

Fabrication of large secondary mirrors for astronomical telescopes

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ABSTRACT

A new class of telescope is being built with primary mirrors as large as 8.4 meters in diameter and as fast as $f/1$. Fabricating the secondary mirrors for these telescopes has presented tough challenges because of their large sizes, up to 1.7 meter diameter; their aspheric departure of more than 300 microns; the required figure accuracy of a few tens of nanometers; and the fact that they are typically convex and difficult to measure. We have developed tools and techniques to meet these demands to produce secondary mirrors efficiently and accurately. A dedicated facility was constructed in the Mirror Lab that integrates a 1.8-m stressed-lap polishing machine with interferometric and mechanical measuring systems. This paper presents data from a 1.15-m secondary that was finished in our shop, and from two other large mirrors that are currently being fabricated.

Keywords: optical fabrication, large optics, aspheres, telescope mirrors

1. INTRODUCTION

The Steward Observatory Mirror Lab at the University of Arizona has developed a number of new fabrication methods for large telescope mirrors. The 6.5-m $f/1.25$ primary mirror for the conversion of the Multiple Mirror Telescope (MMT) is now nearly completed. The first 8.4-m $f/1.1$ primary for the Large Binocular Telescope (LBT) is now annealing in our furnace. These giant telescopes require secondary mirrors that could not be made readily with conventional techniques and equipment. A list of the secondary mirrors finished or planned at the Mirror Lab is given below in Table 1.

Table 1. Secondary mirrors finished or planned for the Steward Observatory Mirror Lab (SOML).

| Mirror | Blank | Diameter | P-V Asphericity | Radius | Conic Constant |
|-----------------|----------------------|----------|-------------------|---------|----------------|
| Sloan Secondary | Hextek gas-fusion | 1.15 m | 109 μm | 7194 mm | -12.11 |
| MMT $f/9$ | Hextek gas-fusion | 1 m | 168 μm | 2806 mm | -1.749 |
| MMT $f/5$ | Zerodur light weight | 1.7 m | 330 μm | 5151 mm | -2.697 |
| MMT $f/15$ | Thin shell | 0.65 m | 82 μm | 1784 mm | -1.406 |
| ARC $f/8$ | Hextek gas-fusion | 0.84 m | 66 μm | 3167 mm | -2.185 |
| LBT $f/15$ | Concave | 0.88m | 123 μm | 1890 mm | -0.733 |
| LBT $f/4$ | Undecided | 1.2 m | 340 μm | 3690 mm | -3.373 |

One traditional method of creating these surfaces would be to generate, then grind and polish to a best fit sphere. The optician would then make a petal lap and polish in the asphere using a Hindle test to guide the figuring process. It is not practical to polish in the large aspheric departure the fast mirrors require, and the size of the mirrors prohibits the Hindle test. We would require a high quality mirror more than 6 meters in diameter for this test.

The method developed at the Mirror Lab takes advantage of several technological innovations that were implemented there: stressed-lap polishing¹, accurate mechanical measurements with a swing arm profilometer², and interferometric measurements of steep convex aspheres using holographic test plates.³ We start by generating the surface and grinding

with loose abrasives to a spherical shape that has the best-fit radius of curvature for the final asphere. Then we grind the aspheric departure into the surface with loose abrasives, guided by measurements from our swing arm profilometer. We finish the mirrors using the stressed-lap polisher, guided by interferometric measurements from a holographic test plate.⁴

| Process step | Tools | Metrology | Accuracy |
|--------------------------------|--|-------------------------|--------------------|
| 1. Fabrication of mirror blank | Diamond generate | Direct measurement | 0.5 mm |
| 2. Grind to best fit sphere | Rigid lap faced with tile | Spherometer, test plate | 2.0 μm |
| 3. Aspherize | Compliant lap or stressed lap, faced with metal pads | Profilometry | 0.1 μm |
| 4. Polish to completion | Stressed lap faced with pitch | Interferometry | 0.02 μm |

We successfully used this fabrication method for the secondary mirror for the 1.15-m secondary for the Sloan Digital Sky Survey Telescope,⁵ which was finished to 42 nm rms surface error.

2. MIRROR BLANKS AND MIRROR CELLS

Unlike the primary mirrors, the secondary mirror substrates are not manufactured at the Steward Observatory Mirror Lab. The secondary mirrors worked so far have been made of low or zero expansion glass and have been extensively light-weighted to improve performance in the telescope. Our process would also be well-suited for mirrors made of other more exotic materials.

