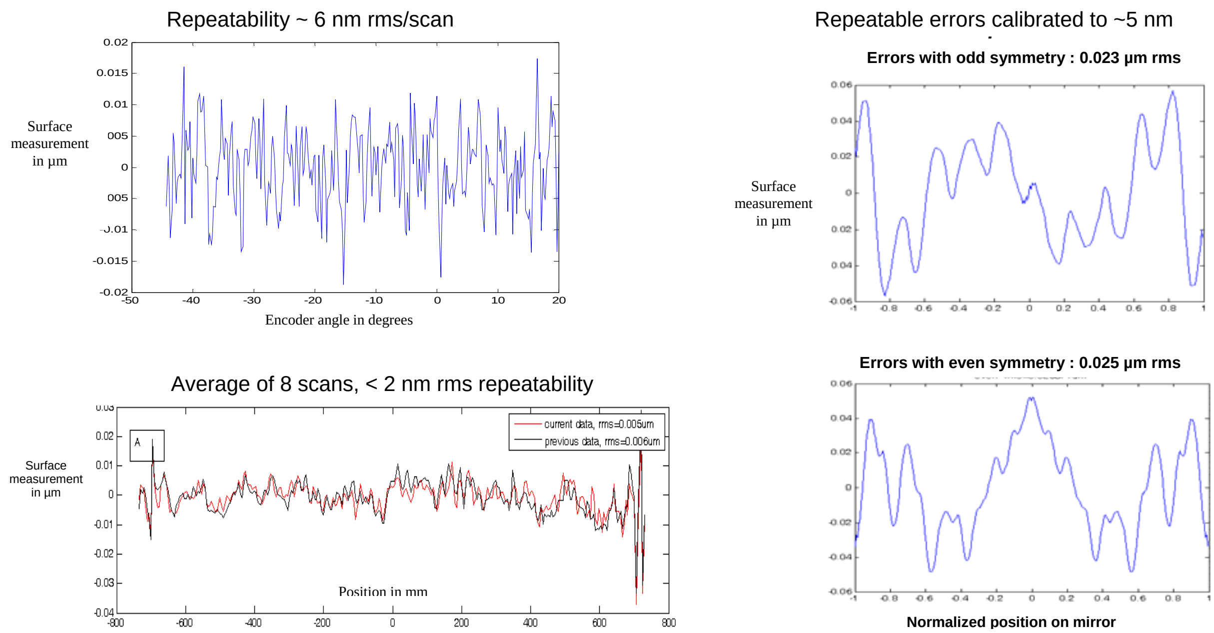

Fig. 5. Individual scans showed ~6 nm rms repeatability, providing measurements that are repeatable to 2 nm rms after averaging 8 scans. The repeatable errors of 35 nm rms are described as a sum of 23 nm rms odd (antisymmetric) and 25 nm rms even (symmetric) terms that are calibrated.

