Fabrication of 4 - meter class astronomical optics

M. J. Valente*, D. W. Kim, C. J. Oh, M. J. Novak, J. H. Burge
University of Arizona, College of Optics, 1630 East University Boulevard, Tucson, AZ, USA 85716

ABSTRACT

The 8-meter mirror production capacity at the University of Arizona is well known. As the Arizona Stadium facility is occupied with giant mirrors, we have developed capability for grinding, polishing, and testing 4-m mirrors in the large optics shop in the College of Optical Sciences. Several outstanding capabilities for optics up to 4.3 meters in diameter are in place:

A 4.3-m computer controlled grinding and polishing machine allows efficient figuring of steeply aspheric and non-axisymmetric surfaces.

Interferometry (IR and visible wavelengths) and surface profilometry making novel use of a laser tracker allows quick, accurate in-process measurements from a movable platform on a 30-m vertical tower.

A 2-meter class flat measured with a 1-m vibration insensitive Fizeau interferometer and scanning pentaprism system; stitching of 1-m sub-apertures provides complete surface data with the technology ready for extension to the 4 m level.

These methods were proven successful by completion of several optics including the 4.3-m Discovery Channel Telescope primary mirror. The 10 cm thick ULE substrate was ground and polished to 16 nm rms accuracy, corresponding to 80% encircled energy in 0.073 arc-second, after removing low order bending modes. The successful completion of the DCT mirror demonstrates the engineering and performance of the support system, ability to finish large aspheric surfaces using computer controlled polishing, and accuracy verification of surface measurements. In addition to the DCT mirror, a 2-meter class flat was produced to an unprecedented accuracy of <10 nm-rms, demonstrating the combined 1-m Fizeau interferometer and scanning pentaprism measurement techniques.

Keywords: fabrication, computer control, grinding, polishing, figuring, metrology, large optics

1. INTRODUCTION

The capability of the optical fabrication facility at the University of Arizona has been improved dramatically over the course of the recent five year period. We have constructed computer controlled polishing machines to fabricate 1.5 meter optics, including difficult optics such as large, convex aspheric parts. In addition to these challenging surfaces, we have developed capabilities for large flat mirror fabrication and also an even larger machine capable of greater than 4 meter class optical fabrication. In this paper, we detail the 4 meter optical fabrication platform and technologies used to compliment the processing of larger optics as well as the technology we have developed for use on 2 m computer controlled machines which is ready for extension to the larger fabrication platform. We foresee the technology developed for the several smaller 2 m class computer controlled machines as a stepping stone to enabling a more efficient and accurate processing of larger astronomical mirrors on the 4.3 m machine in our facility.

*marty@optics.arizona.edu, 520.621.2341

Modern Technologies in Space- and Ground-based Telescopes and Instrumentation, edited by Eli Atad-Ettedgui, Dietrich Lemke, Proc. of SPIE Vol. 7739, 77392D · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.861979

1.1 4.3 meter fabrication platform

Recently, we completed the fabrication of a 4.3 meter primary mirror for use in the Discovery Channel Telescope (DCT), located at Happy Jack, AZ, on a computer controlled fabrication platform in our facility. In addition to having infrastructure in place for handling mirror blanks of this size, in order to complete this project we upgraded a machine from the R.H. Strasbaugh company from 2 meter capacity to greater than 4 meter capacity. The larger capacity system is shown in the schematic in Figure 1:

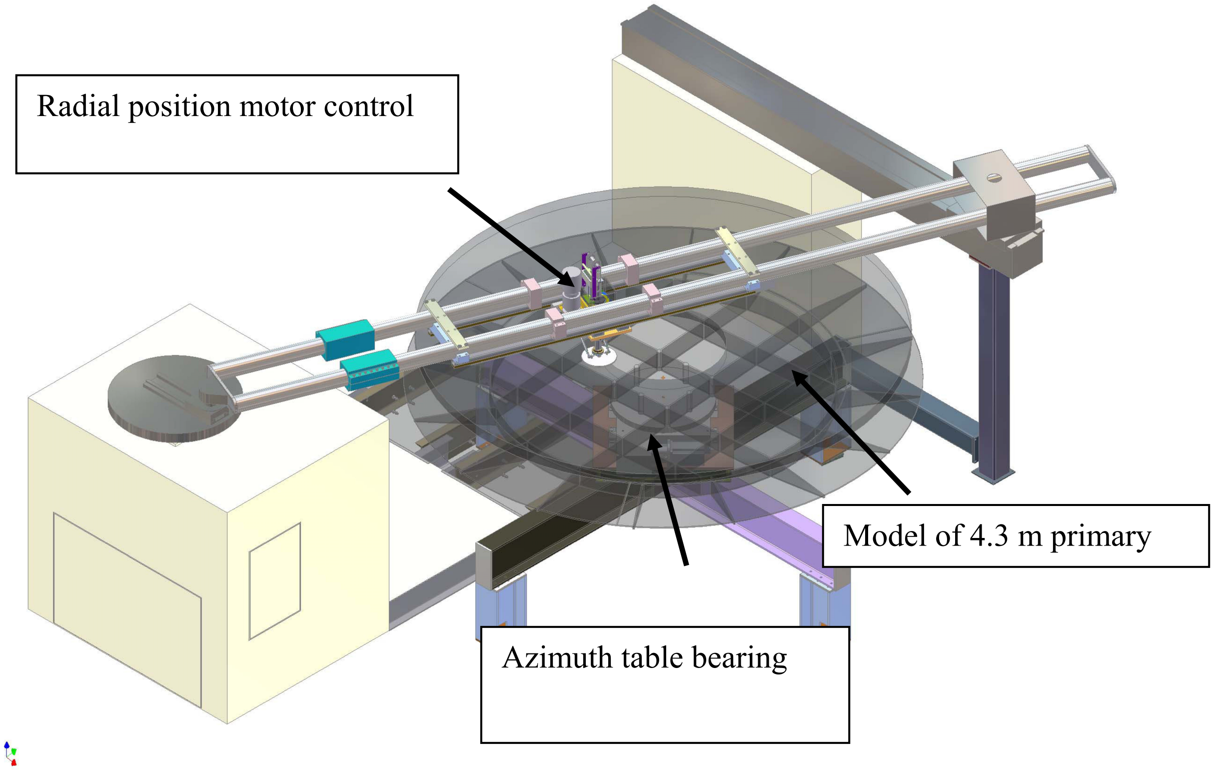

Figure 1. 4 m Computer controlled grinding and polishing machine – schematic.