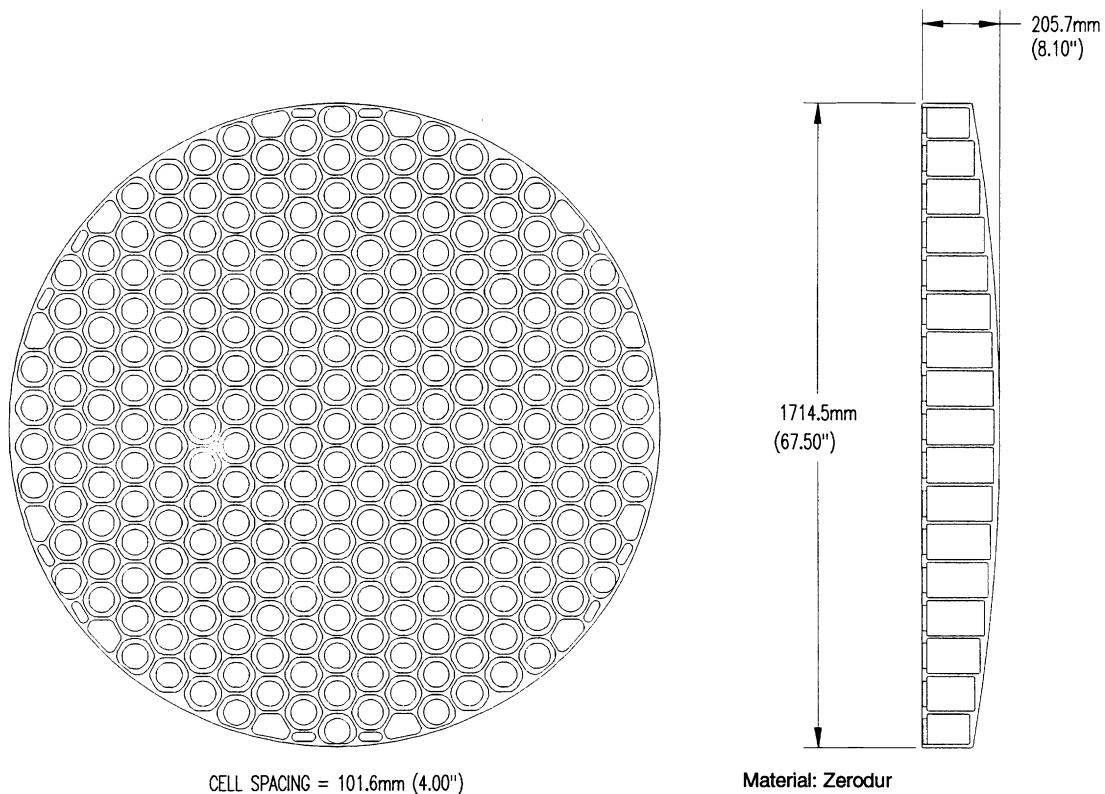


Figure 1. 1.7-m lightweighted blank for the MMT $f/5$ secondary mirror.

The Sloan and MMT $f/9$ secondary mirrors are made from borosilicate glass using the gas-fusion technique by Hextek. The face plate and back plates are about 12mm thick and the cell size is roughly 75 mm. These mirrors are around 150 mm thick and are made plano-plano and slumped, so the rear surface of convex mirror is always concave. The MMT $f/5$ secondary mirror uses a lightweighted Zerodur blank, shown in Fig. 1. The finished blank is plano-convex with 10-cm hexagonal cells and a face plate thickness of nominally 18 mm. The MMT $f/15$ mirror will be made as a 2-mm thick shell of Zerodur. The manufacturing process for this, described in detail elsewhere,⁶ allows the shell to be ground and polished while it is bonded to a rigid blocking body, so the techniques described here apply to this mirror as well.

All large optics, whether primary or secondary mirrors, are sensitive to deflections caused by force variations that could easily occur if care is not taken in the design of supports for polishing and testing. The distribution of mirror support forces for the telescope support is chosen to limit the gravitational deflections that occur in the transition from zenith to horizon pointing. The support forces for optical testing in the lab (the testing support) can be chosen to match the telescope support at a particular orientation, e. g. zenith pointing. The polishing support need not match the telescope support precisely, but it does need to avoid concentrated forces that would create a significant deflection (say, 20 nm) over the area of the lap, for these local deflections would be polished into the surface forming support print-through. (This is a more serious concern for a relatively large and stiff lap.) An additional requirement of the polishing support is at least some minimal stiffness against piston and tilt caused by the force and moment applied by the lap.

Support of primary mirrors during polishing and testing is relatively straightforward. The testing support can match the telescope support as accurately as one cares to make it, and the polishing support can be identical, with the addition of the rigid-body constraint. If the primary mirror is to be supported at a number of discrete points in the telescope, then a polishing support of the passive flotation type (e. g. hydraulic cylinders) that matches the telescope support in the absence of lap forces, and resists lap forces as a distributed whiffletree (e. g. by fluid connections among all cylinders in each of the three sectors), is adequate.

The situation is more complicated for secondary mirrors, as they are generally polished face-up and used face-down. Since we test the mirror face-down, we can make the testing support match the telescope support, in the case of the Sloan secondary, a 9-point whiffletree with 9 rods in tension attached to the back plate of the mirror. If we used the same whiffletree as a polishing support, the rods would be in compression and there would be a tendency to create print-through of twice the gravitational deflection (actually, worse because of the additional lap forces). Instead, the cell built for the Sloan mirror keeps the rods in tension by attaching them to a plate of the same mass as the mirror. The mirror hangs from this plate for testing, and vice versa for polishing. The necessary upward force during polishing should be as uniform as practical, so as to

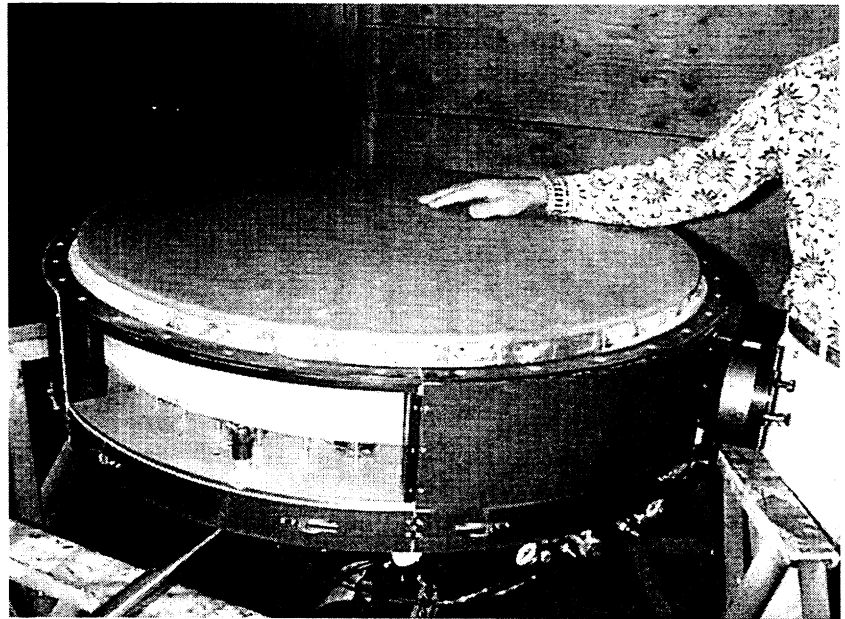


Figure 2. 1-m MMT $f/9$ secondary mirror in its polishing/testing cell.

support both the weight of the mirror and the lap forces, with minimal local deflection. The cell used for this is a 36-point hydraulic whiffletree that engages only when the mirror is face-up. The other secondary mirrors use similar supports.

