Invited Paper

Large Optics Fabrication and Testing at the College of Optical Sciences

James H. Burge

College of Optical Sciences and Steward Observatory Mirror Lab
University of Arizona
Tucson, AZ USA 85721

ABSTRACT

The origin of the Optical Sciences Center (OSC) at the University of Arizona was closely tied to the need to expand the national capability for manufacturing large optics. This connection allowed OSC to grow quickly to become a truly unique place where new technologies are born and applied and where students have opportunities to apply academic lessons to real-world projects. In the decades that follow, OSC has grown to become a leader in many other optical disciplines, including photonics, imaging, optical engineering, and optical physics. But the core capability of optical fabrication and testing has remained as a unique University of Arizona asset. The last decade has seen explosive growth in development and implementation of new technologies for manufacturing and measuring large optics at the College of Optical Sciences. The classic polishing techniques have given way to advanced computer controlled machines and highly engineered laps. New measuring methods have enabled accurate metrology of steeply aspheric surfaces, concave and convex, symmetric and freeform. This paper discusses the history of optical fabrication and testing at University of Arizona and reviews some recent major projects and the technical developments that have enabled their success.

Keywords: Optical Sciences Center, Optical fabrication, large optics, optical testing

1. INTRODUCTION

When Aden Meinel started the Optical Sciences Center at the University of Arizona in 1964, technologies and facilities for Large Optics were literally at the core of the program. The national need for optical technologies and trained optical scientists for the growing space programs provided the impetus for the Air Force funding that initiated the Center. The building for the Optical Sciences Center was completely designed around the Large Optics shop, which is four stories underground with a 100-foot test tower that projects through the center of the building. While the 50 years of growth has led to prestigious programs in a wide variety of optical technologies and sciences, the Large Optics shop remains at the core, providing telescope mirrors, advanced technologies, and educational opportunities.

This paper summarizes the history of the Large Optics shop at the College of Optical Sciences. Some early projects illustrate the connection between Optical Sciences and Astronomy. As the capabilities at Optical Sciences increased, projects were undertaken with a wider variety of applications. Throughout the years, the Large Optics shop has been an economic engine, supporting the efforts at Optical Sciences directly, and spinning out entrepreneurial activities.

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2. THE EARLY DAYS

Large Optics fabrication played an important role in the inception of the Optical Sciences Center. In the beginning, Don Loomis was hired to set up the optics shop and to lead the fabrication of the 90-inch primary mirror for the Bok Telescope on Kitt Peak.[1] The initial large optics shop was set up in a warehouse off campus at 301 7th St. Early work on lightweight mirror technologies for space applications was performed here, in addition to completing the Bok primary mirror and other large optics. Don Loomis also led the effort to incorporate a state-of-the-art Large Optics shop into the design of the new building on campus. The new building, completed in 1969, was constructed around the Large Optics shop. The 8000 square foot shop was built 4 stories underground to provide stability of the ground motion and the thermal environment. A 100-foot test tower extends to the full 8 story height of the building, and it is surrounded with student offices to maintain thermal isolation from the outside.

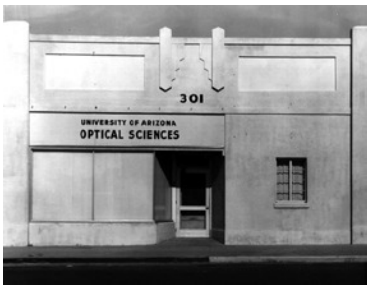

Figure 1. The original Large Optics shop was located off campus at 301 E. 7th St.

Figure 3. The original Optical Sciences building at 1630 E. University Blvd is built around the Large Optics Shop and test tower.

Long-awaited day arrives...

MOVING-IN TIME MARKS THE BEGINNING OF A NEW ERA FOR OPTICAL SCIENCES CENTER

Although the new Optical Sciences Center building was not formally accepted by the University of Arizona until November 14, the moving-in activities began earlier, by special permission from the contractors.

Installation of the first equipment made news in the local papers and over local TV stations, for it was indeed a spectacular sight to see a 10-ton polishing machine being lowered three floors down from ground level into the massive optics room!

October 31: The 100-inch polishing machine is lowered into the massive optics laboratory.

Most of the massive optics lab extends from the test tower area (the point of observation for this photo) southward under the back parking lot. The hatch allows any large equipment or materials to be moved into this level.

Figure 4. Excerpt from the 1969 *Optical Sciences Newsletter*. Since the optics shop is underground, large deliveries are made with a crane through a hatch in the ceiling that is at ground level.

Figure 2. A view looking up at Aden Meinel (left) and Don Loomis (right). The test tower is seen above them. The tower includes a movable platform that can be set at heights of ~12 – 30 meters above the polishing machine on the floor.