Optimization software previously developed by Dr. Chang Jin Oh, as well as new software developed in collaboration with our fabrication shop, was used to guide fabrication runs on the large platform machine during fabrication of the DCT primary mirror. We also used the combination of accurate metrology, known tool influences with computer control, and experimental research for tool influence development to move forward with the development of MATRIX^{TM}, a computer controlled optical surfacing optimization software. This code provides a computer controlled optical surfacing (CCOS) process which implements non-sequential optimization techniques utilizing multiple tool influence functions (TIFs) simultaneously in a run optimization. This is type of optimization differs from conventional CCOS processes using TIFs in a sequential manner[1].

Polishing runs on the optic are still sequentially completed as tools are added and removed for surface processing. This latest technique, which enables simultaneous use of an ensemble of TIFs, forms an attractive solution for the fabrication of high quality optical surfaces. Additionally, we employ parametric edge modeling[2] for accurate control of the optic edge figure (a typical region of difficulty during processing). The precise control provided by these software tools allows opticians to selectively grind and polish the areas of inadequate optical figure in a predictable and systematic manner.

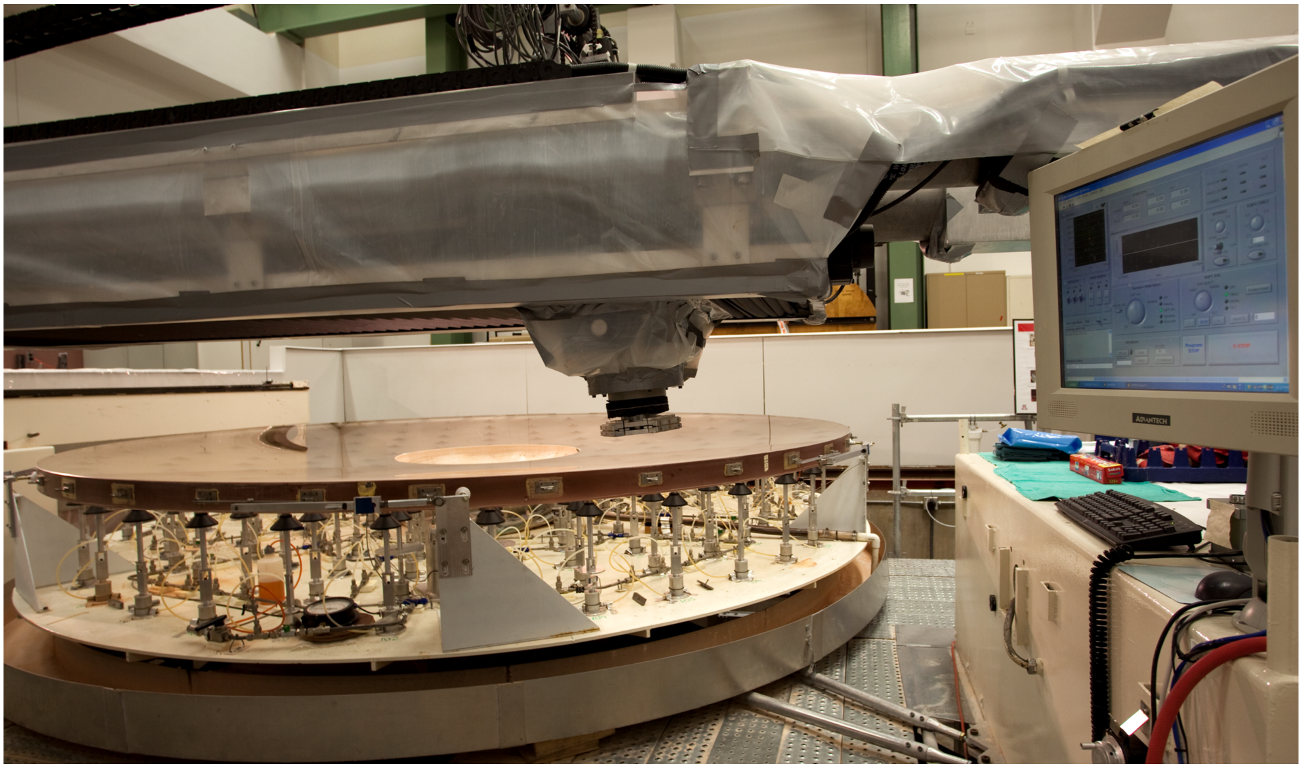

Figure 2. Computer controlled grinding and polishing machine – photo details polishing support system and Labview GUI interface for optician use.

The software control for the CCP machine is provided to the opticians in the shop with a Labview GUI interface for ease of use. Metrology output is provided for use in generation of dwell time maps for proper processing of the optical surface, and the dwell time map is converted to controller code and supplied to the PMAC controller for the system. The control allows for automated execution of the dwell time for a given tool shape and removal function characteristics.