The lightweighted mirrors are prone to “quilting”, a type of figure where the cells in the mirror will appear puffed up in the center. The polishing pressure deflects the face sheet at each cell and smoothes the surface. After the tool is lifted, the cells spring up and cause the quilted appearance. We minimize this effect by countering with air pressure, inside the mirror, that pushes out with the same pressure as the polishing loads. This works quite well, but it requires the mirror cell to be sealed. It is important that this pressure seal does not distort the mirror.

3. OPTICAL PROCESS -- STEP 2, GRIND THE MIRROR SPHERICAL

We start work on the optical surface by grinding it to the best-fitting spherical surface. This is done for several reasons. First, it is easy to achieve a good sphere using a large rigid tile-faced tool. Large grits and long running times can be used to achieve rapid removal and the sphere can be readily figured to a few microns. As long as we support the mirror correctly, it will take a spherical shape after running with the large rigid tool. We count on this surface to be free of azimuthal variations, as we have no good way to make a full surface map until the part has been aspherized and can be measured optically.

The shape during spherical grinding is monitored with spherometers and subaperture test plates. The Sloan and MMT *f/9* secondary mirrors were ground spherical by an outside vendor. The MMT *f/5* secondary was ground at the Mirror Lab, including a large change in the radius of curvature that was made to accommodate a change in the optical design. This work was done using a 1.36-m diameter tool cast from plaster that has an internal steel weldment. After making the radius change using the tile-faced tool, the tile was thin and needed to be replaced. The tool was then retiled, using 91 Gugolz pitch to make up the 1.8 mm difference in sag between the tool and the new radius. The 91 pitch is very stiff and allows good blocking, but is difficult to press out. We ran hot water through the lap to get the pitch to flow. The resulting tool behaved well and the tile showed even wear after the first run. This tool was used to bring the mirror to a 0.31 μm rms sphere (See data in Fig. 2.), finishing with 9- μm grit. The only metrology used during the grinding was an eight inch two ball spherometer with a 1 micron resolution. At the point where the spherometer indicated the appropriate radius of curvature, a Fizeau test was done with a 12-in test plate. We verified that the part does not have large azimuthal errors using a 38-in bar spherometer and making profilometer scan across several diameters, but we will not be able to see the small-scale figure errors until the interferometric test can be performed when the mirror is near completion. It is important that we start with a good sphere.

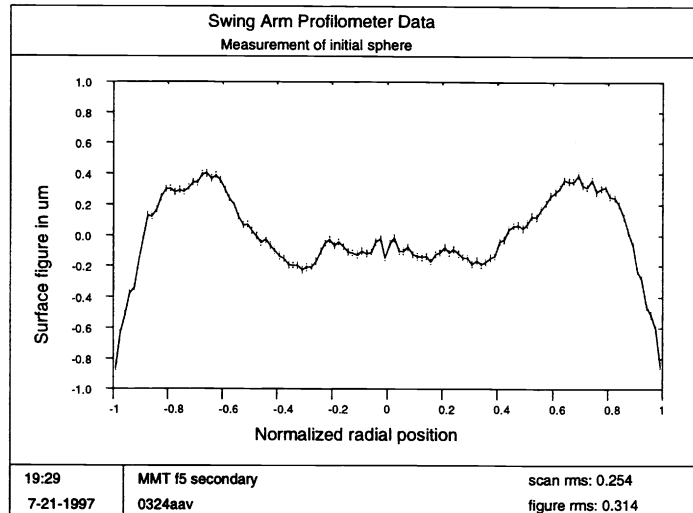


Figure 3. Measurement profile across a diameter of the 1.7-m diameter MMT *f/5* secondary mirror after spherical grinding. This shows figure errors of about 0.3 μm rms.

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4. OPTICAL PROCESS -- STEP 3, GRIND IN THE ASPHERE

The convex secondary mirrors require a large amount of positive spherical aberration, meaning that material must be removed from the 70% zone relative to the center and edge. This can be seen in Fig. 4, which shows the scan of the MMT *f/5* secondary after aspherizing. We have used both large, flexible laps and smaller computer controlled active laps successfully for aspherizing.

The rough-ground surfaces are measured using a swing-arm profilometer modeled after a machine built by Dave Anderson.⁷ The profilometer is mounted to the secondary polishing machine to allow rapid measurements for guiding aspherizing and rough figuring. Our instrument measures surface profiles with 50 nm rms accuracy so it also provides verification of the interferometric CGH test.

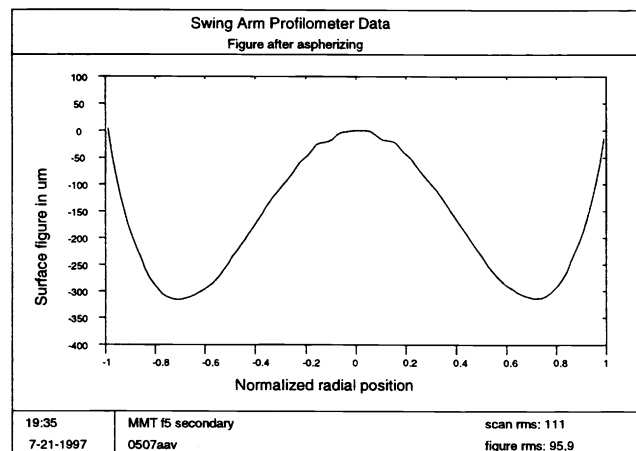


Figure 4. Measurement of the aspheric departure of the MMT *f/5*.

The swing-arm profilometer uses an LVDT indicator at the end of an arm to make mechanical measurements of the optical surface. The geometry for this test is shown in Figure 5. The probe is mounted at the end of an arm that swings across the test optic such that the axis of rotation goes through the center of curvature of the optic. The arc defined by the probe tip trajectory (for no change in probe reading) lies on a spherical surface defined by this center. This is the geometry used for generating spherical surfaces using cup wheels. For measuring the aspheric optics, the probe, which is aligned so its travel is in the direction normal to the optical surface, reads only the surface departure from spherical.

