Fabrication of large convex mirrors

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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. Due to the large size and aspheric departure of these convex mirrors, traditional fabrication and testing techniques are impractical. We have developed tools and techniques and to manufacture large, steep convex aspheres and have built a dedicated facilty that integrates a 1.8-m stressed-lap polishing machine with interferometric and mechanical measuring systems. We have used this facility to process 4 secondary mirrors, up to 1.7 meters in diameter.

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

Introduction

The Steward Observatory Mirror Lab (SOML) is manufacturing secondary mirrors for large ground based telescopes, including the 6.5-m Multiple Mirror Telescope Conversion (MMT) and the 8.4-m Large Binocular Telescope (LBT). 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.[1]

Table 1. Secondary mirrors finished or planned for SOML.

Mirror	Diameter	P-V Asphericity
Sloan Secondary	1.15 m	109 μm
MMT *f*/9	1 m	168 μm
MMT *f*/5	1.7 m	330 μm
MMT *f*/15	0.65 m	82 μm
ARC *f*/8	0.84 m	66 μm
LBT *f*/15	0.88m	123 μm
LBT *f*/4	1.2 m	340 μm

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 polishing[2], accurate mechanical measurements with a swing arm profilometer[3], and interferometric measurements of steep convex aspheres using holographic test plates.[4] 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.[5]

Process step	Tools	Metrology	Accuracy
Fabrication of mirror blank	Diamond generate	Direct measurement	0.5 mm
Grind to best fit sphere	Rigid lap faced with tile	Spherometer, test plate	2.0 μm
Aspherize	Compliant or stressed lap	Profilometry	0.1 μm
Polish to completion	Stressed lap with pitch	Interferometry	0.01 μm

We have successfully used this fabrication method for completing 3 secondary mirrors, including the 1-m MMT f/9 secondary, which was finished to 14 nm rms surface error.

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 lightweighted to improve performance in the telescope. Our process would also be well-suited for mirrors made of other more exotic materials.

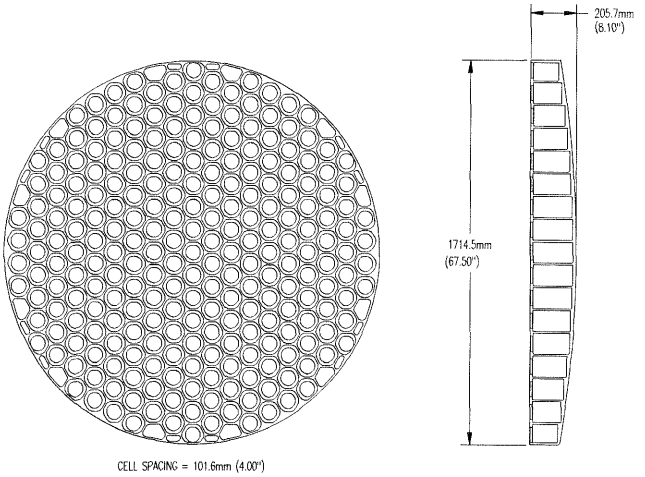

Figure 1. 1.7-m Zerodur blank for the MMT $f/5$ secondary mirror.
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The Sloan, MMT $f/9$, and ARC secondary mirrors are made from borosilicate glass using the gas-fusion technique by Hextek. The face plate and back plates are about 12mm thick and the 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 64 cm MMT $f/15$ mirror is made as a 1.8-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, however, does not need to match the telescope support precisely, but it does need to provide rigid body constraint of the mirror in such a way that it does not distort under the polishing loads.

The secondary mirrors are generally polished face-up and used face-down. Our support cells accommodate both by using two sets of actuators. During polishing, the mirror is supported face-up by a large number of hydraulic actuors. The mirror is then inverted for testing so it hangs from a set of actuators the simulate the telescope support.

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.