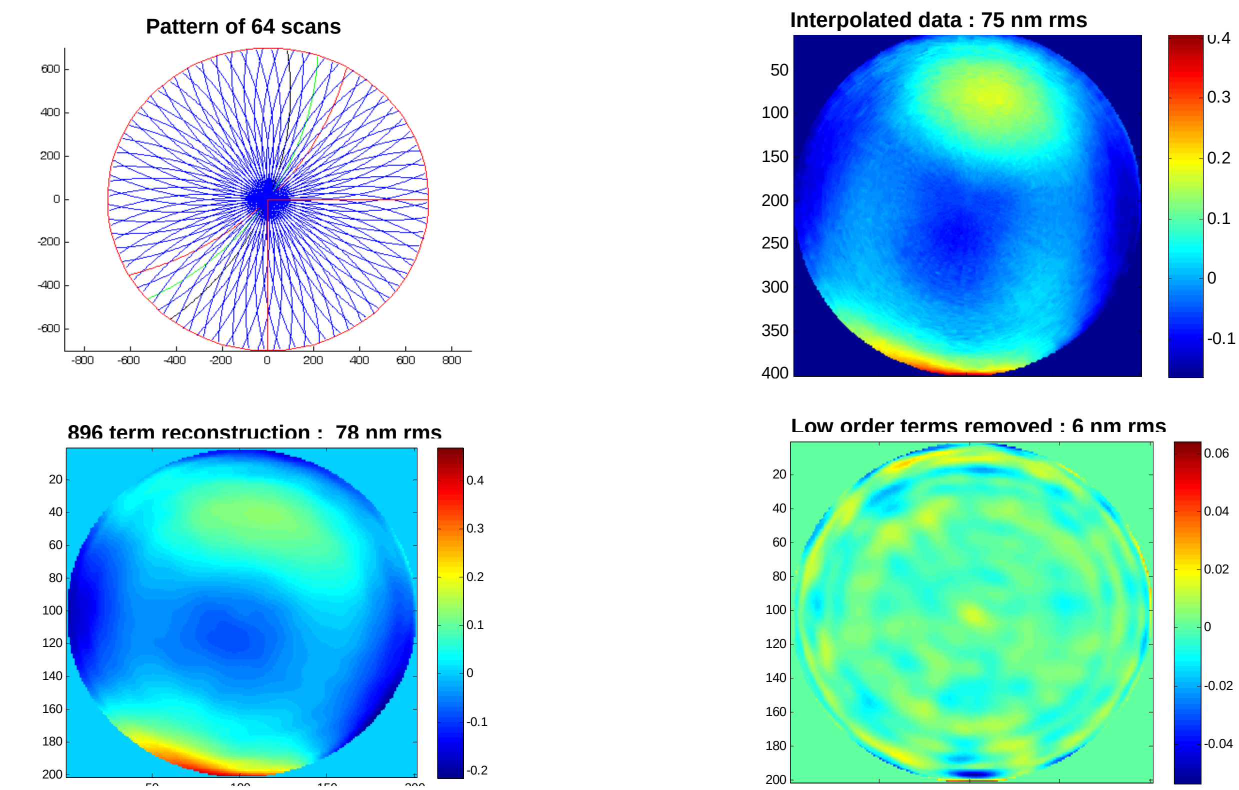

Fig. 6. Multiple scans from the SOC are combined to create full surface maps. The data above show results for 64 scans. An initial interpolation is first provided. Then a maximum likelihood reconstruction using 896 terms is performed. The high frequency information shown in the residual after removing low order terms shows the fine spatial resolution achieved with the modal reconstruction. (The color bars show surface in µm).

The SOC does not accurately measure power of radius of curvature error. The radius of curvature of the SOC was determined using a separate 3-ball spherometer, shown in Figure 7. This instrument rested on three points near the edge of the OAP and measured the sag to ~0.3 µm using a contact probe. The system geometry was carefully calibrated with data from a CMM. The probe was calibrated offline, and the system was zeroed on a high quality flat. The radius of curvature is calculated for the off-axis parts from this data.[4]

Fig. 7. The OAP curvature was measured with a custom 3-ball spherometer. The spherometer consists of a monolithic aluminum skeleton, covered with thermal insulation, that rests on 3 tooling balls near the edge of the OAP. A displacement probe at the center measures the sag to 0.3 µm.

4. SURFACE METROLOGY WITH FIZEAU INTERFEROMETRY WITH CGH

The final surface measurements were made using a Fizeau interferometer that used a spherical reference surface and relied on computer generated holograms (CGHs) to correct for the aspheric departure of the optical surface. We use a refinement of a technique that was developed for measuring mirror segments for large primary mirrors.[5,6] The test design, assembly, and performance for the OAPs are discussed here. A companion paper in this conference provides another application of this testing method.[7]

The Fizeau test, shown in Figures 8 and 9 have many important benefits:

- Only one large precision surface needs to be made, and this a concave sphere that serves as the reference.
- The test and reference wavefronts travel together through the system, reducing sensitivity to vibration, air motion, refractive index variations in the OAP substrate or surface errors on the back of the OAP.
- The test can accommodate numerous OAPs that have different off axis distance by simply replacing the computer generated holograms.
- The radius of curvature control is easy. This is determined by controlling the 1 cm gap between the reference surface and the OAP.
- Phase shifting interferometry is used to obtain high accurate data with excellent spatial resolution. Subsequent developments have used simultaneous phase shifting interferometry.[7] A spinning ground glass diffuser near the laser eliminates the speckle noise.