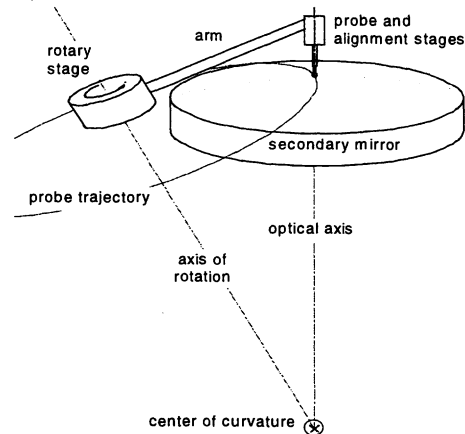


Figure 5. Geometry for the swing arm profilometer.

The SOML profilometer is mounted rigidly to the stressed-lap polishing machine to allow efficient measurements while the mirror is on the turntable. (See Figs. 6 and 7.) The arm itself is balanced so it does not exert any changing forces on the frame while it scans. The machine is supported on three air bags to isolate it from vibration and from deflections in the floor. The combination of electrical noise, random variations in the probe-glass interface, and mechanical instabilities gives measurement errors around 100 nm rms over the 10 minutes required for a full scan. After these random errors are averaged out, the fixed error in the bearing of around 40 nm rms remains.

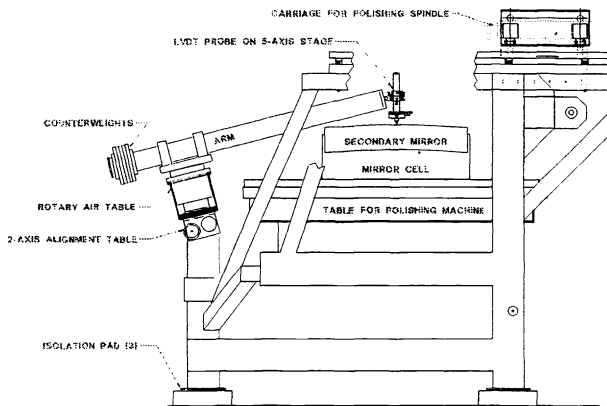


Figure 6. Layout of swing arm profilometer mounted to the stressed lap polishing machine.

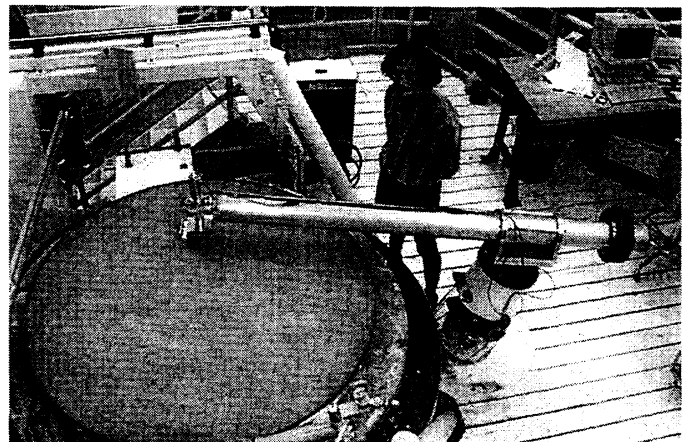


Figure 7. Photo of profilometer measuring the 1.7-m MMT $f/5$ secondary mirror.

The accuracy of the profilometer was assessed using two methods. When the Sloan mirror was nearly spherical, the same arc on the surface was scanned with the arm mounted at different orientations on the rotation stage. The difference between these scans shows the expected bearing errors of 40 nm rms. Also the profilometry of the nearly finished mirror shows agreement with the data from the holographic test plate of about 50 nm rms.

Since the profilometer always measures relative to a virtual reference sphere, it does not give the absolute radius of curvature of the part. We control the radius by measuring it carefully when the part is ground spherical using a sub-aperture concave test plate. We grind small dimples into the surface of the mirror, one at the center, and the other outside the clear aperture. The profilometer is used to measure the depths of these while the part is spherical. Then, during aspherizing, the dimple depths are measured routinely and a direct calculation gives the radius of curvature of the asphere given the initial radius of the sphere, the change in dimple depths due to material removal, and the aspheric departure of the mirror. We track the aspherizing progress by plotting the vertex radius of curvature R against the conic constant K , as shown in Fig. 8.

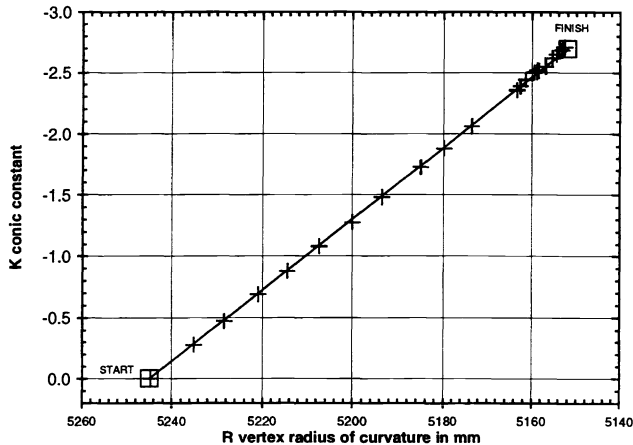


Figure 8. Path for aspherizing the 1.7-m $f/5$ MMT secondary mirror.

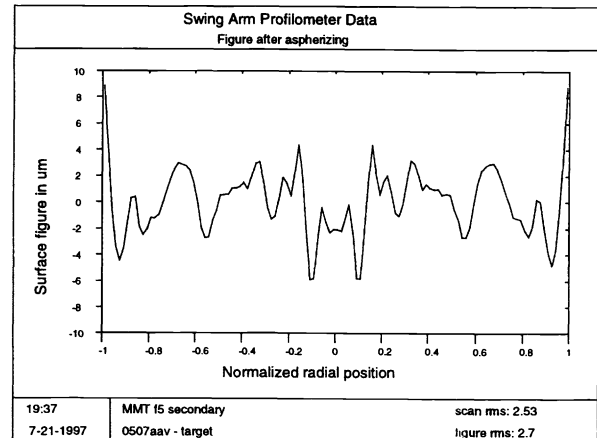


Figure 9. Profile of figure errors after aspherizing the MMT $f/5$ secondary mirror. This is computed by subtracting the ideal shape from the data shown in Fig. 4.