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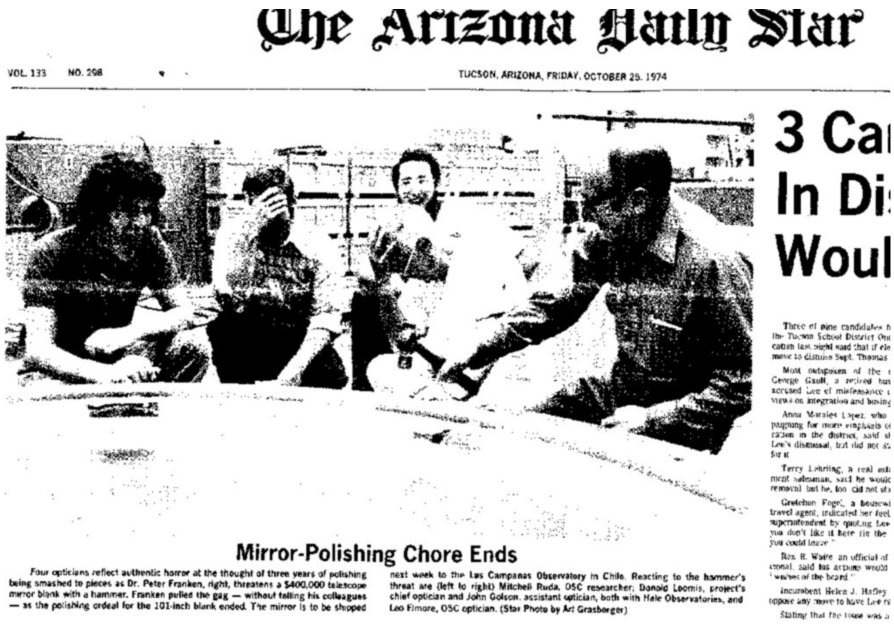
The first big project in the new Large Optics shop on campus was the 101" primary mirror for the du Pont Telescope in Chile.[2] Don Loomis moved on to start his own company *Loomis Custom Optics* that manufactured high performance optics for astronomy for decades. Greg Sanger took over the leadership for the shop and Peter Frankin took over the position of Director of the Optical Sciences Center. When the DuPont mirror was finished, Peter Frankin played a cruel practical joke taking a swing at the mirror with a hammer, but stopping just short of striking the surface. This was captured in an article in the Arizona Daily Star.


The Arizona Daily Star

VOL. 133 NO. 298

TUCSON, ARIZONA, FRIDAY, OCTOBER 25, 1974

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Incumbent Helen J. Hadley
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Stating that the issue was a

Mirror-Polishing Chore Ends

Four opticians reflect authentic horror at the thought of three years of polishing being smashed to pieces as Dr. Peter Franken, right, threatens a $400,000 telescope mirror blank with a hammer. Franken pulled the gag — without telling his colleagues — as the polishing ordeal for the 101-inch blank ended. The mirror is to be shipped next week to the Las Campanas Observatory in Chile. Reacting to the hammer's threat are (left to right) Mitchell Ruda, OSC researcher; Donald Loomis, project's chief optician and John Golson, assistant optician, both with Hale Observatories, and Leo Elmore, OSC optician. (Star Photo by Art Grasberger)

Figure 5. Excerpt from 1974 Arizona Daily Star when the 101" DuPont primary mirror was completed.

3. ADVANCING LARGE OPTICS TECHNOLOGY

The next large optics project at the Optical Sciences Center was the Multiple Mirror Telescope.[3] This innovative telescope combined the light from six 1.8-m telescopes. The primary mirror substrates are fused silica sandwich type mirrors weigh much less than the conventional solid mirrors. The mirror substrates were donated from a cancelled government space project. The primary and secondary mirrors were ground and polished at the Optical Sciences Center.

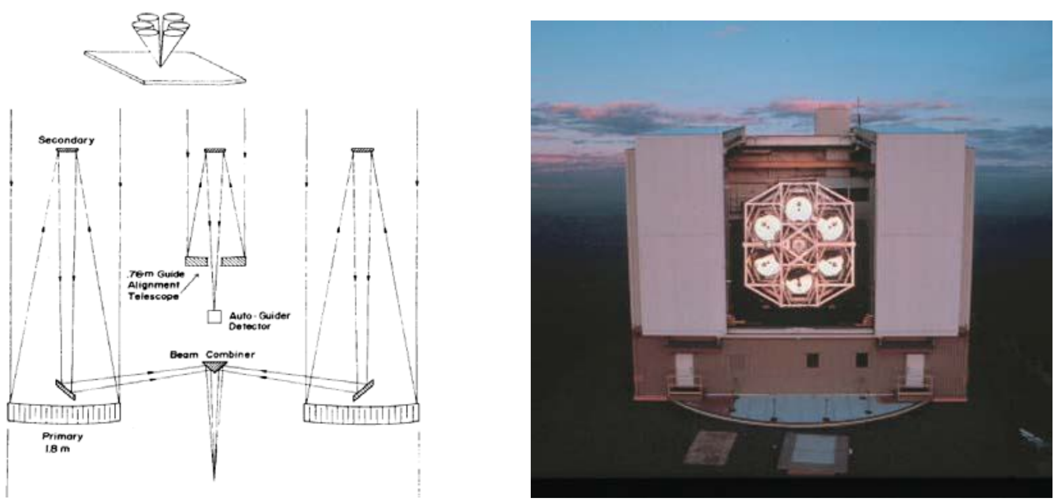

Figure 6. The Multiple Mirror Telescope MMT was built on Mt. Hopkins in Arizona using 1.8-m telescopes polished in the Large Optics shop at the Optical Sciences Center.