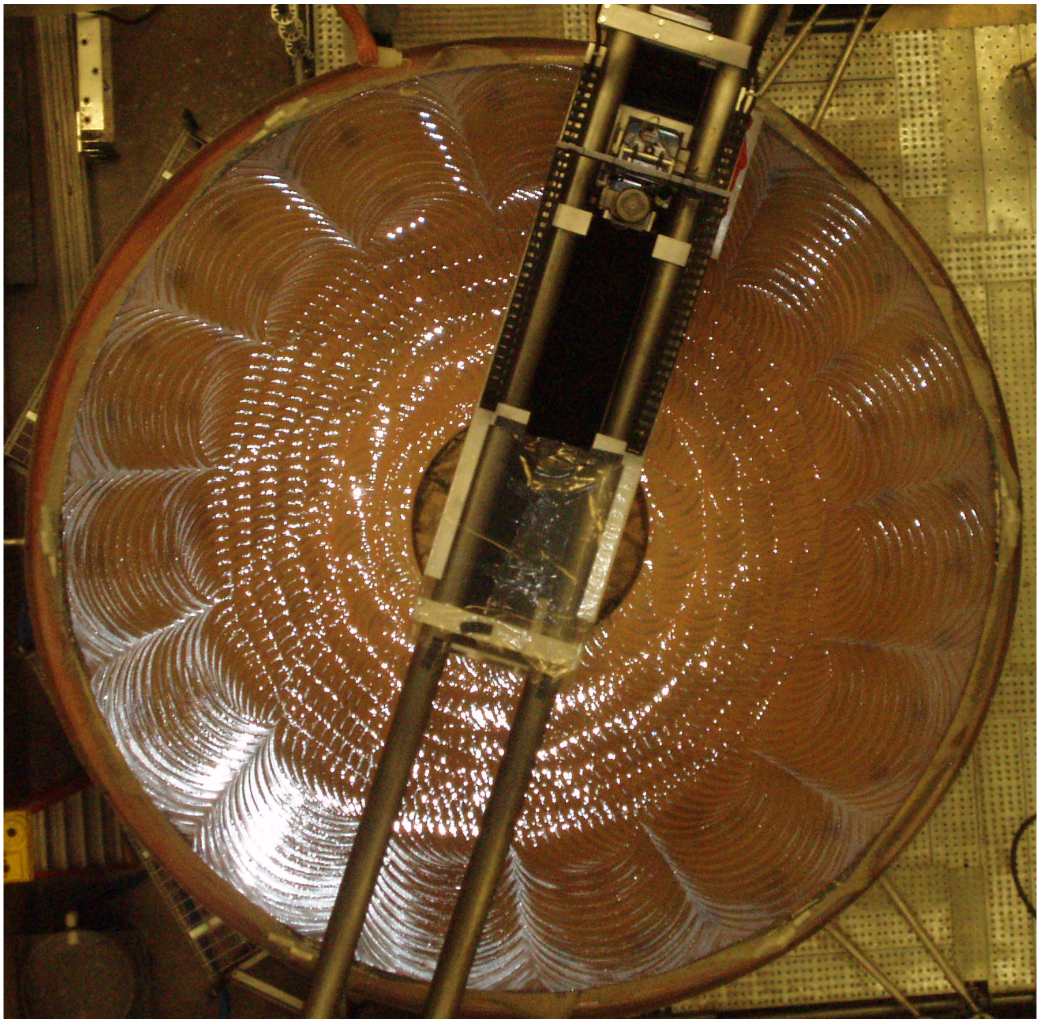

Figure 3. 4.3 m primary mirror for DCT situated on 4.3 m CCP machine in our optical shop. The position of the optic under a vertical tower allows for *in situ* metrology.

The dual cylinder 'trombone' structure shown in Figure 3 supports the radial stroke tools and motor assembly. This trombone can be driven out of the line of sight for *in situ* metrology (laser tracker, IR interferometry, visible interferometry). Also, Figure 3 shows the stable working platform which has been constructed around the edge and base of the machine for ease of operator use.

A careful marriage of traditional optical fabrication techniques and sophisticated computer-controlled algorithms on this updated platform enabled the successful loose abrasive grinding, polishing and final figuring of the 4.3 meter DCT primary mirror. Accurate metrology ensured that the final surface beat specification for the structure function (surface error as a function of spatial separation) by 30% at all spatial scales, and measured at 16.2 nm RMS after correcting for low order substrate bending shapes.

1.2 Laser tracker and IR interferometry - early fabrication guidance for large optics

An additional improvement to the capabilities in our shop has been the adoption of use of laser tracker distance measurement systems. We have begun to use these tools in our facility to facilitate support pad bonding, and as well to provide accurate determination of optical surfaces according to methods developed within the research group over the recent several years[3].

The photograph in Figure 4 shows a laser tracker (located in the mirror center hole) used to locate support pad bonding templates on the rear surface of the 4.3 meter DCT primary mirror.