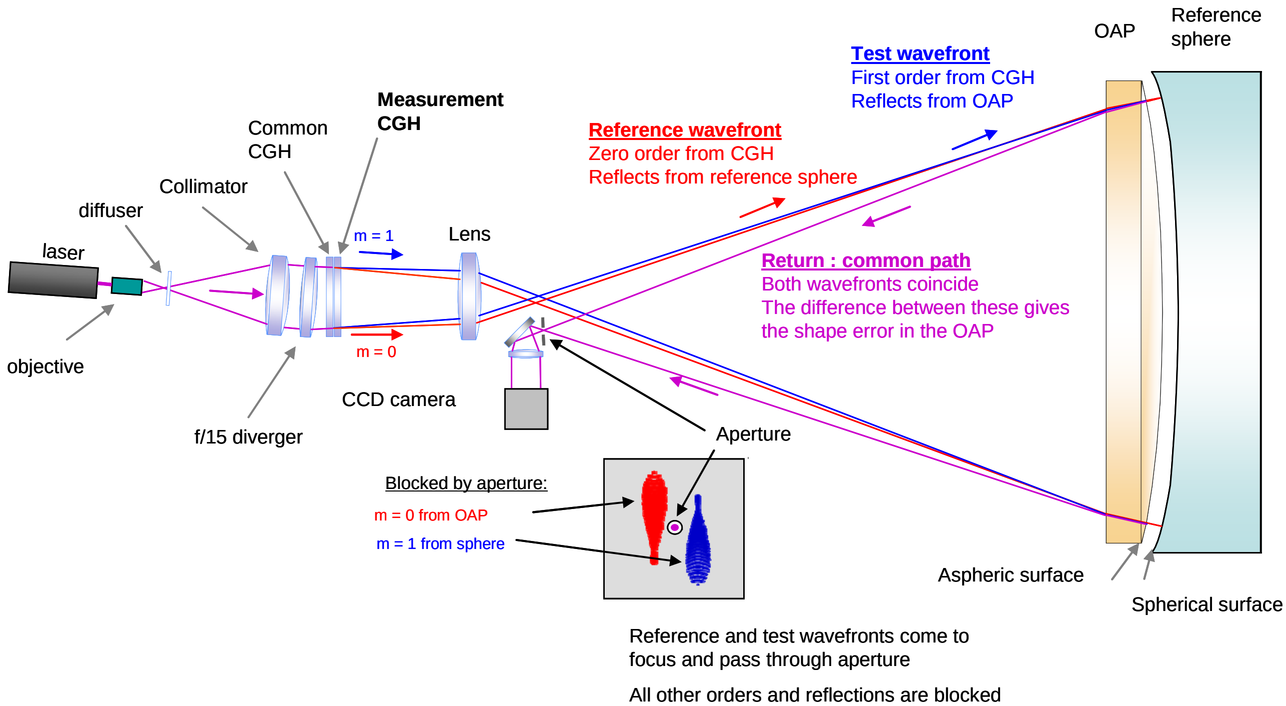

Fig. 8. The Fizeau test uses two different orders of diffraction from a CGH to define the reference and measurement wavefronts for the interferometer. Both wavefronts use the same order from the second, common CGH. The combination of different reflections and orders of diffraction provides two wavefronts that come to focus at the aperture of an imaging system where all other reflections and orders of diffraction are blocked.

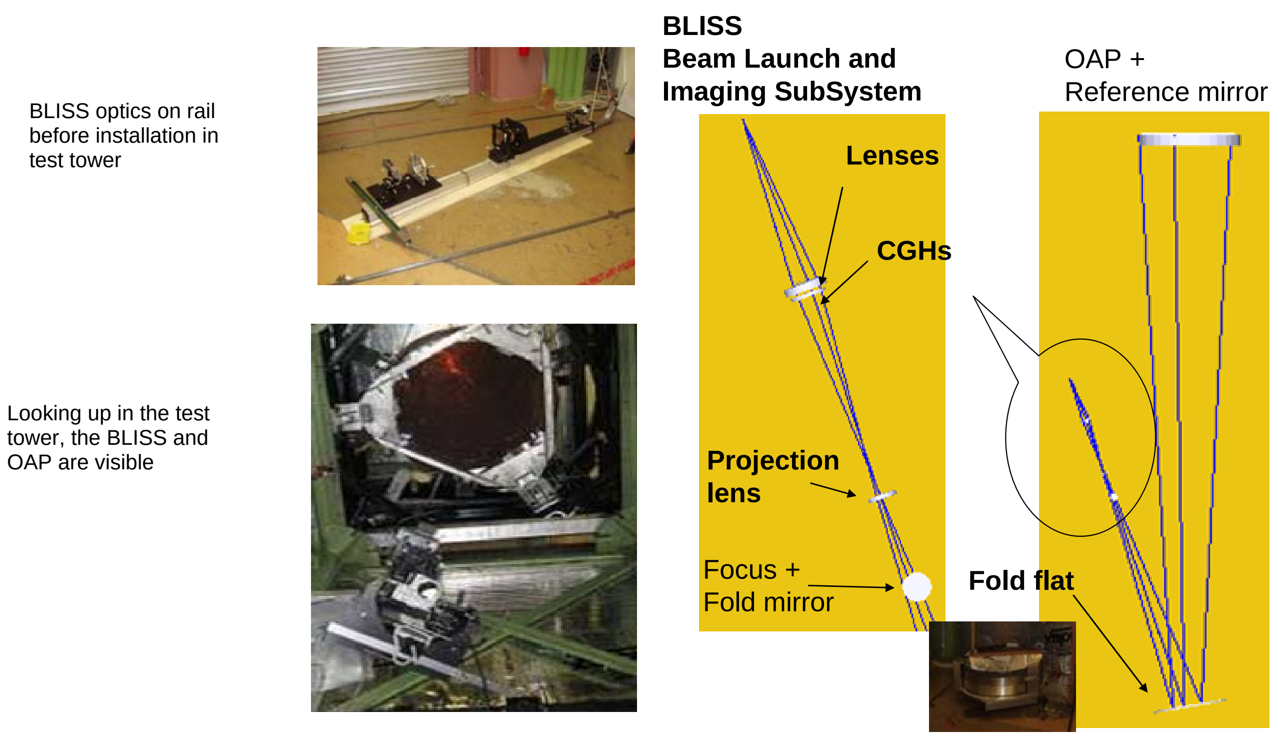

Fig. 9. The optical layout of the test is show to scale, including the Beam Launch and Imaging SubSystem BLISS that points down to a fold flat and the OAP and reference sphere located at the top of the test tower.