5. THE LAPS

The aspherizing has been performed with large flexible laps and with the computer controlled stressed lap. We rely on the stressed lap for polishing and finishing the mirrors. The Sloan secondary, the first to be finished in our lab was aspherized with the stressed lap.

The stressed lap is a relatively large and stiff tool that maintains fit to the aspheric surface through continuous active shape changes.⁸ The lap used for the Sloan secondary consists of a 750 mm aluminum plate 25 mm thick, with a 600 mm polishing surface, and 12 moment generating actuators around the edge of the plate to bend it elastically. Three more actuators apply lifting forces to control polishing pressure and pressure gradients. (The full weight corresponds to 0.7 psi, which is more than we would ever use.) The bending actuators are programmed to make the lap shape match a desired mirror surface at all times, while the lifting actuators can be programmed to vary the pressure according to the current figure error -- applying more pressure at the high points. Pressure gradients can be used to correct figure errors and also to balance moments that occur when the lap extends over the edge of the mirror, as it commonly does.

We performed loose-abrasive grinding with thin aluminum grinding pads on the pitch lap. Active bending of the lap creates the possibility of a substantial shape error in certain failure modes, and use of pitch instead of ceramic tiles makes the mirror much less vulnerable to damage.

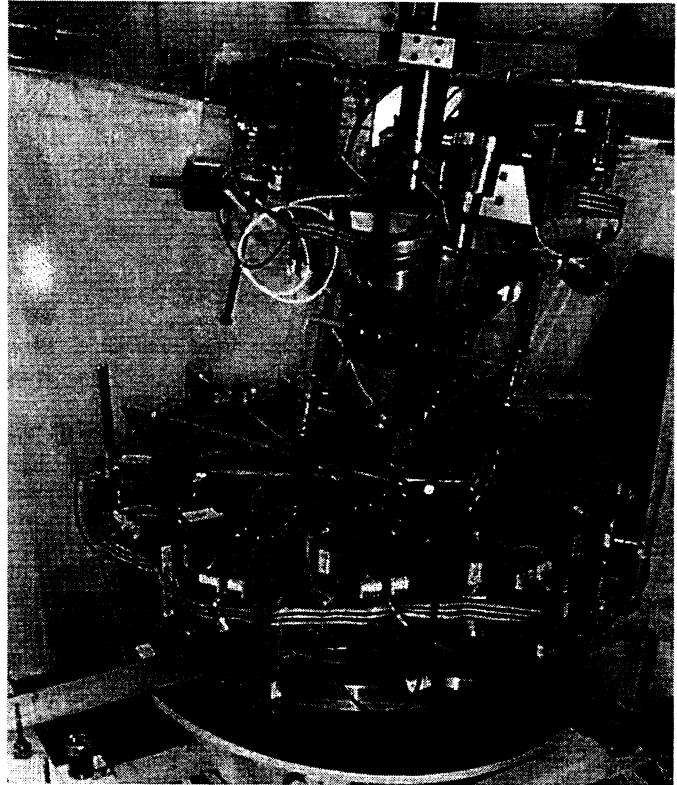


Figure 10. The 30-cm stressed lap. The lap is deformed under computer control so it always fits the aspheric shape of the mirror.

The MMT $f/9$ and the MMT $f/5$ were aspherized using large flexible laps. This proved to be effective and economical, as it uses the large tools that were built for spherical grinding. For aspherizing, the lap is covered with 0.25" thick closed cell neoprene. This makes the tool compliant enough to fit the aspheric mirror during a small stroke. Pitch is stuck to the neoprene and aluminum pads are placed on the pitch according to the aspherizing strategy. The large tool is placed on the mirror and locked in rotation while the mirror spins beneath it. The tool is stroked radially to avoid driving zones into the mirror and tool.

The tool for MMT $f/5$ aspherizing is shown in Fig. 11. The fill pattern (area fraction of the tool that has grinding pads) was initially set by a computer optimization. As the aspherizing progressed, the profilometer measured exactly how the tool was working and the pattern fill was tuned by adding or removing aluminum pads. The pitch fill remains the same and only the aluminum fill patterns change. Since the grinding pads are thin, (about 0.035" thick) new pads could be added and the lap would press out overnight.