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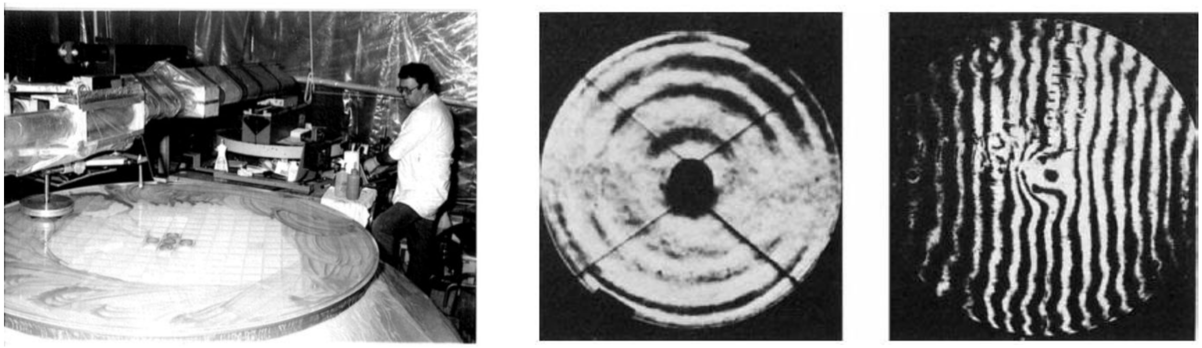

Figure 7. Master Optician Bob Crawford developed tooling and methods for polishing the MMT primary mirrors at reduced polishing pressure to avoid "print-through" of the rib structure into the optical surface. The square pattern of ribs that connect the front sheet to the back is seen in this view. The images on the right show the knife edge test in the telescope and the interferogram of mirror number 5 with PV amplitude of only 1/6 of a wave. In 2014, Bob was given a Lifetime Achievement Award by Optical Sciences Dean Tom Koch for his highly productive 5 decades of work as an optician at the University of Arizona

A number of technical advances enabled efficient fabrication of the MMT mirrors. New types of polishing tools that conform to the aspheric shape and operate at lower pressure were implemented. Interferometry was used to provide accurate surface measurements. When the MMT was commissioned, astronomers were surprised by the excellent image quality enabled by the use of the lightweight mirrors. The conventional solid glass mirrors were so massive that the mirror temperature never matched the temperature of the air, which caused convection in the light path which distorted the images. This observation provided the impetus for Roger Angle to develop much larger mirrors that maintain the lightweight concept of the MMT mirrors

As director of the Large Optics shop in the early 1980's, Bob Parks pursued precision grinding using computer controlled machines. The Large Optics Generator (LOG)[4] was installed in the Large Optics shop and was used for pre-processing optical mirrors and for finishing parts and molds for sub-millimeter telescopes. The LOG has been subsequently moved to the Steward Observatory Mirror Lab where it is used for generating, grinding, and polishing Roger Angel's 8-m mirrors.

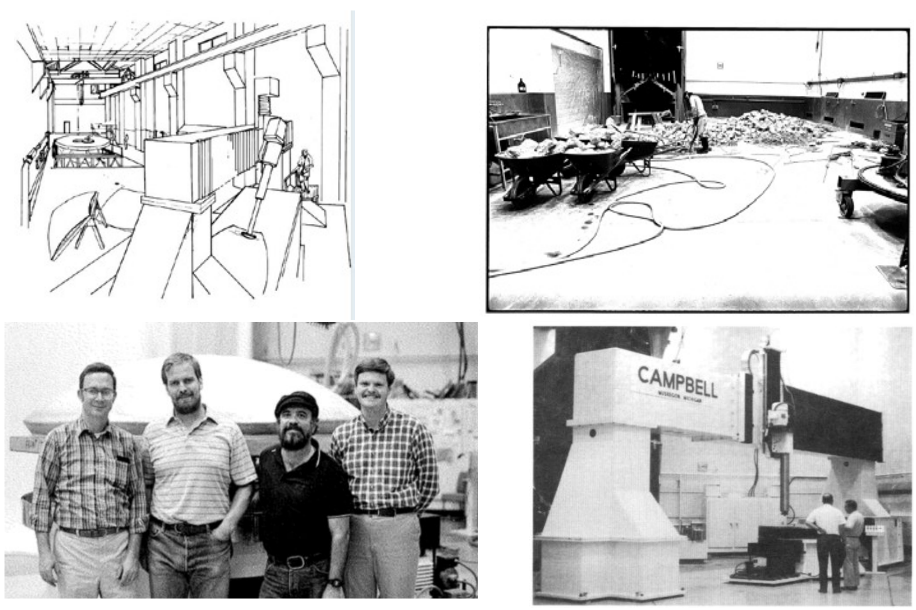

Figure 8. The Large Optics Generator, made by Campbell, was installed in the Large Optics shop and was used for a variety of surfaces, including a reflector for the Arecibo radio telescope. Bob Parks, Dean Ketelsen, Cary Kittrell, and Dave Anderson are shown here. Bob has since formed the *Optical Perspectives Group* and Dave leads the *Rayleigh Optical Corporation.*

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In addition to the large optics projects, the opticians at the Optical Sciences Center were renowned for making custom high-performance optics of smaller size. Throughout the latter 1980's and into the 90's while Dick Sumner directed the optics shop, there were usually several different projects that required advanced capabilities for fabrication or testing.