One complication for this test is the requirement to view through the OAP substrate from below. This required the hardware to be mounted in the top of our 8-m test tower and for the beam train to be folded with a flat mirror. Figure 10 below shows much of the mechanical hardware, and Figure 11 shows the assembly sequence.

The load path that constrains the reference sphere with respect to the OAP was carefully designed to allow robust measurements in our noisy shop environment without isolation. The reference sphere is supported with vacuum, but constrained in position with hardpoints instrumented with load cells. The hardpoints are rigidly connected to the OAP support frame. Coarse adjustments are provided at this interface. Fine control for position and tilt of the OAP uses PZT actuators under the three support points. These are also used for phase shifting. The entire OAP frame/reference sphere combination is positioned with jackscrews.

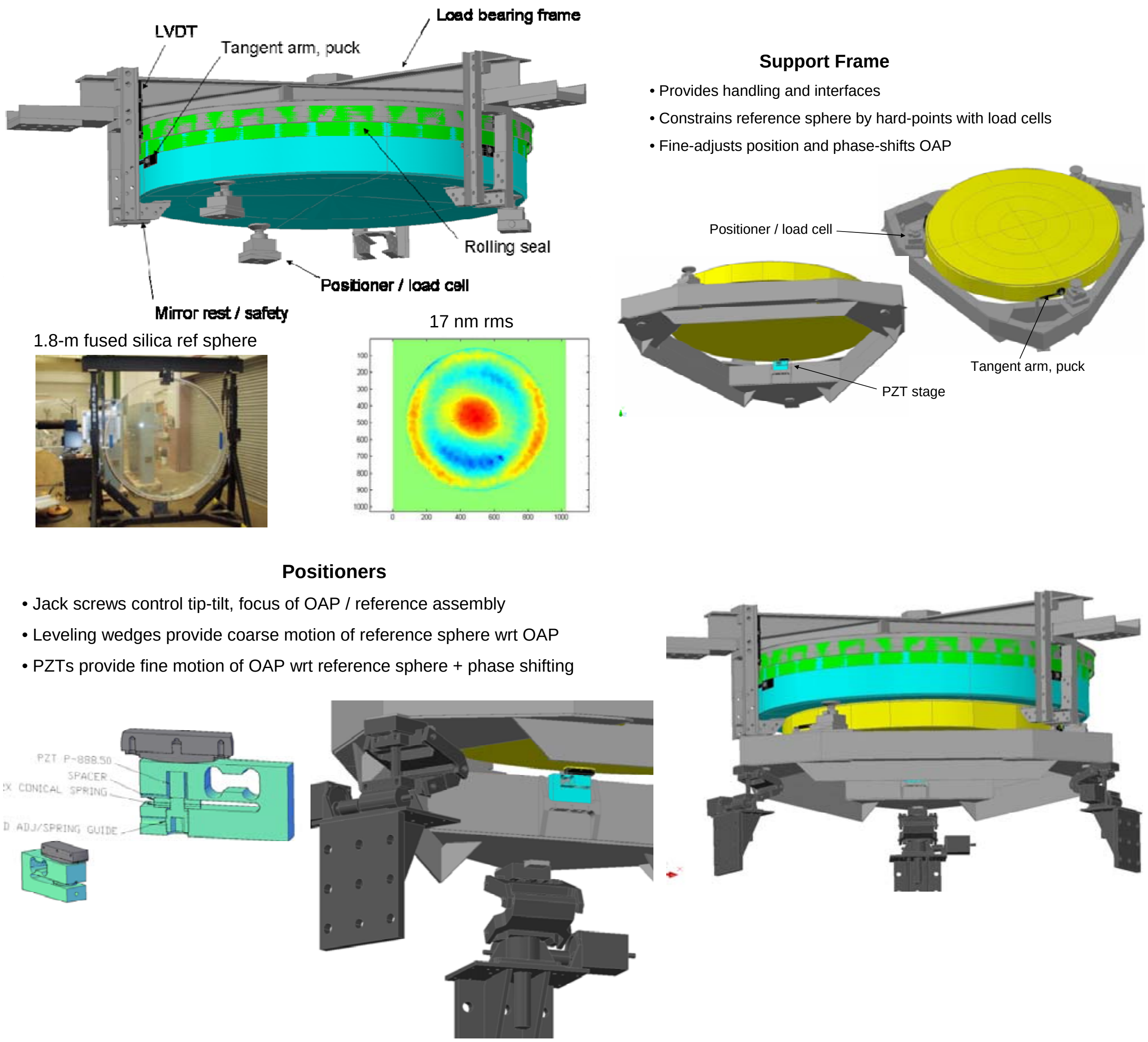

Fig. 10. The hardware used to support the 1.8-m diameter fused silica reference sphere and the OAP allowed efficient installation of the OAP, motion control of the OAP-Reference sphere combination and control of the OAP with respect to the reference sphere. The reference sphere itself is supported with vacuum, yet is constrained in position with 3 hardpoints coupled closely to the OAP support.