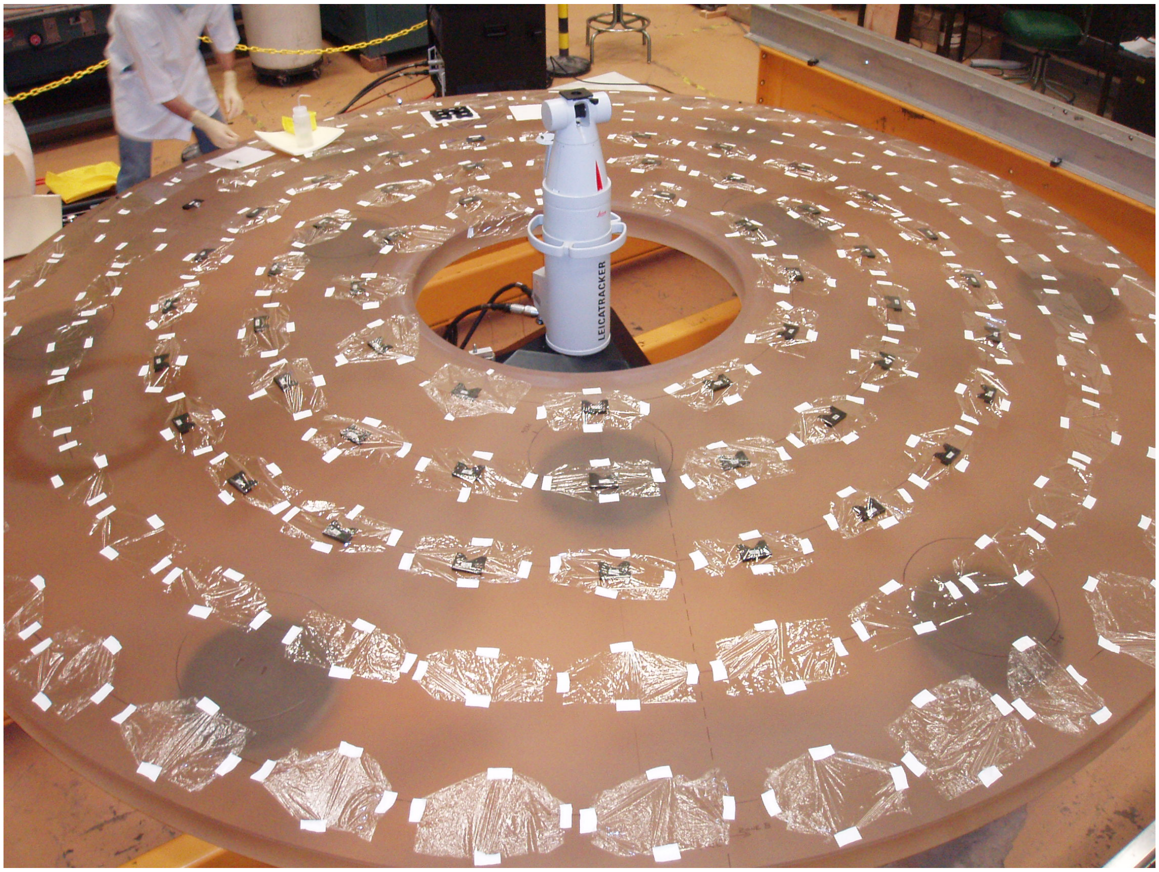

Figure 4. A laser tracker is used to locate the support pad bonding templates for the polishing and primary mirror telescope cell invar support pads.

In addition to this type of use of the laser tracker, we have adopted the use of the tracker to characterize the generated figure of optical surfaces. The picture in Figure 5 shows a collection of data used to fit the optical surface during processing.

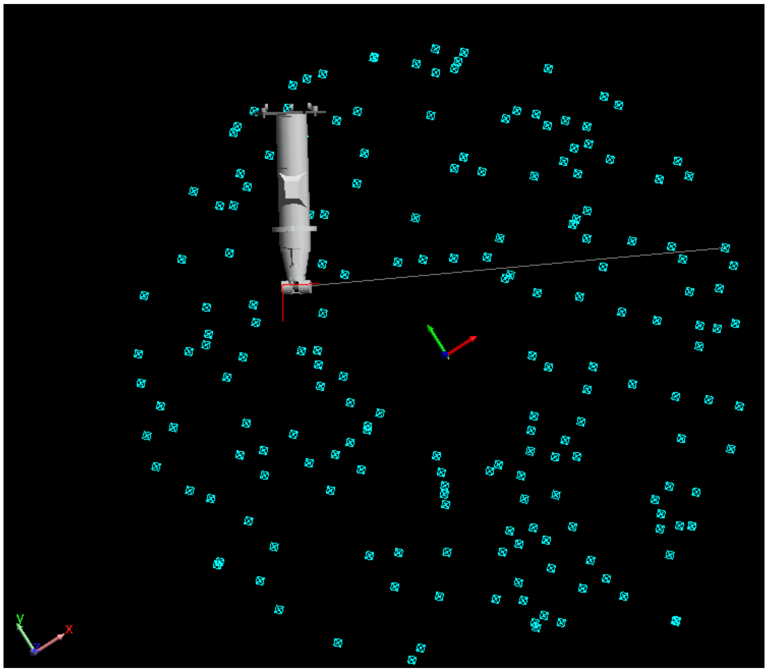

Figure 5. Schematic showing laser tracker above DCT 4.3 meter primary mirror, measurement of individual points enables fit of data to optimal optical surface.

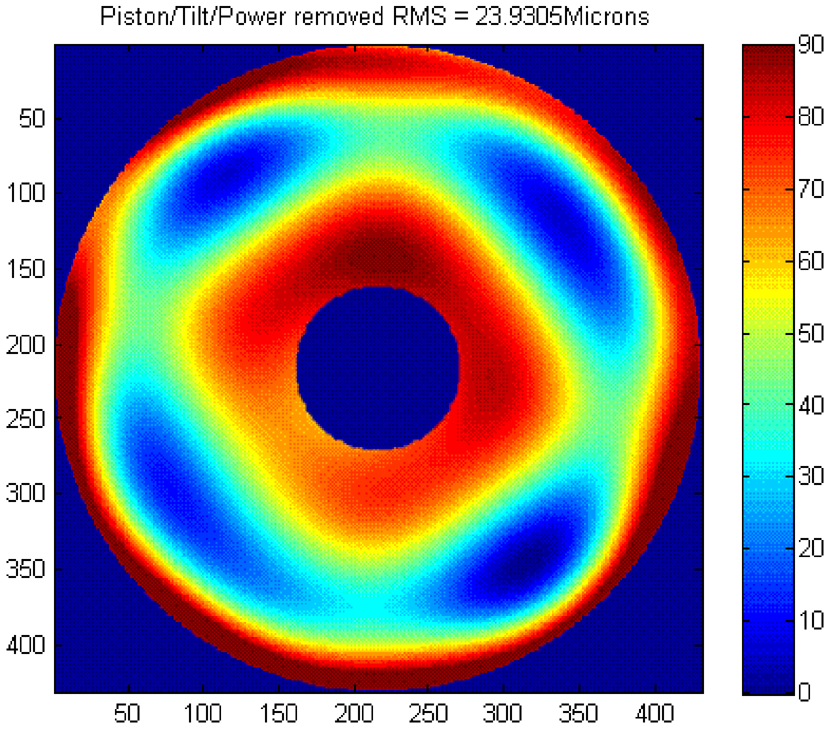

Figure 6. A surface map generated by performing a least squares fit of the data shown in Figure 5 to the ideal optical surface prescription during early processing.