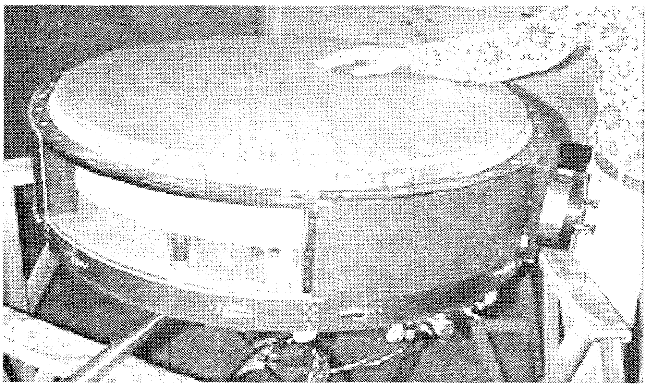

Figure 2. 1-m MMT $f/9$ secondary mirror in its polishing/testing cell.
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Grind to best fit sphere

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. Hextek castings 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. This tool was used to bring the mirror to a 0.31 μm rms sphere, 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.

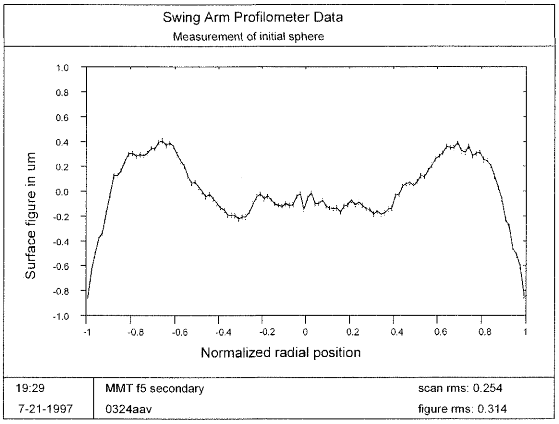

Figure 3. Measurement profile across a diameter of the 1.7-m diameter MMT *f*/5 secondary mirror after spherical grinding.
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Aspheric grinding

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, as shown in Fig. 4. The mirrors are aspherized by loose abrasive grinding with large tools. We track the progress of the aspherizing using an R- K plot, shown in Fig. 5.

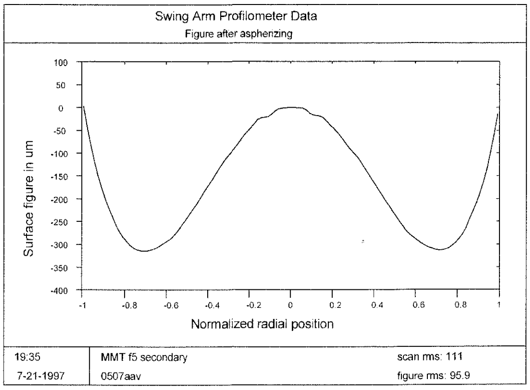

Figure 4. Measurement of the aspheric departure of the MMT *f*/5.
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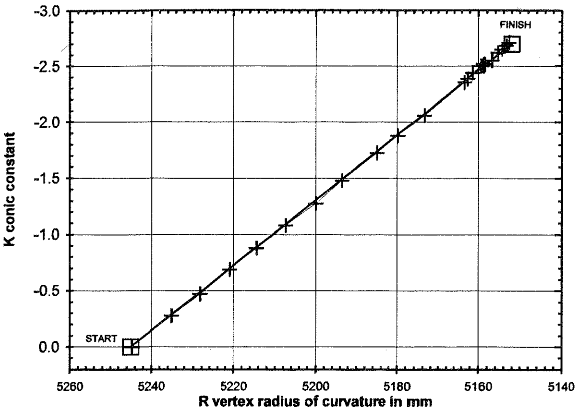

Figure 5. Path for aspherizing the 1.7-m *f*/5 MMT secondary mirror.
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The 1-m MMT *f*/9, 1.7-m MMT *f*/5, and the 0.8-m ARC secondaries were aspherized using large flexible laps. This proved to be effective and economical, as it uses the large tools 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.