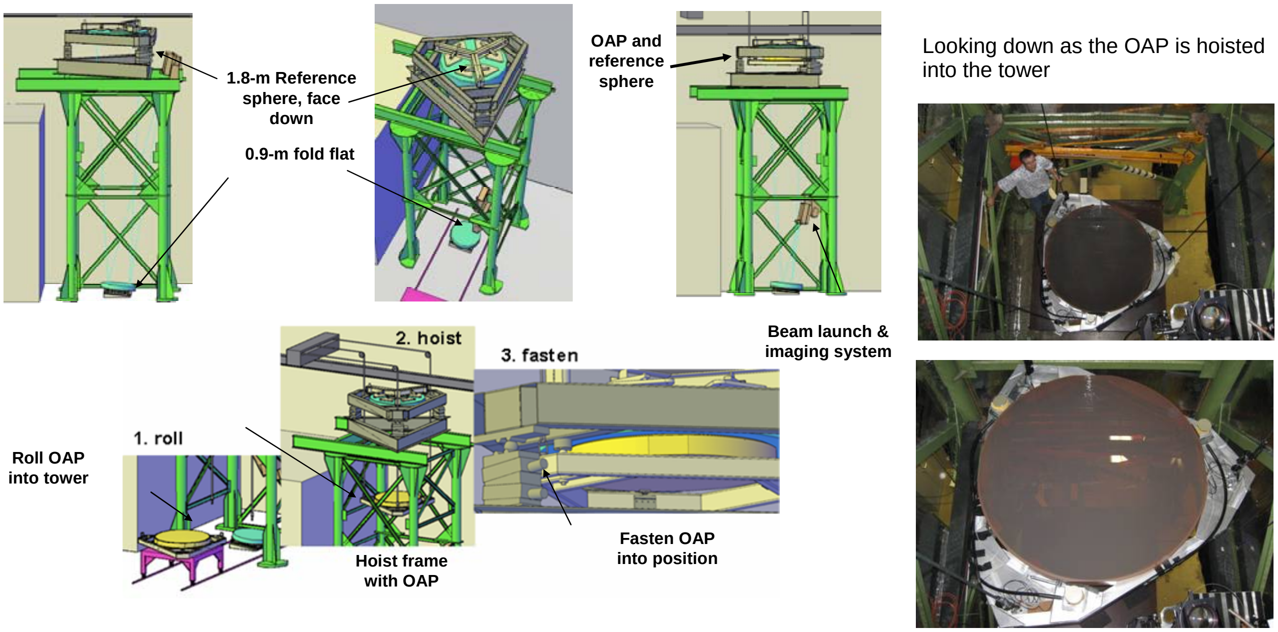

Fig. 11. The OAP on its frame is loaded into the tower with a roll cart, then hoisted into position with 3 cables. Then it is rotated and captured with the main support hardware.

Two computer generated holograms were used. Both CGHs were laser-written onto 150 x 150 x 6 mm fused silica windows. The common CGH is fully common path, shared by both wavefronts. This pattern was phase etched into the surface. The measurement CGH defines the two wavefronts – the zero order light provides the reference and the first order diffraction provides the test wavefront. This pattern was made of chrome with 50% duty cycle.

The computer generated holograms included features that facilitate alignment. The alignment between the two CGHs was controlled to about 10 µm using the moiré effect from matching patterns of concentric circles. The alignment of the CGHs to the BLISS optics was assisted with unresolved patterns written onto the CGHs that could be viewed with an alignment telescope. The alignment of the OAP to the BLISS was defined using patterns on the CGH that were images to CCD cameras attached to the OAPs. These alignment aids are shown below in Figure 12. . The distance from the optical system to the OAP is set by measurement with a laser tracker. The measurement light, the laser tracker beam, and the alignment fiducials are all folded with the same flat mirror, which eliminates the need to know the position of the fold flat.[8]

The system provides accurate, low noise measurements as seen in Figure 13. Excellent fringe contrast was available. There were two interesting problems with the system. The solid state laser used had a small side lobe that would vary with time. This was measured with a spectrum analyzer and mitigated by carefully tuning an edge-pass filter. We did see two sets of ghost fringes that affected the data. One set, due to reflection between the holograms was easily corrected with alignment. A second set, which is a multiple reflection inside the hologram substrate remains, providing a background noise of ~1.5 nm rms.

Most errors in the phase shift interferometry system were eliminated by adding a slowly varying bias to the phase shift used for the measurements. This insures that the different maps in the average are taken at different bias phase. As long as the bias averages to zero, the effect of most types of error, such as phase shift error, detector nonlinearity, etc., will average to zero. Equivalently, many errors cause a phase measurement that "prints through" the fringe pattern into the phase data. If we shift the fringe pattern between measurements, then these types of errors average out.