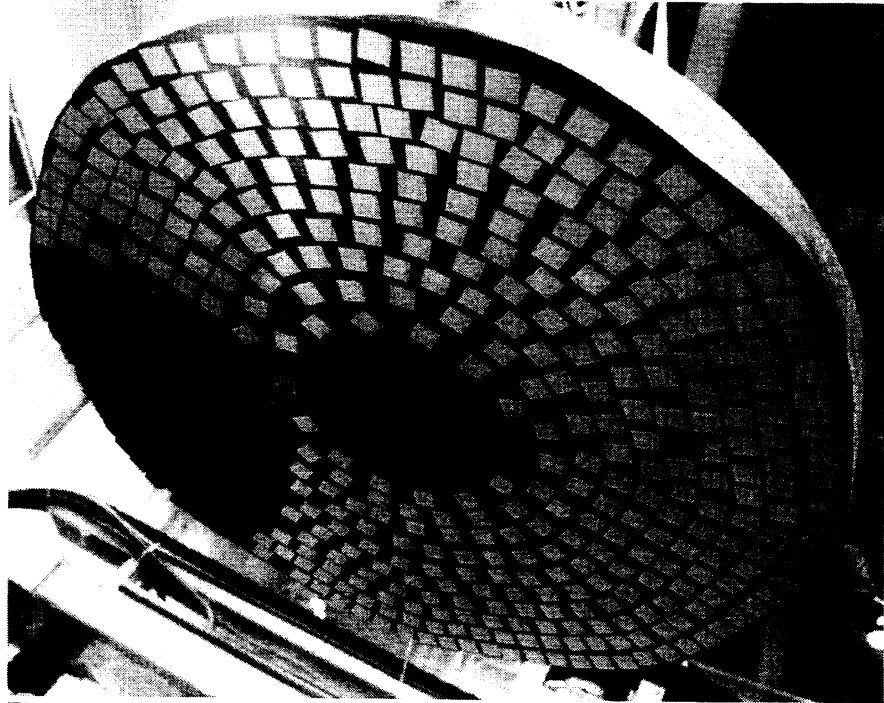


Figure 11. Photo of lap showing fill pattern for aspherizing the 1.7-m MMT $f/5$ secondary. The 1.36-m plaster tool was faced with neoprene and pitch. The pattern of aluminum grinding pads attached to the pitch was optimized for aspherizing.

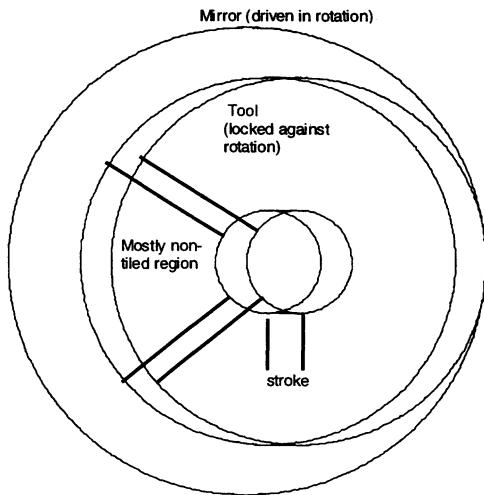


Figure 12. Diagram of the stroke the corresponds to the tool in Fig. 11 and the data in Fig. 13.

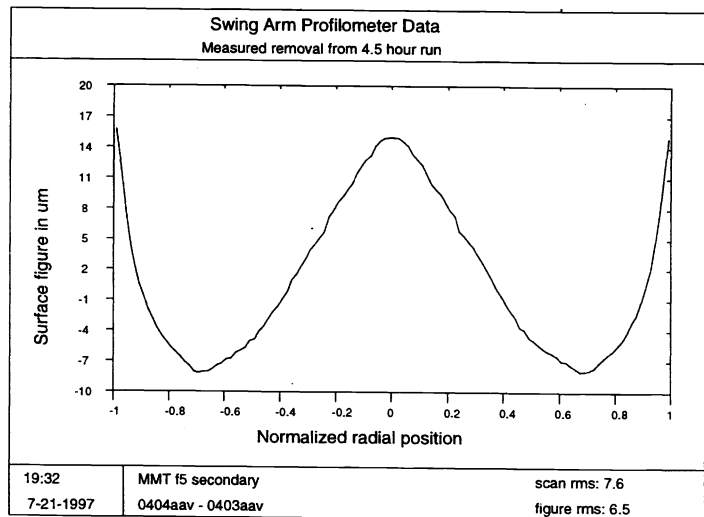


Figure 13. Measured removal from a 4.5-hour run using the lap and stroke shown above in Figs. 11 and 12.

Our convergence rate has rapidly increased with each secondary mirror, as shown in Fig. 14. The first took 12 weeks and 130 machine hours on the stressed lap to grind in 109 μm of asphere. The most recent used the flexible tool to grind in 320 μm in 6 weeks and 100 machine hours.

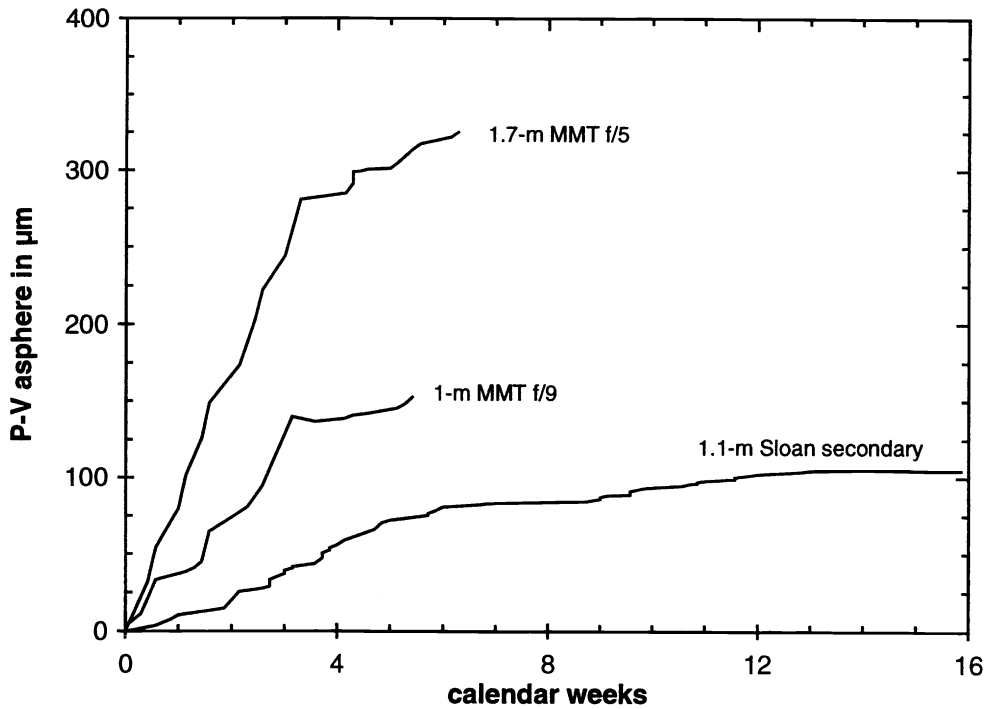


Figure 14. Rates for aspherizing secondary mirrors at Steward Mirror Lab.