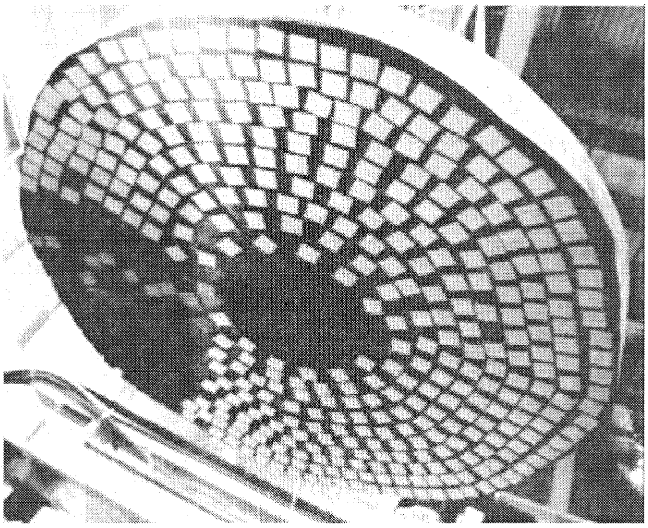

Figure 6. Photo of lap showing fill pattern for aspherizing the 1.7-m MMT *f*/5 secondary. The 1.36-m plaster tool was faced with neoprene and pitch. The pattern of aluminum grinding pads attached to the pitch was optimized for aspherizing.
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The tool for MMT *f*/5 aspherizing is shown in Fig. 6. 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.

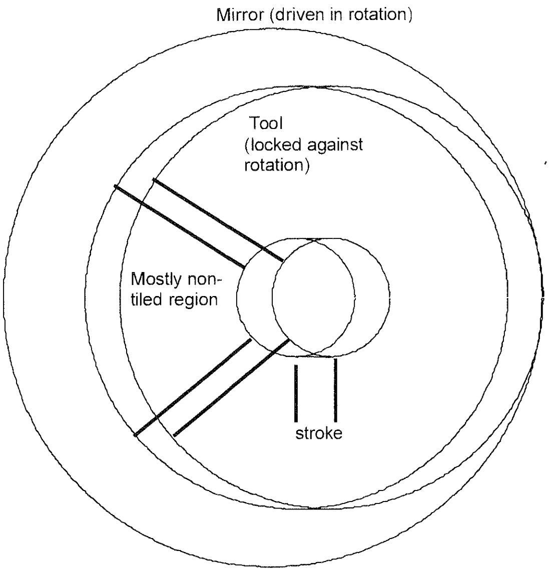

Figure 7. Diagram of the stroke for aspherizing the MMT *f*/5 secondary mirror. This corresponds to the tool in Fig. 6 and the data in Fig. 8.
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Aspherizing with this large tool has proven to be extremely efficient. Fig. 8 shows the effect from a single run with the tool shown above. Fig. 9 shows the rate of aspherization for 4 large mirrors made at the Mirror Lab.