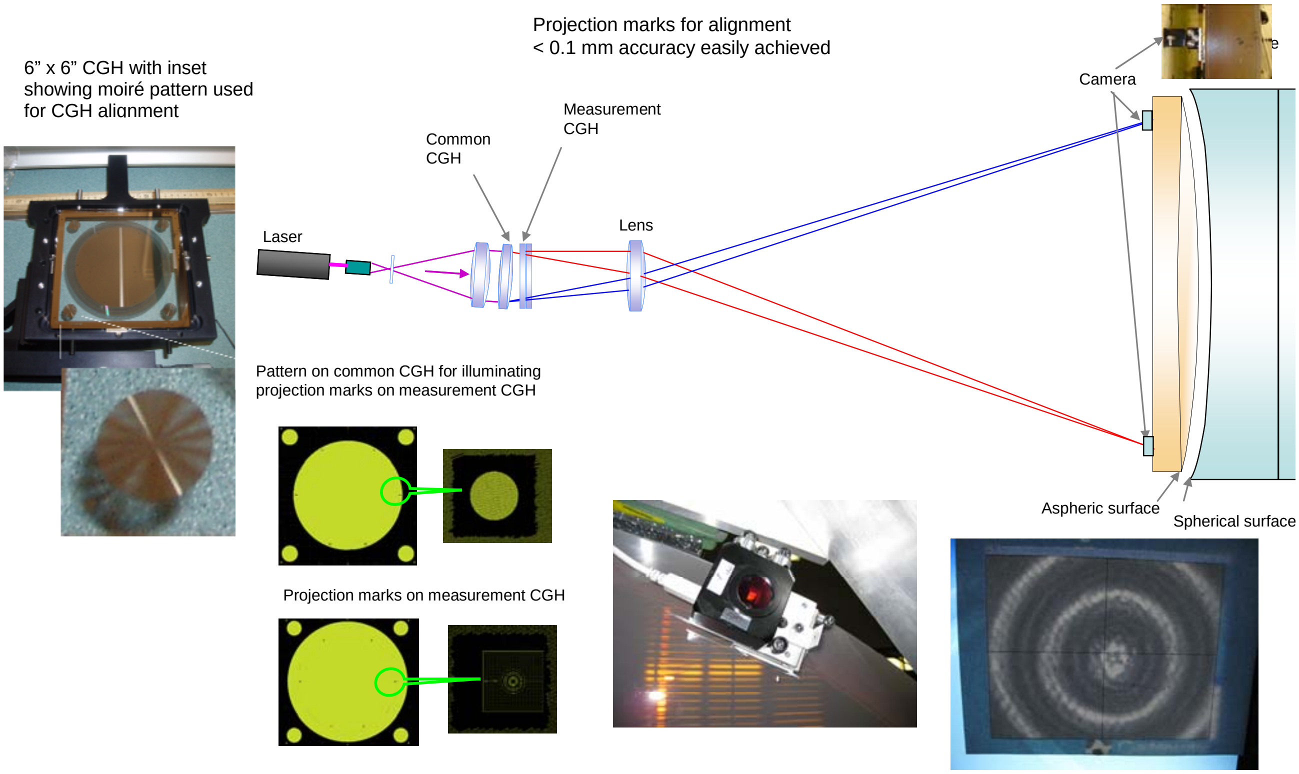

Fig. 12. CGH references provide feedback for system alignment. The two CGHs are mutually coaligned by looking at a moiré pattern defined by matching concentric patterns. The OAP position is moved according to the location of images projected onto CCD cameras mounted at known positions on the OAP. The distance from the optical system to the OAP is set by measurement with a laser tracker. The measurement light, the laser tracker beam, and the alignment fiducials are all folded with the same flat mirror, which eliminates the need to know the position of the fold flat.

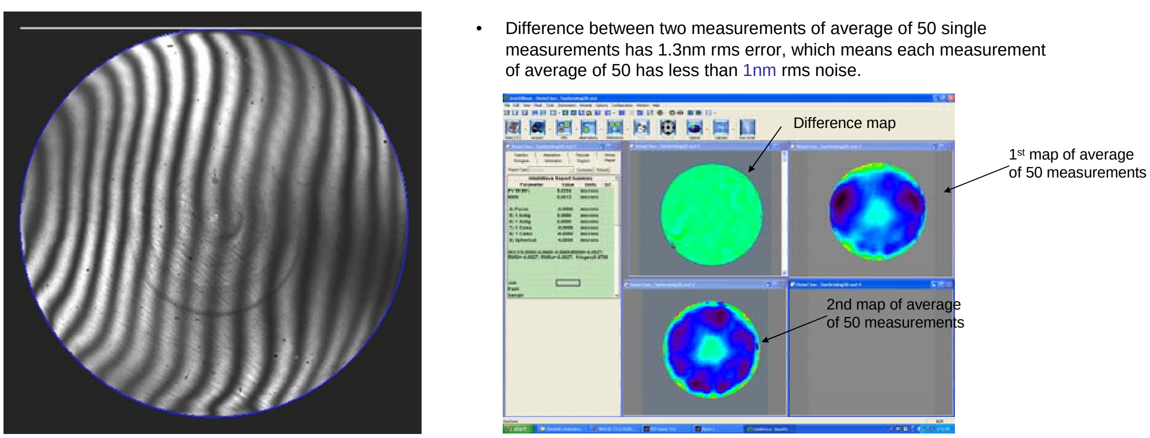

Fig. 13. The Fizeau system provides excellent contract, low noise measurements. The repeatability of a single measurement, which consists of an average of 50 maps, shows only 1.3 nm rms.