6. OPTICAL TESTING

After the mirrors are aspherized, we wax them to get a specular reflection and measure the surfaces interferometrically using test plates with computer generated holograms.⁹ The test plates have concave spherical reference surfaces with computer generated holograms written onto them to compensate for the aspheric departure of the secondary mirrors. Fringes of interference are viewed through the test plates, which are supported several millimeters from the secondary mirrors. The hologram consists of annular rings written into a chrome coating, with spacing at intervals as small as 80 μm and as large as 500 μm . The accuracy of the surface measurement using this technique is 8 nm rms for mirrors with up to 331 μm departure from the best-fit sphere.

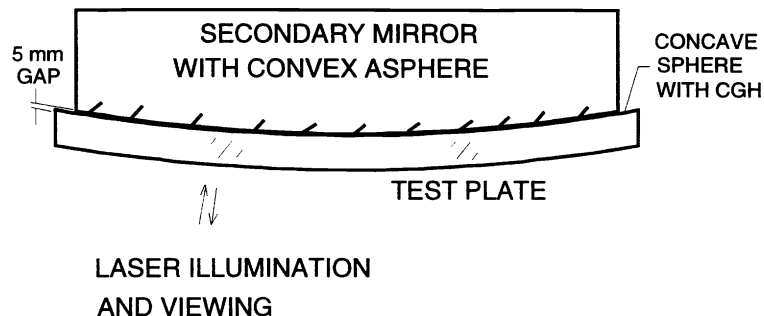


Figure 15. Layout of holographic test of a secondary mirror.

Additional optics are required to illuminate the test plate and to collect the light into a CCD array. Low-quality optics are used without degrading the test accuracy because the reference and test beams are coincident and equally affected by the illumination system. Only the difference between the two wavefronts is measured. This fact allows the test to be economical as the requirements on the optical system, including the test plate refractive index variations and the local seeing and vibration, are quite loose. Only the reference spherical surface of the test plate must be figured and measured accurately.

The ring positions are calculated to give the required shape of the diffracted wavefront. The duty cycle of the hologram, defined as the ratio of line width to center-to-center spacing, is chosen as 20% to match the intensities of the reference and test beams. The holograms are fabricated on a custom laser writing machine built at SOML. This machine can fabricate holograms up to 1.8 meters in diameter and has been used to write holograms as fast as $f/1$ and up to 1.2 meters across.

The CGH test is implemented in the SOML shop using a dedicated secondary test system (STS). This system uses a small test tower attached to our larger 24-m vibration isolated tower. The equipment, shown in Fig. 16, was built for measuring secondary mirrors up to 1.8 meters in diameter. The test tower has three levels: a platform with an interferometer that measures the test plates, a platform that supports the test plates and secondary mirrors, and a lower platform that holds the illumination primary, and the projection and imaging optical system.

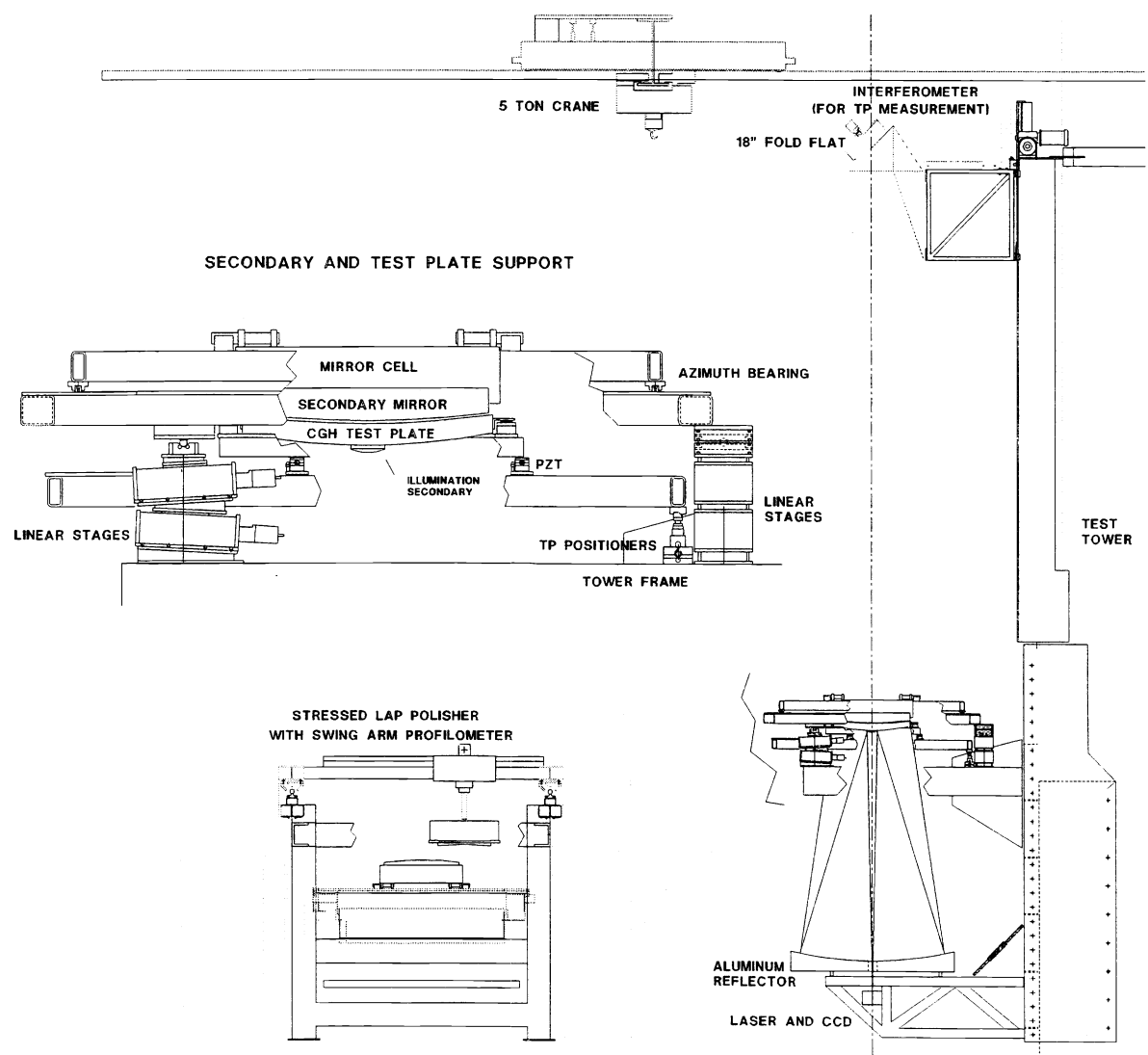


Figure 16. Layout of the secondary test system including details of optics support.