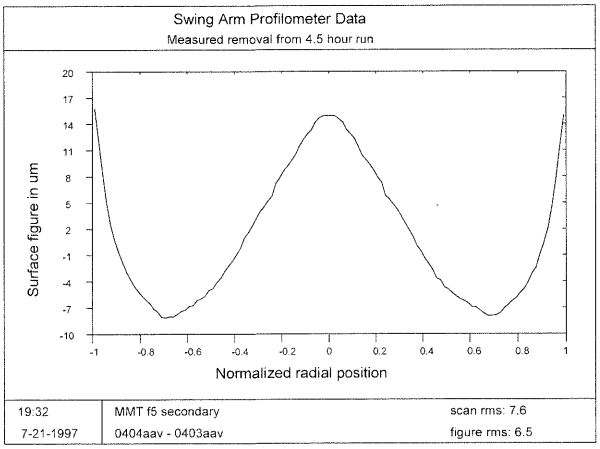

Figure 8. Measured removal from a 4.5-hour run on the MMT *f*/5 secondary using the lap and stroke shown above in Figs. 6 and 7.
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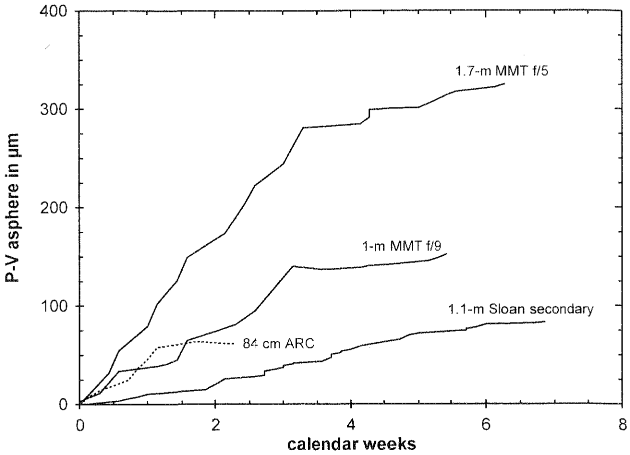

Figure 9. Rates for aspherizing secondary mirrors.

Swing arm profilometer

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.

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 10. 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.

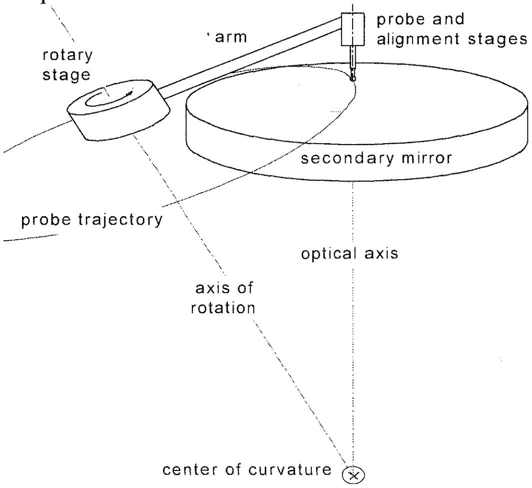

Figure 10. Geometry for the swing arm profilometer.
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The SOML profilometer is mounted rigidly to the stressed-lap polishing machine to allow efficient measurements while the mirror is on the turntable. The arm itself is balanced so it does not exert 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.

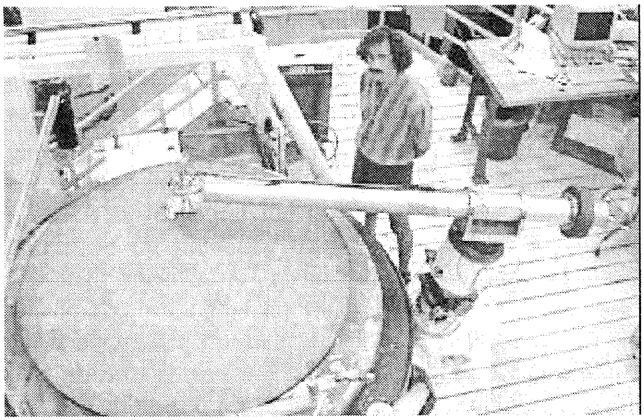

Figure 11. Swing arm profilometer, measuring the 1.7-m MMT *f*/5 secondary mirror.

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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.

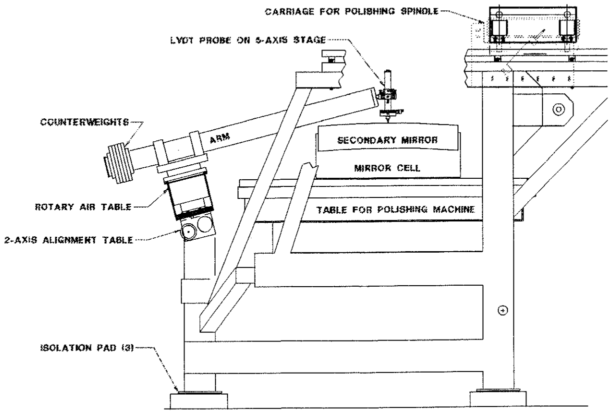

Figure 12. Layout of swing arm profilometer mounted to the stressed lap polishing machine.