Maps such as the one shown in Figure 6 are used during the initial fabrication stages to guide loose abrasive grinding. This early surface information is invaluable during the course of processing in that it enables rough figuring to occur before the surface of the generated blank is ground finely enough to give a specular reflection of the 10.6 µm IR wavelength.

The 4θ-dependent term seen in Figure 6 is thought to have been imparted due to a minor (on the order of 50 µm over 4.3 meters) bearing wobble during generation. Using laser tracker metrology on the generated and initially rough ground surface, we were able to correct this feature before the transition to interferometry was made, thus saving valuable processing time.

1.3 Traditional null optics testing of asphere mirrors

Once the optical surface is ground to a fine enough level, metrology can maintained with a 10.6 µm interferometer which we upgraded with a microbolometer array camera to improve resolution of the resulting measurements. Figure 7 shows a photograph of the Offner null lens and IR system used for measurements during the processing of the DCT primary mirror.

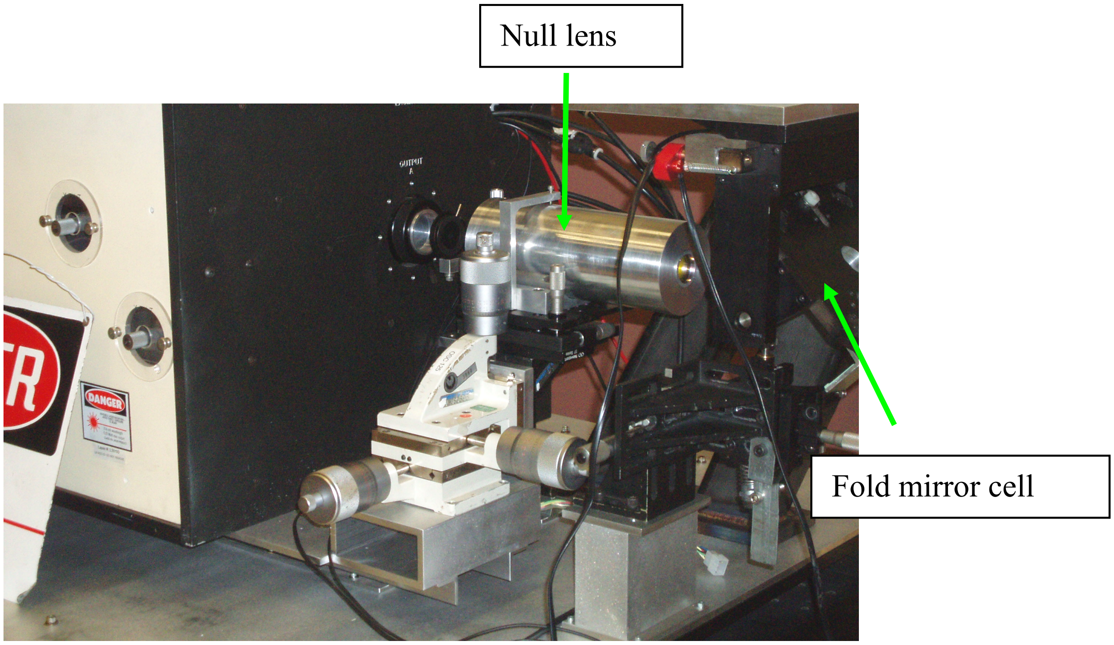

Figure 7. IR interferometer and Offner lens for 10.6 µm null test of DCT primary mirror.

The IR interferometry and laser tracker systems were used to process the surface to approximately 1 µm RMS (1/10 wave quality for the interferometer), in order to minimize polishing material removal.

After an optic is polished out to a specular surface, visible interferometry can be used to accurately complete the polishing and final figuring to exacting standards. We have vibration insensitive instruments in our shop which are capable of providing low noise, high accuracy determination of the surface. These quality data in turn enable the opticians to figure the mirror with confidence. Figure 8 contains a photograph showing the visible Offner lens and vibration insensitive interferometer used during our recent 4.3 meter mirror fabrication.