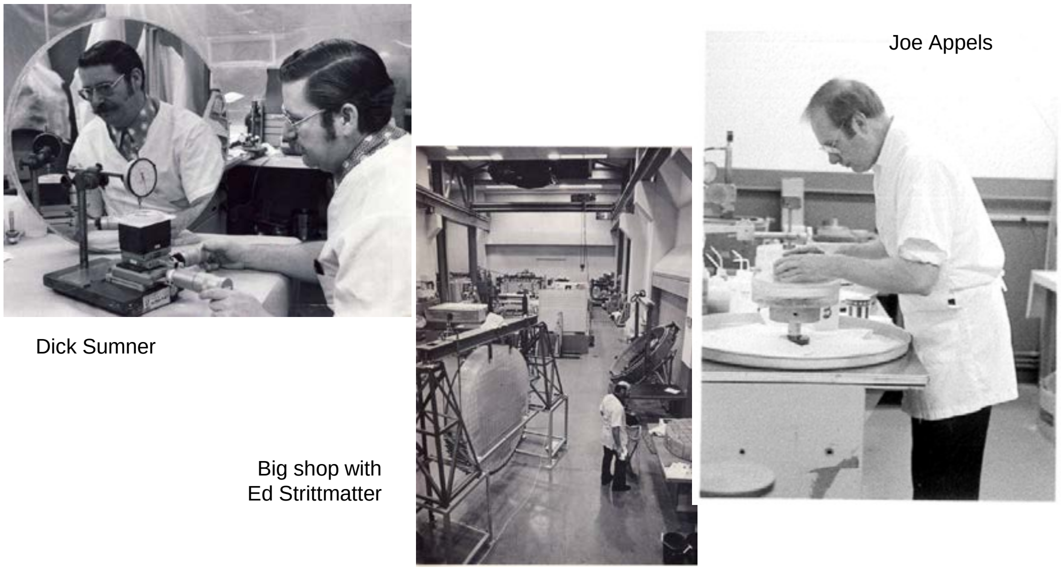

Figure 9. Dick Sumner directed the optics shop in the 1980's until passing the role on to Marty Valente in 1994. Joe Appels left the University to run the highly successful *Tucson Optical Research Corporation*.

4. THE STEWARD OBSERVATORY MIRROR LAB

During the 1980's and 90's, the growth for Large Optics fabrication at the University of Arizona was dominated by Roger Angel's Mirror Laboratory[5]. Some important technical advances at the Mirror Laboratory include

- spin casting lightweight mirrors to 8.4 meters in diameter[6]
- stressed lap polishing, using a computer controlled deformable polishing lap[7]
- computer generated hologram calibration of null correctors[8]
- testing techniques for large convex secondary mirrors[9,10]

Figure 10. The Steward Observatory Mirror Lab is built into the East side of Arizona Stadium. The enclosure for the 28-m test tower is seen in this image.

Figure 11. Lightweight mirrors up to 8.4 meters are cast in a spinning oven and polished with a computer-controlled stressed lap polisher.

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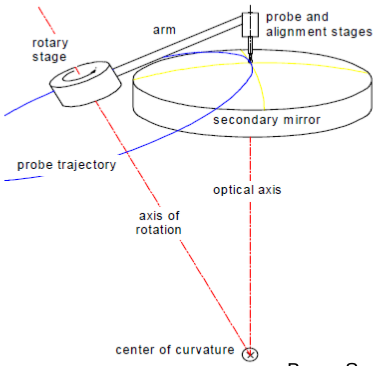
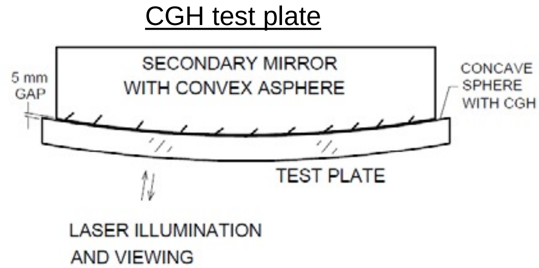




Bryan Smith

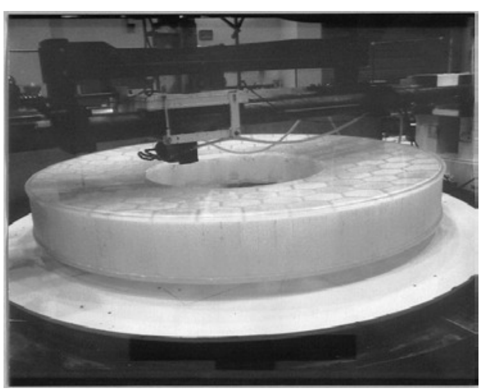
Lee Dettmann

Figure 12. New technologies were developed at the Mirror Lab for measuring large convex aspheric secondary mirrors. The swingarm profilometer measures profiles with 0.05 µm accuracy. Accurate measurements of the aspheric surfaces are made interferometrically using test plates with computer generated holograms fabricated directly onto them. This required the development of the world's largest laser writing machine shown here. This machine can write holograms onto curved surfaces up to 1.8 meters across, providing optical test accuracy of λ/100.

5. THE LATTER YEARS

The Large Optics shop saw continual growth after Marty Valente took over the leadership in 1994. Throughout the 1990's Marty led the shop to manufacture and measure some interesting optical components. The largest of these was the 2.5-m diameter primary mirror for the Sloan Digital Sky Survey Telescope.[11] Also the precision reference surfaces on the quartz blocks used for the Gravity Probe-B[12] spacecraft were polished at OSC. Other large parts, including numerous 50 cm off-axis paraboloids and a 2-meter diameter convex optic were made during this time

2.5-m primary mirror for the Sloan Digital Sky Survey Telescope



Quartz reference for Gravity Probe B

A 2-m diameter f/1 convex mandrel for JPL, used as master for replication

Figure 13. Some interesting projects in the 1990's include a 2.7-m primary mirror, quartz reference for Gravity Probe B, and a 2-m convex mandrel used as a master for replication

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Into the 2000's the types of projects expanded into complete optical systems, which included custom mechanical and electrical systems as well as precision optics. Most included proprietary information and were never published. Marty led the expansion of the technical staff to create OEFF, the Optical Engineering and Fabrication Facility. This growth was closely coupled to the development of my research group *LOFT*, Large Optics Fabrication and Testing.