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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.

Final figuring

The optical surface is polished to completion using a computer-controlled stressed-lap polisher.[8] The surface measurements are made using interferometry with CGH test plates[9].

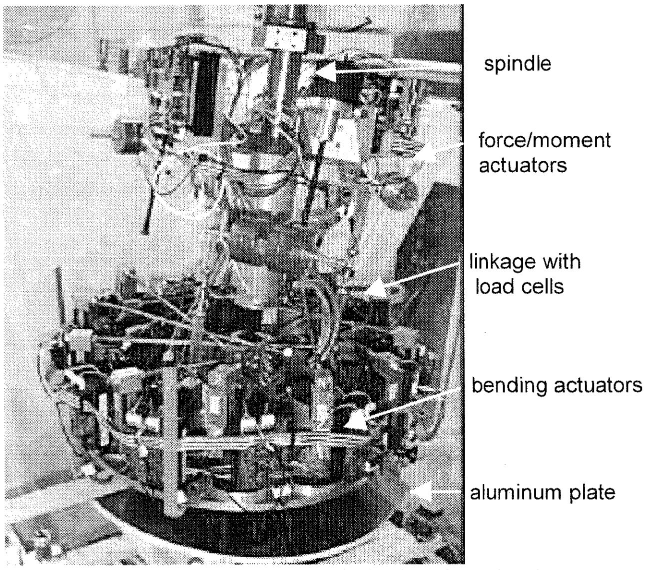

Figure 13. The 30-cm stressed lap. The lap is deformed under computer control so it always fits the aspheric shape of the mirror.

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Stressed lap

The stressed lap is a relatively large and stiff tool that is actively deformed to fit to the aspheric surface. The 30-cm stressed lap shown above consists of a 60 cm diameter aluminum plate, 19 mm thick, giving a 30 cm 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 a commonly does.

We perform 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.

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. 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 is 8 nm rms for mirrors for the most severe secondary.

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 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.

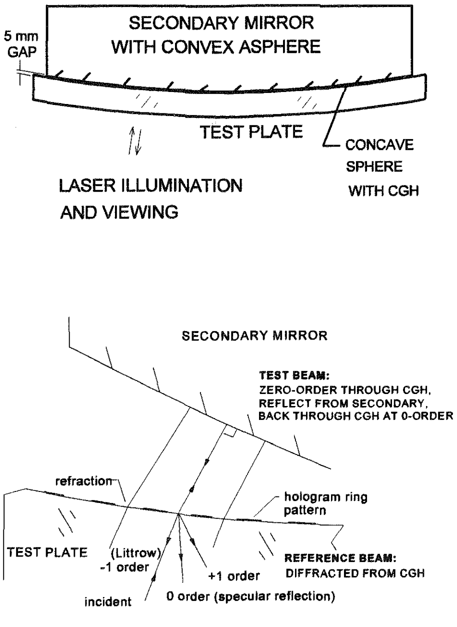

Figure 14. Layout of holographic test of a secondary mirror, showing definition of the test and reference wavefronts.