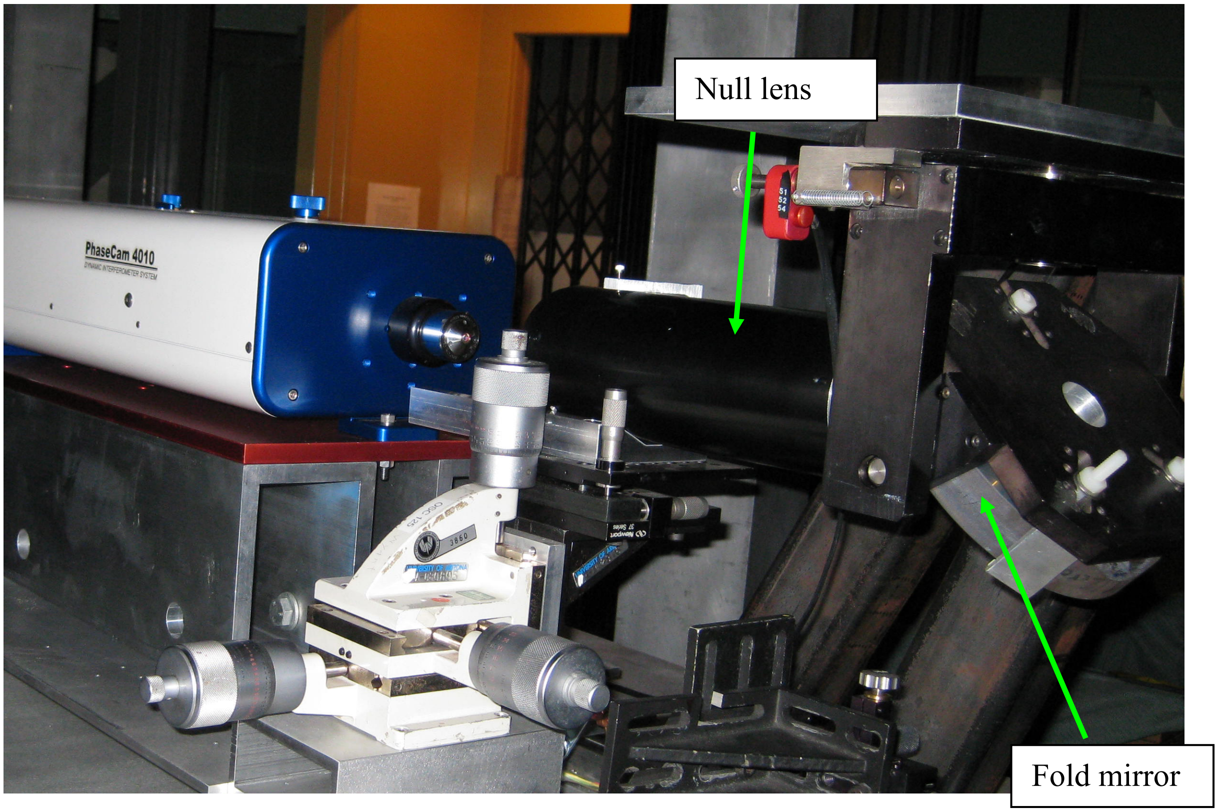

Figure 8. Visible null test system showing interferometer, null lens, and fold mirror.

The Offner null lenses used in our shop are certified using CGHs to reflect a nearly perfect aspheric wavefront representative of the ideally fabricated primary mirror. In this particular case, we built the null lens and certified the accuracy to a level of 12 nm RMS spherical aberration, ensuring accurate conic constant determination for the part.

2. TECHNOLOGIES READY FOR EXTENSION TO 4 – METER CLASS

2.1 CCP platform with Swing arm Optical Coordinate Measurement Machine (SOCMM)

We have successfully completed fabrication of convex, off axis aspheres[4] using tools and technology developed within our shop. One of the tools is the Swing arm Optical Coordinate Measuring Machine (SOCMM), integrated onto a 2 m class computer controlled polishing platform. A photograph of the SOCMM in operation is shown in Figure 9.

Figure 9. Photograph showing the SOCMM in use over a convex, off axis asphere (1.5 m diameter).

This SOCMM is built in combination with a polishing arm on the same machine platform, enabling *in situ* metrology for efficient division of shop time between fabrication and characterization of the optic during processing, effectively eliminating the need for complicated part movements or geometry changes during the course of production.

A unique combination of table bearing and tool head motions allow for accurate control of the polishing and figuring of parts on the order of 2 m diameter. Additionally, research within our fabrication group has been done to advance the types of tools which can be used to provide accurate surface finishing on aspheric parts[5]. These technologies (which have been proven[6] on aspheres at the 1.5 meter level) are ready for extension to our current 4 m computer controlled platform. A photograph of one of the tools processing a 1.5 meter optic is shown in Figure 10.

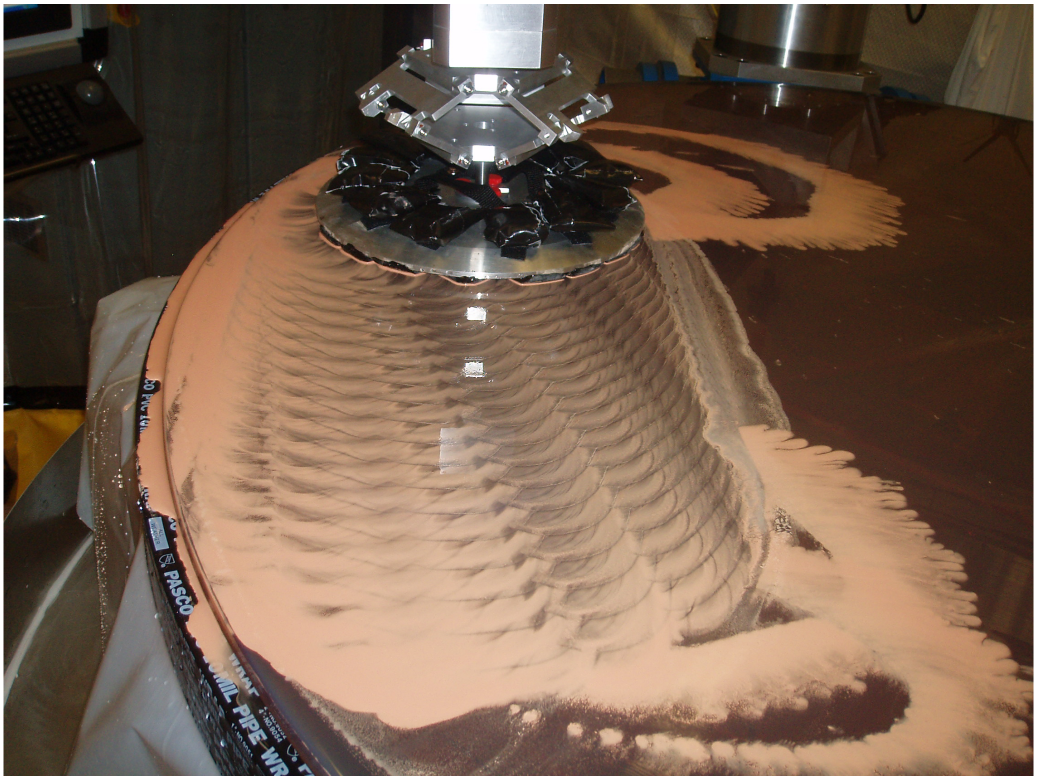

Figure 10. Photograph showing a polishing run on a 1.5 m diameter convex asphere, characterized by SOCMM data.

Due to the efficiency of pairing fabrication and metrology on the same working platform, we plan to extend this technique to larger production platforms pending future contracts. The technologies have already been proven effective so the extension from 2 m to greater than 4 m class machines would be accomplished via best engineering practices and system construction. This extension of capability would enable the engineering and fabrication team members to measure large, non-axisymmetric parts *in situ* on the fabrication platform and would make the processing of larger off-axis parts achievable in a rapid timeframe.