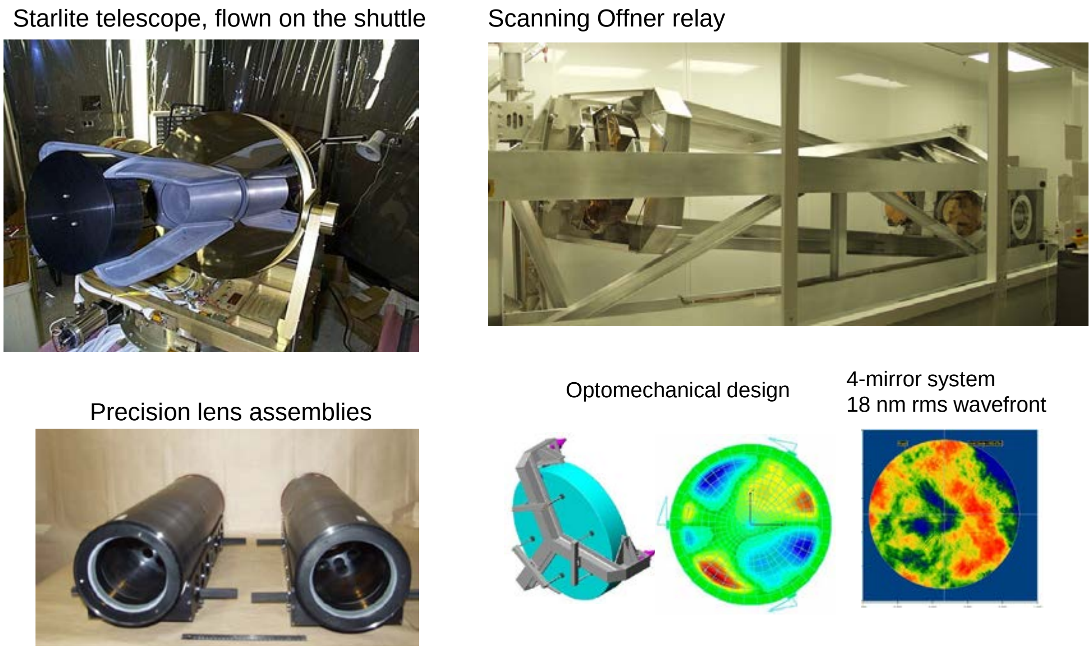

Figure 14. Into the early 2000's the Optical Engineering and Fabrication Facility grew into a diverse, highly capable enterprise that designed, manufactured, tested, and delivered state of the art optical systems.

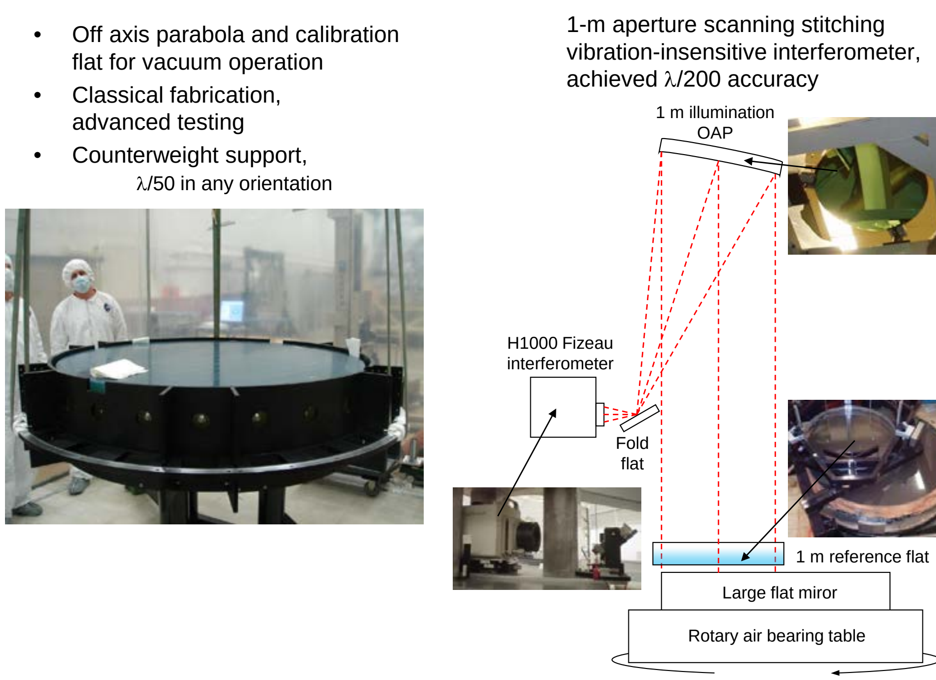

Figure 15. OEFF designed, manufactured, and tested a pair of 1.6-m mirrors for vacuum operation.[13] This required development of a 1-m vibration-insensitive scanning, stitching interferometer that achieved 3 nm rms measurement accuracy.

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The projects at OEFF benefitted from new applications of computer generated holograms CGHs for measurement and alignment. At the request of multiple companies, Chunyu Zhao and I formed *Arizona Optical Metrology*[14] as a spinoff private company that provides computer generated holograms commercially.