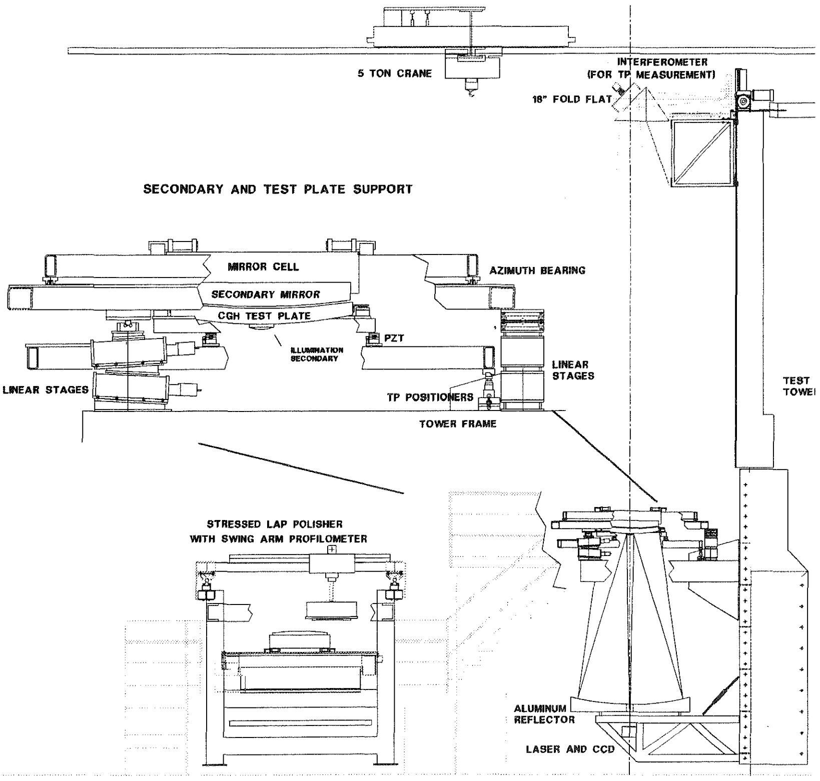

Figure 15. Layout of the secondary test system including details of optics support.
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The secondary mirrors are supported with the optical surface down, in the orientation they will be used for zenith pointing in the telescope. The mirrors are transported 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 test plates 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 PZT piezo transducers. 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 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. 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.

The final figuring is performed using the stressed lap polishing tool 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.[10] The sequence of events during final figuring with the stressed lap is shown below

- 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 to design, simulate, and optimize the polishing strokes.
- The measurement is also fed to a computer that controls polishing pressure variations during the run.
- The lap is set down on the mirror and the stroke (or strokes) are run. Polishing strokes run typically several hours.
- After polishing, the mirror is cleaned and prepared for testing.
- The mirror is lifted to the test station, inverted and set down for the next measurement.

We also use some local figuring with small tools, but most of the figuring is done with the stressed lap. We show data from the MMT f/9 secondary mirror. This 1-m mirror, with 170 μm aspheric departure from best fit sphere, was finished at the Mirror Lab to 14 nm rms.

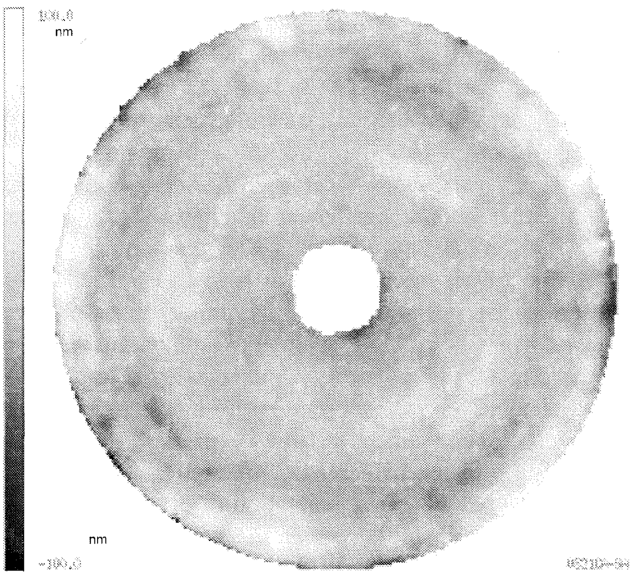

Figure 16. Gray scale map showing final measurement of the 1-m MMT *f*/9 secondary mirror showing surface departure from ideal of 14 nm rms.

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