We did have concern about the effect of straie in the OAP substrates, which are small scale refractive index irregularities. The optical test uses two wavefronts that are not purely coincident in this region. There is up to 100 μm shear, or lateral shift, of the reference wavefront with respect to the test wavefront as the two go through the glass. This small difference is of no consequence for normal, low order variation in surface figure of refractive index. Although we could observe the effect of straie in the light system by defocusing or cutting the focused image with a knife edge, we could never find any measurement artifacts that correlated with the straie. Data shown below in Figure 14.

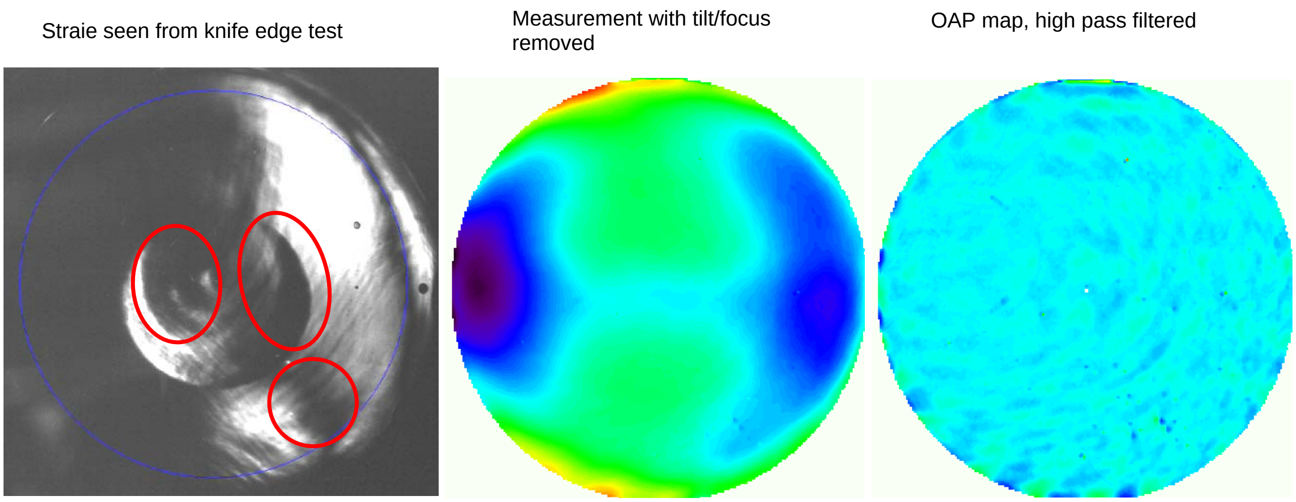

Fig. 14. Although straie were visible in the OAP glass substrates, there was no discernable effect in the measurements. This image shows an interferogram with the straie clearly visible as gaps in the data from a knife edge test. When the knife is removed and the surface is measured, we can find no features in the data correlated with the straie. The residual features are around 1 nm rms, so we conclude that this effect must be < 1 nm rms for the OAP measurements.

The data from the Fizeau system matches nearly perfectly with that from the SOC, shown in Figure 15. The primary differences are due to uncalibrated errors in the SOC and noise from the ghost fringes in the Fizeau test.