The secondary mirrors are supported with the optical surface down, in the orientation they will be used for zenith pointing in the telescope. The mirrors are transported from the polishing machine to the STS, and then flipped using a special mechanism and an overhead crane. The inverted cell rests at three points on a frame in the STS. This frame is mounted on an azimuth bearing to allow full rotation of the optic relative to the test, which allows us to isolate azimuthal errors in the mirror from those in the test. The bearing is mounted on a six-axis positioning system that provides the fine movement needed to null the interference fringes. In practice, the mirror is moved in 5 axes to remove tilt, focus, and coma from the interferogram. (The sixth degree of freedom gives a fine rotation about the optical axis.) The alignment system uses three sets of stages, each set consisting of two stacked linear stages with a small wedge between them. The two stages of each set give pure horizontal when run simultaneously in the same direction and pure vertical motion when driven in opposite directions. All six stages are synchronized under computer control to give the user independent control of x and y tilt, x and y coma, focus, and axial rotation. This system allows fine motion in all degrees of freedom for loads as large as a ton with no backdrive. It also gives the rigid support required by the interferometric tests.

The test plates were cast and slumped from E6 glass and were fabricated by an outside company. They are held in the STS by a distributed set of hydraulic actuators pushing on support brackets bonded to the edges of the glass. The actuators are held in a steel ring that is supported at three points on mechanisms with piezo transducers (PZT's). High resolution surface measurements are made using phase shifting interferometry by pushing the test plates while images of the fringe patterns are captured by a CCD camera and digitized. The PZT's can also be used for making fine tilt adjustments of the test plate.

The figures of the test plates are measured *in situ* using a phase shifting Shack cube interferometer supported in the tower above the optic. The test is remotely aligned by steering a 10 cm fold flat and by translating the interferometer on a linear stage. The overhead crane must go over the optical axis, so the optics for the test plate measurement were built with the ability to fold out of the way. We achieve this by using a 46 cm fold flat that is swung to the side to clear the crane. This entire system is attached to a platform that can be driven to the proper height for each test plate. The radius of curvature of the test plate is measured to ± 0.5 mm using a calibrated steel tape.

7. OPTICAL PROCESS -- STEP 4, FINAL FIGURING

The final figuring is performed using the stressed lap faced with pitch and using standard cerium oxide polishing compound. We make extensive use of software that predicts the performance of polishing strokes to achieve rapid convergence of the figure. The sequence of events during final figuring with the stressed lap is shown below

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- First thing in the morning, the figure errors are measured using the CGH test.
 - The secondary mirror is lifted off the test fixture, flipped over, and set down on the polishing machine.
 - The test plate figure may be measured and subtracted from the mirror figure.
 - The surface measurement is fed to a program called "SLAP" which is used to design, simulate, and optimize the polishing strokes. The optician adjusts the stroke parameters based on a combination of experience and the computer simulation.
 - The measurement is also fed to a computer that controls polishing pressure variations during the run. The azimuthal errors in the mirror are not treated by SLAP and must be controlled by dynamic pressure variations.
 - The lap is set down on the mirror and the stroke (or strokes) are run. Typical running time for a single stroke is one hour.
 - The mirror is cleaned off and prepared for testing.
 - The mirror is lifted to the test station, inverted and set down for the next morning's measurement.

We also use some local figuring with small tools, but most of the figuring is done with the stressed lap. This process worked extremely well on the Sloan secondary. It was brought to the final figure in just 40 hours of polishing. The requirements for this mirror were not too severe and we completed the part to 50 nm rms surface error. After subtracting 0.2 waves of astigmatism and 0.04 waves of spherical aberration, which do not affect the telescope, we compute a figure of 42 nm rms, shown below in Figs. 17 and 18.

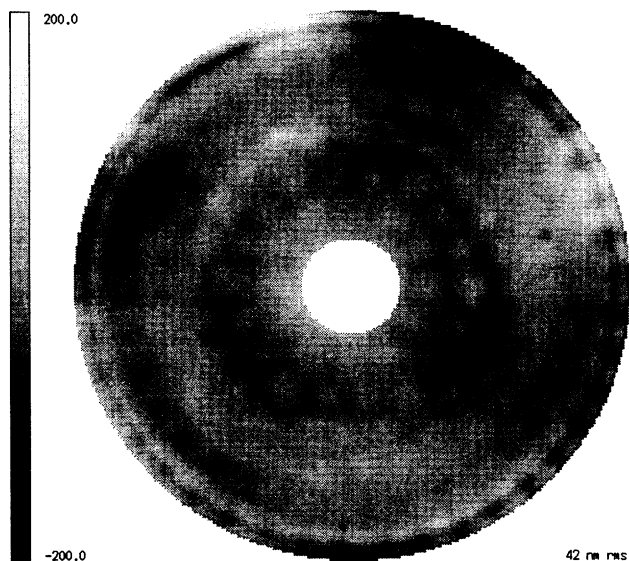


Figure 17. Gray scale map showing final measurement of the 1.15-m Sloan secondary mirror. The gray bar is labeled in nm surface error.



Figure 18. Interferogram at 633 nm calculated from the final data shown in Fig. 17.

8. CONCLUSION

At the time of this paper, the 60-cm stressed lap has been removed and a new 30-cm stressed lap has been installed. This newer version can bend further to meet the requirements for the current and future mirrors. We are also working on the optics for the CGH tests of the MMT secondary mirrors.

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