A new class of computer controlled polishing machine was developed for making 2-m class aspheric optics. These machines use the swingarm geometry to position grinding and polishing tools. New tools were developed that use a combination of elastic deflection and conformance from non-Newtonian fluids to fit the shape of steeply aspheric surfaces.[15] These machines were used to manufacture a set of 1.5-m diameter off-axis convex aspheric optics[16] and the 1-m class mirrors for the Wide Field Corrector for the Hobby Eberly Telescope.[17]

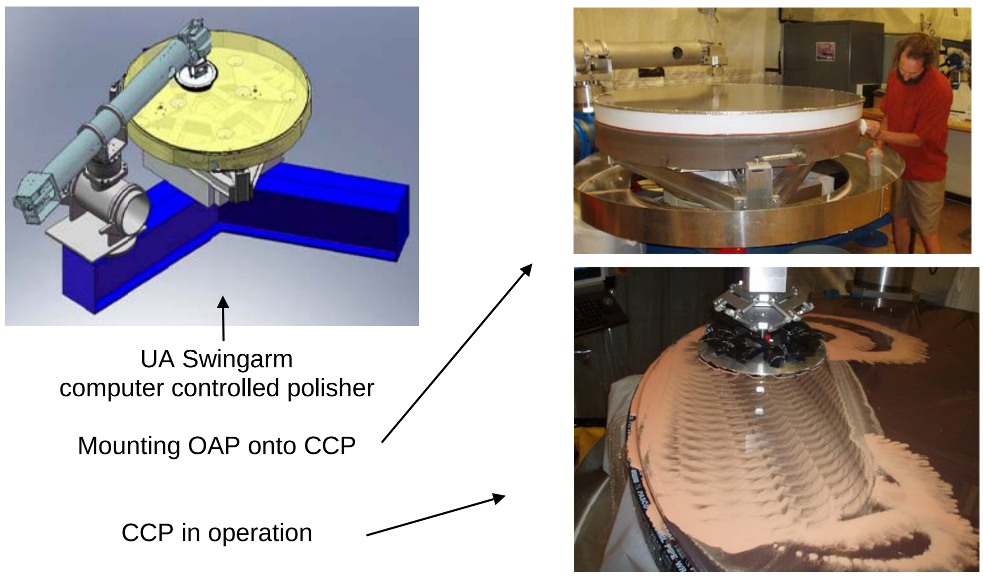

Figure 16. The computer controlled polishers at the University of Arizona use the swing arm geometry to control the position of the polishing head. A combination of swinging the arm rotation and rotating the table provides control to position the lap anywhere on the optical surface. The polishing laps are driven in both orbit and rotation to provide directed removal and smoothing, as designed by computer optimization.

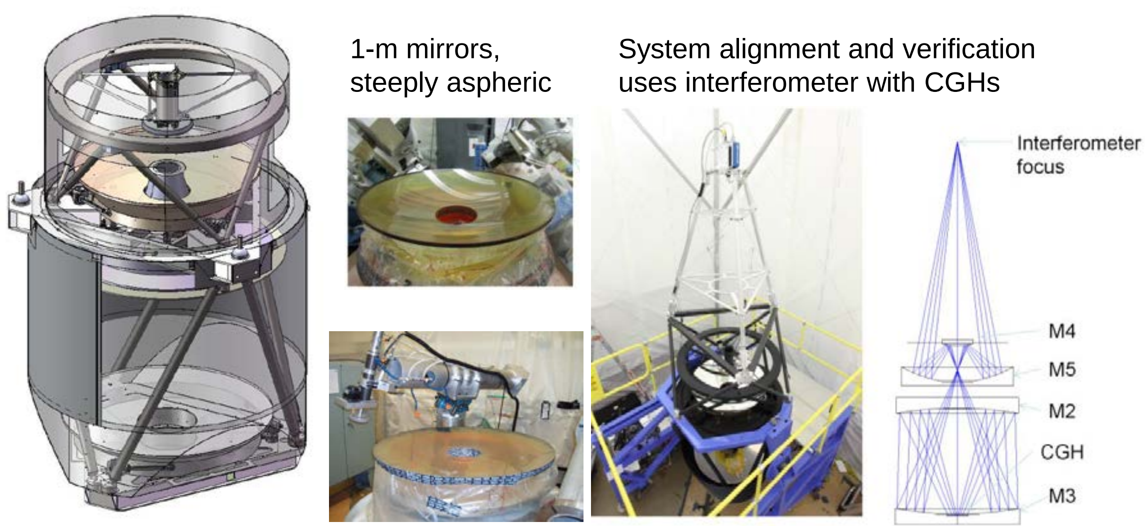

Figure 17. The Wide Field Corrector for the Hobby Eberly Telescope is currently being built by in the Large Optics Shop at the College of Optical Sciences. This project has required precision optomechanical design, manufacturing of highly aspheric mirrors, and optical system alignment ant testing

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Going back to the roots of the Optical Sciences Center, large primary mirrors for astronomical telescopes are being ground and polished at OEFF. The 4.2-m primary mirror for the Discovery Channel Telescope was manufactured using one of Aden Meinel's machines that was modified for the larger size and for computer controlled operation.[18] The surface was finished to 16 nm rms.