2.2 CGH based Fizeau Interferometry

In order to accurately measure the optical surface figure of large convex aspheres, large null optics on the order of the size of the asphere have been traditionally employed. The cost and complexity of such systems has led to the development of CGH based solution methods[7]. We have extended these ideas to create a CGH based Fizeau system which can be used to measure large convex or concave aspheres.

The basic layout of a system using this concept is shown in Figure 11. In this case, the unit under test is shown to be concave and is tested against a reference convex spherical surface. A pair of CGHs is used to correct the wavefront aberrations based on the reference beam passing through the spherical reference optic, and as well the aberrated wavefront reflected from the aspheric surface under test.

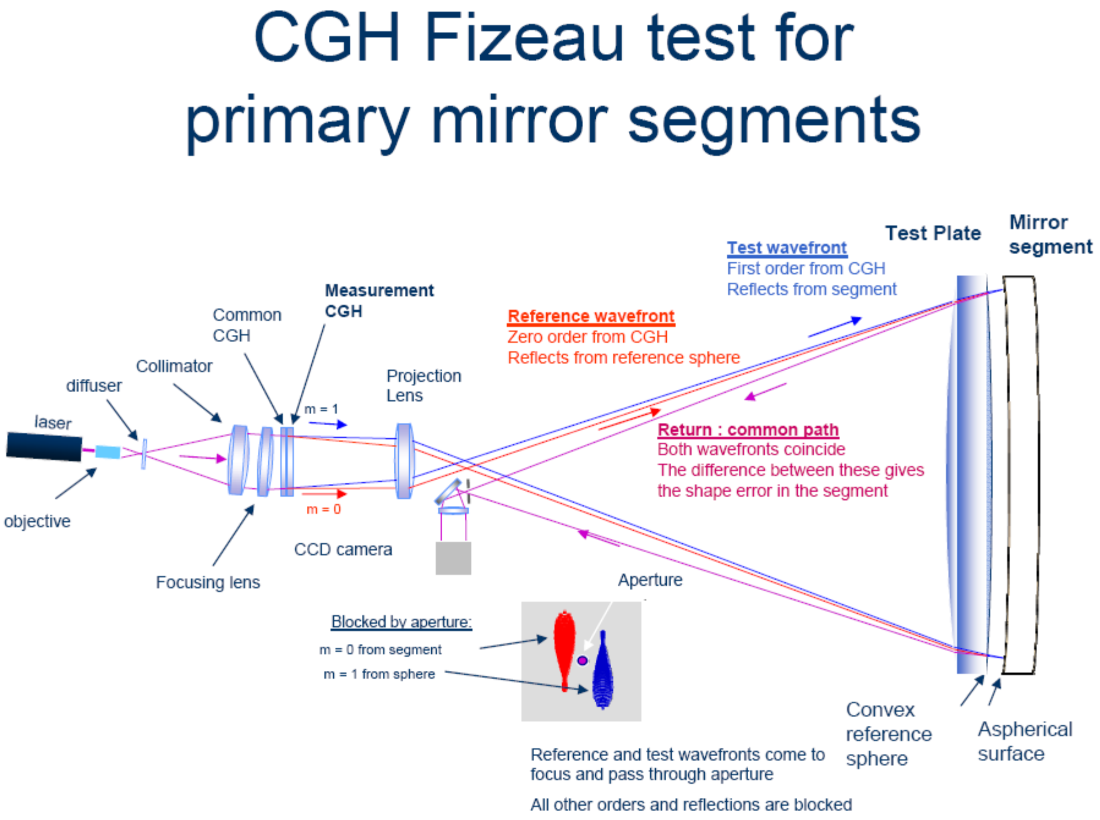

Figure 11. Schematic showing CGH based Fizeau system for measurement of an asphere with a convex spherical reference.

Convex[8] or concave aspheric surfaces can be measured in this manner. Extension of the technique to larger surfaces through stitching algorithms will make the measurement of up to 4 meter surfaces possible.

The accuracy of this method was verified by comparison to data collected using the SOCMM measurement platform for a 1.5 meter convex asphere. As can be seen from the data shown in Figure 12, the system provides high quality, accurate data, which agrees with the comparison method within 7 nm RMS for a 1.5 meter surface.

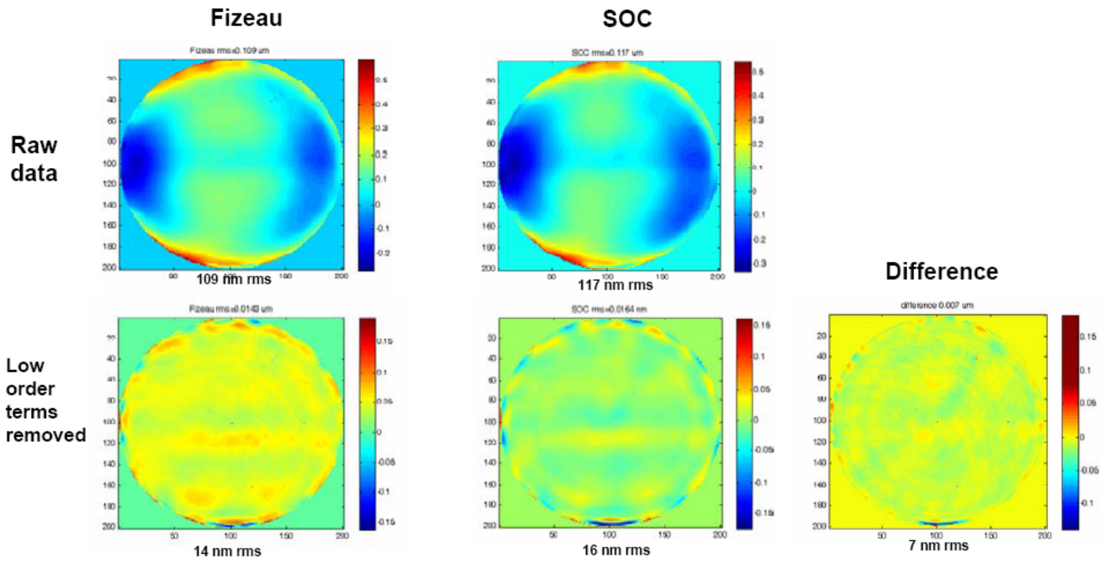

Figure 12. Comparison between CGH based Fizeau and SOCMM data. The difference map has 7 nm RMS.