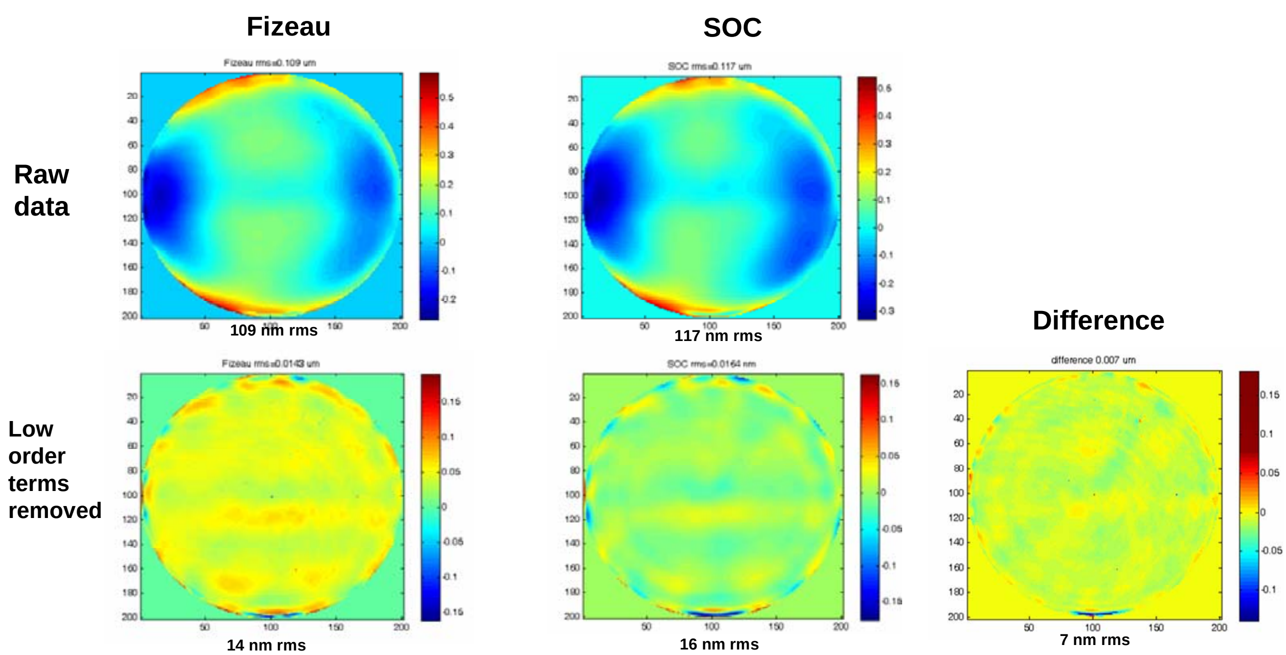

Fig. 15. The measurements with the SOC and the Fizeau system show excellent agreement. After removing low order terms, the SOC is expected to be accurate to 6 nm rms and the Fizeau test was constructed to be accurate to 3 nm rms.

5. CONCLUSION

Our team at the College of Optical Sciences, University of Arizona has successfully demonstrated advanced capabilities for making non-symmetrical aspheric optics:

- Rapid finishing of aspheres with computer controlled polishing
- Efficient accurate measurements using Swingarm Optical CMM
- Accurate measurement of aspherics using Fizeau interferometer with spherical reference surface and CGH

This work paves the way for other applications of the technology:

- Measurement of larger, more challenging convex aspheric surfaces by combining the Fizeau + CGH method with subaperture stitching interferometry.[9]
- Development of a vibration insensitive version of the Fizeau test that uses two polarization states for the reference and measurement wavefronts, and couples with an existing phase sensor.[7]
- Possible development of the Fizeau+CGH test for measurement of primary mirror segments for large telescopes such as TMT and EELT.
- Application of the efficient polishing with on-board metrology for rapid fabrication of other optics. These methods work for solid glass as well as lightweighted substrates of glass or SiC.

REFERENCES

1) P. Su, J. H. Burge, R. E. Parks, C. J. Oh, "Swing-arm optical CMM for aspherics," in *Optical Manufacturing and Testing VIII*, J. Burge, O. Faehnle, and R. Williamson, eds., Proc. SPIE **7426**, (these proceedings 2009).

2) J. H. Burge, B. Anderson, S. Benjamin, M. Cho, K. Smith, M. Valente, "Development of optimal grinding and polishing tools for aspheric surfaces," in *Optical Manufacturing and Testing IV*, H. P. Stahl, ed., Proc. SPIE **4451**, 153-164 (2001).

3) D. S. Anderson and J. H. Burge, "Swing arm profilometry of aspherics," in *Optical Manufacturing and Testing*, V. J. Doherty and H. P. Stahl, eds., Proc. SPIE **2536**, 169-179 (1995).

4) H. K. An and R. E. Parks, "Calculation of the vertex radius of an off axis parabolic surface using the sag measured with a three ball spherometer," presented at SPIE *OptiFab*, Rochester, NY (2009).

5) J. H. Burge, "Efficient testing of off-axis aspheres with test plates and computer-generated holograms," in *Optical Manufacturing and Testing III*, H. Stahl, ed., Proc. SPIE **3782**, 349-357 (1999).

6) F. Y. Pan, J. Burge, **"**Efficient testing of segmented aspherical mirrors by use of reference plate and computer-generated holograms. I. Theory and system optimization," Applied Optics, **43**, 5303-5312, (2004).

7) M. B. Dubin, C. Zhao, James H. Burge, "Fizeau interferometer with spherical reference and CGH correction for measuring of large convex aspheres," in *Optical Manufacturing and Testing VIII*, J. Burge, O. Faehnle, and R. Williamson, eds., Proc. SPIE **7426**, (these proceedings, 2009).

8) J. H. Burge, P. Su, T. Zobrist, C. Zhao, "Use of a commercial laser tracker for optical alignment," in *Optical System Alignment and Tolerancing*, J. Sasian and M. Ruda, eds., Proc. SPIE **6676**, (2007).

9) C. Zhao and J. H. Burge, "Stitching of off-axis sub-aperture null measurements of an aspheric surface," in *Interferometry XIV: Techniques and Analysis*, J. Schmit, K. Creath, C. Towers, eds., Proc. SPIE **7063**, 706316 (2008).