- 4" thick ULE mirror, supported at 120 points
- Classic Draper polishing machine, outfit with computer controlled axes
- Interferometric testing, null corrector, finished to 16 nm rms

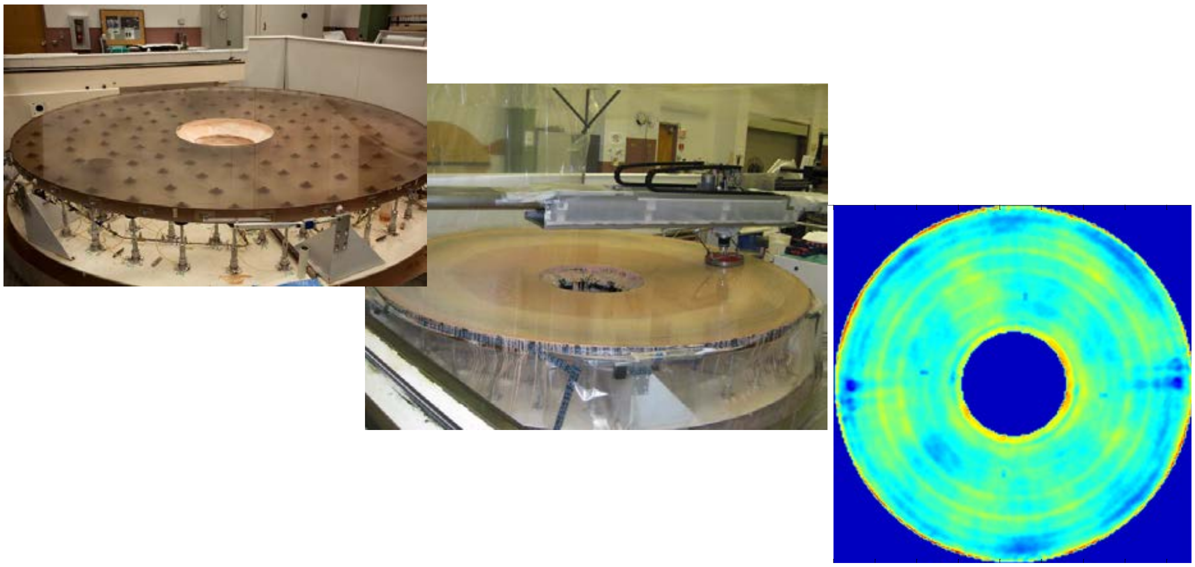

Figure 18. The 4.2-m primary mirror for the Discovery Channel Telescope was ground and polished in the Large Optics shop using a modified Draper machine from the days of Aden Meinel.

Another 4-m project is the primary mirror for the D. K. Inouye Solar Telescope,[19] formerly call the Advanced Technology Solar Telescope.[20] This telescope provides an unobscured aperture using an f/0.7 off-axis paraboloidal primary mirror. The primary itself is 4.2 meters in diameter made of Schott's Zerodur glass, and is only 75 mm thick. The telescope design is shown below as well as some images of the primary mirror in the Optical Sciences Large Optics shop.

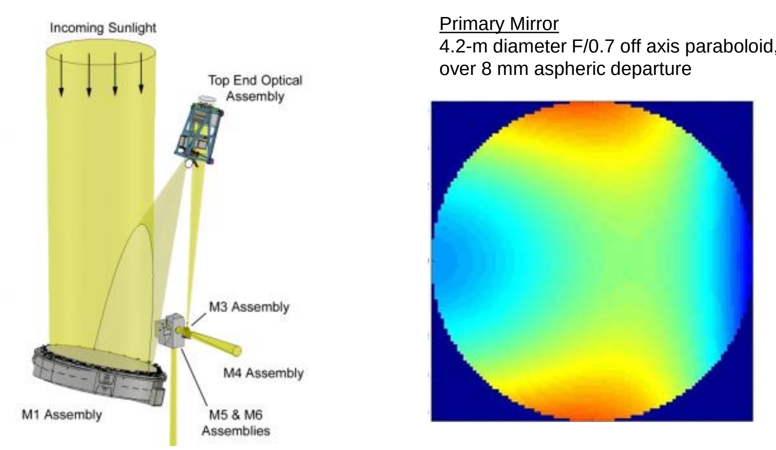

Figure 19. The D. K. Inouye Solar Telescope uses a 4.2-m primary mirror, which is an off axis portion of an f/0.7 paraboloid. The aspheric departure for this mirror is over 8,000 µm.