2.3 Scanning Pentaprism System

As a final compliment to larger aperture stitching interferometry, we have developed a scanning pentaprism system to enable accurate measurement of large optical flats or aspheres. The drawing in Figure 13 shows a basic scanning prism test setup; the concept has been used to verify the fabrication of a flat mirror to 10 nm RMS accuracy in our shop.

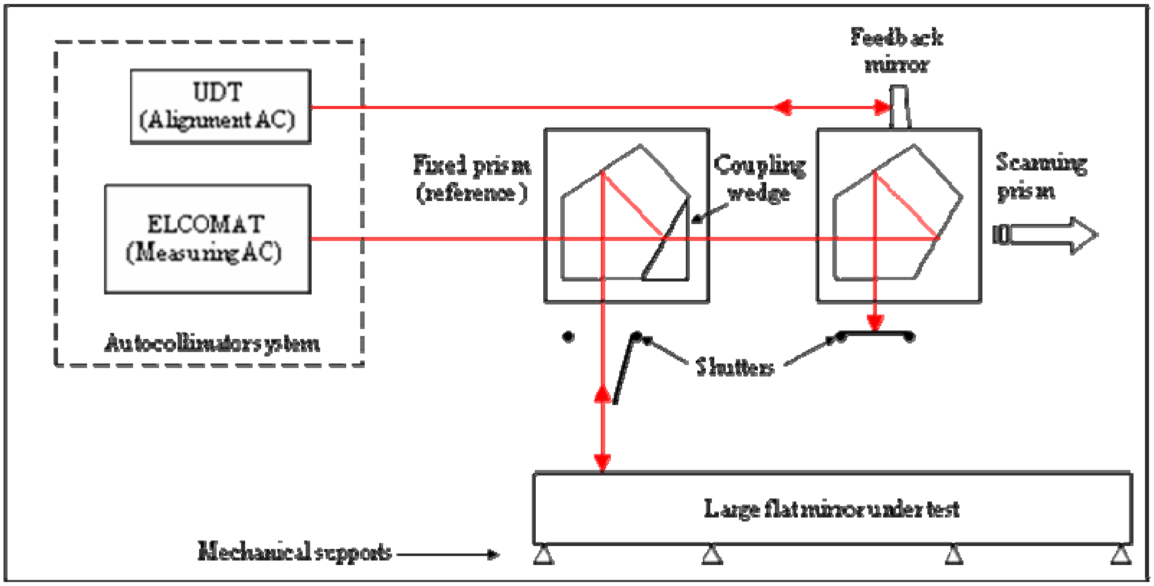

Figure 13. Scanning pentaprism system, with stable and moving prism enabling slope computation across the part under test.

In addition to use for verification of stitched flat mirror data, this technique has been extended to the verification of slope errors for large concave aspheric surfaces[9] in the last few years.

3. SUMMARY

A discussion of the capability for large (greater than 4 meters in this case) optical fabrication in the Optical Fabrication and Engineering Facility in the College of Optical Sciences has been made. We describe a computer controlled platform for fabrication and *in situ* metrology for 4 meter class optics, as well as novel and traditional metrology technologies used to support our fabrication efforts. We have also described the details of 2 meter class developments within our facility which are ready for expansion through careful engineering to the 4 meter class platform.

REFERENCES

[1] Dae Wook Kim, Sug-Whan Kim, and James H. Burge, "Non-sequential optimization technique for a computer controlled optical surfacing process using multiple tool influence functions," Opt. Express. 17, 21850-21866 (2009).

[2] Dae Wook Kim, Won Hyun Park, Sug-Whan Kim, and James H. Burge, "Parametric modeling of edge effects for polishing tool influence functions," Opt. Express. 17, 5656-5665 (2009).

[3] T. L. Zobrist, J. H. Burge, H. M. Martin, "Laser tracker surface measurements of the 8.4m GMT primary mirror segment," in Optical Manufacturing and Testing VIII, ed. by J. Burge, O. Faehnle, and R. Williamson, Proc. SPIE 7426, (2009).

[4] J. H. Burge, S. Benjamin, D. Caywood, C. Noble, M. Novak, C. Oh, R. Parks, B. Smith, P. Su, M. Valente, C. Zhao, "Fabrication and testing of 1.4-m convex off axis aspheric optical surfaces," in Optical Manufacturing and Testing VIII, ed. by J. Burge, O. Faehnle, and R. Williamson, Proc. SPIE 7426, (2009).

[5] Dae Wook Kim and James H. Burge, "Rigid conformal polishing tool using non-linear visco-elastic effect," Opt. Express. 18, 2242-2257 (2010)

[6] P. Su, J. H. Burge, R. E. Parks, C. J. Oh, "Swing-arm optical CMM for aspherics," in Optical Manufacturing and Testing VIII, ed. by J. Burge, O. Faehnle, and R. Williamson, Proc. SPIE 7426, (2009).

[7] Hua Liu, Zhenwu Lu, Fengyou Li, Qiang Sun, "Design of a novel hologram for full measurement of large and deep convex aspheric surfaces," Opt. Express, 19 March 2007, Vol. 15, No. 6.

[8] M. B. Dubin, C. Zhao, J. H. Burge, "Fizeau interferometer with spherical reference and CGH correction for measuring of large convex aspheres," in Optical Manufacturing and Testing VIII, ed. by J. Burge, O. Faehnle, and R. Williamson, Proc. SPIE 7426, (2009).

[9] P. Su, J. H. Burge, B. Cuerden, H. M. Martin, "Scanning pentaprism measurements as a verification test for off-axis aspherics," in Optical Manufacturing and Testing VIII, ed. by J. Burge, O. Faehnle, and R. Williamson, Proc. SPIE 7426, (2009).