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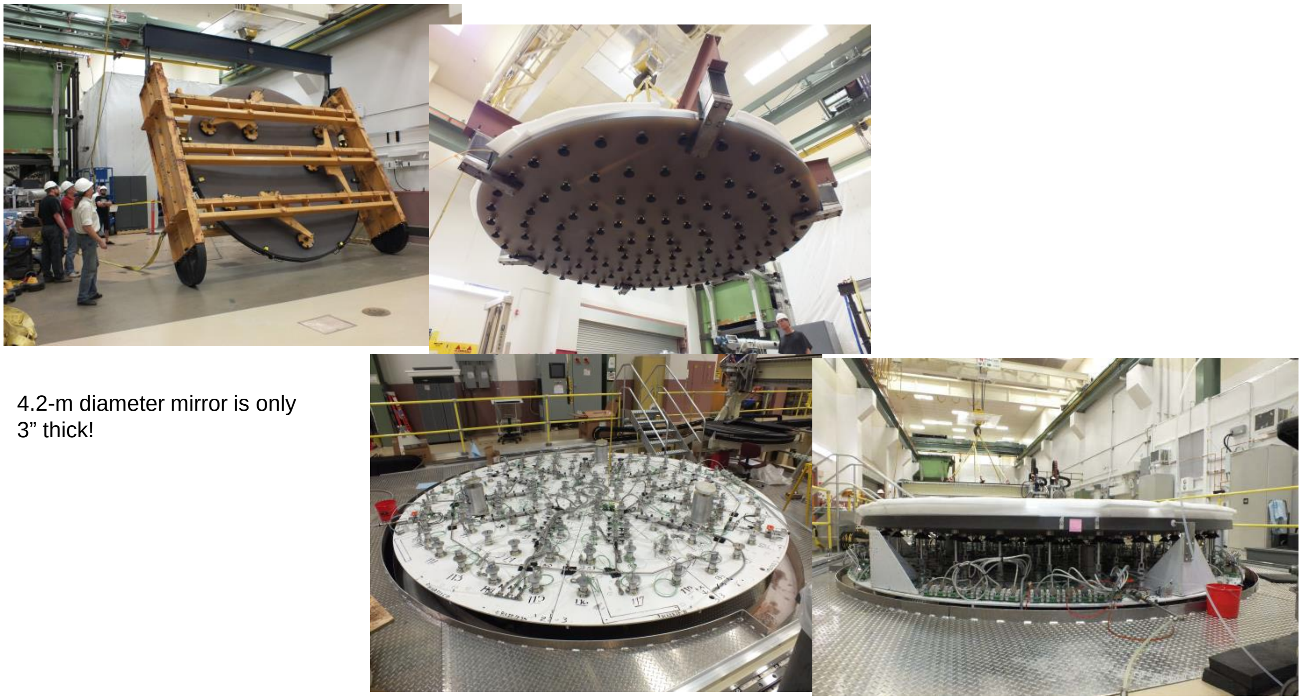

Figure 20. The primary mirror for D. K. Inouye Solar Telescope (DKIST) is handled in the Optical Sciences shop, and ultimately supported by 118 actuators on the polishing table.

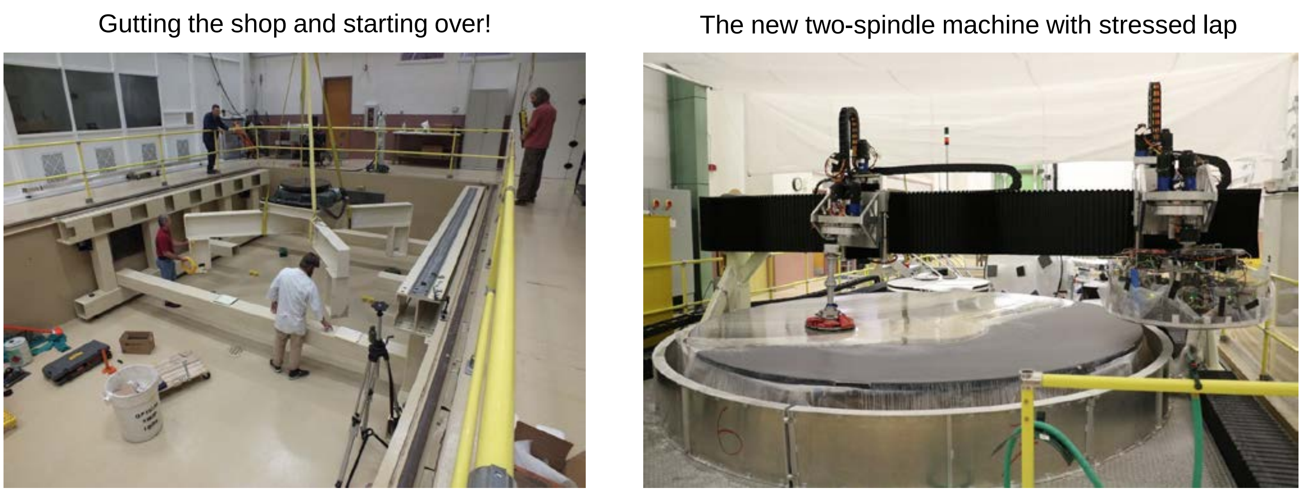

Figure 21. A new 4-m capacity, two-spindle computer controlled grinding/polishing machine was recently installed in the Large Optics shop and is currently being used for the DKIST primary mirror.

At the time of this writing, the DKIST mirror was being fabricated in the Large Optics shop using the computer controlled grinding/polishing machine above. The surface was in the process of loose abrasive grinding and was measured with SLOTS, the Scanning Longwave Optical Test System[21] as having ~ 1 µm rms surface departure from ideal.

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6. CONCLUSION

The Large Optics shop at the College of Optical Sciences continues to manufacture some of the world's most challenging large optics. In addition, the large projects provide opportunities for students to both perform groundbreaking research and to contribute to a "real" project that has deliverable hardware. The Large Optics shop also continues to enable individuals to create spinoff companies that build our local economy and increase the impact on the broader scientific and aerospace communities. In 2008, Marty Valente and I formed *Arizona Optical Systems*,[22] which is now a multi-million dollar company that develops advanced technologies[23] and manufactures custom optical systems up to 1.8 meters.

At the time of this conference, the Optical Engineering and Fabrication Facility at the College of Optical Sciences, the Steward Observatory Mirror Laboratory, and the Steward Engineering and Technical Services Group have been combined and fall under common management. This enables staff, students, technologies, and equipment to move more fluidly between different projects that involve large optics. Jeff Kingsley, with joint appointment in Optical Sciences and Steward Observatory, leads the combined activities.

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