Toward first light for the 6.5-m MMT telescope

S. C. West (UA), S. Callahan (MMTO), F. H. Chaffee (MMTO), W. Davison (UA), S. DeRigne (UA), D. Fabricant (SAO), C. B. Foltz (MMTO), J. M. Hill (UA), R. H. Nagel (UA), A. Poyner (MMTO), and J. T. Williams (MMTO)

1.0 Abstract

Operated by the Multiple Mirror Telescope Observatory (MMTO), the Multiple Mirror Telescope (MMT) is funded jointly by the Smithsonian Institution (SAO) and the University of Arizona (UA). The two organizations equally share observing time on the telescope. The MMT was dedicated in May 1979, and is located on the summit of Mt. Hopkins (at an altitude of 2.6-km), 64-km south of Tucson, Arizona, at the Smithsonian Institution's Fred Lawrence Whipple Observatory (FLWO).

As a result of advances in the technology at the Steward Observatory Mirror Laboratory for the casting of large and fast borosilicate honeycomb astronomical primary mirrors, in 1987 it was decided to convert the MMT from its six 1.8-m mirror array (effective aperture of 4.5-m) to a single 6.5-m diameter primary mirror telescope. This conversion will more than double the light gathering capacity, and will by design, increase the angular field of view by a factor of 15. Figure 1 depicts the conversion process. Because the site is already developed and the existing building and mount will be used with some modification, the conversion will be accomplished for only about $20M.

During 1995, several major technical milestones were reached: 1) the existing building was modified, 2) the major steel telescope structures were fabricated, and 3) the mirror blank was diamond wheel ground (generated). All major mechanical hardware required to affect the conversion is now nearly in hand. Once the primary mirror is polished and lab-tested on its support system, the six-mirror MMT will be taken out of service and the conversion process begun. We anticipate that a 6-12 month period will be required to rebuild the telescope, install its optics and achieve f/9 first light, now projected to occur in early 1998. The f/5.4 and f/15 implementations will then follow. We provide a qualitative and brief update of project progress.

KEYWORDS: Telescopes, honeycomb mirrors, wide-field imaging, control systems, mirror supports.

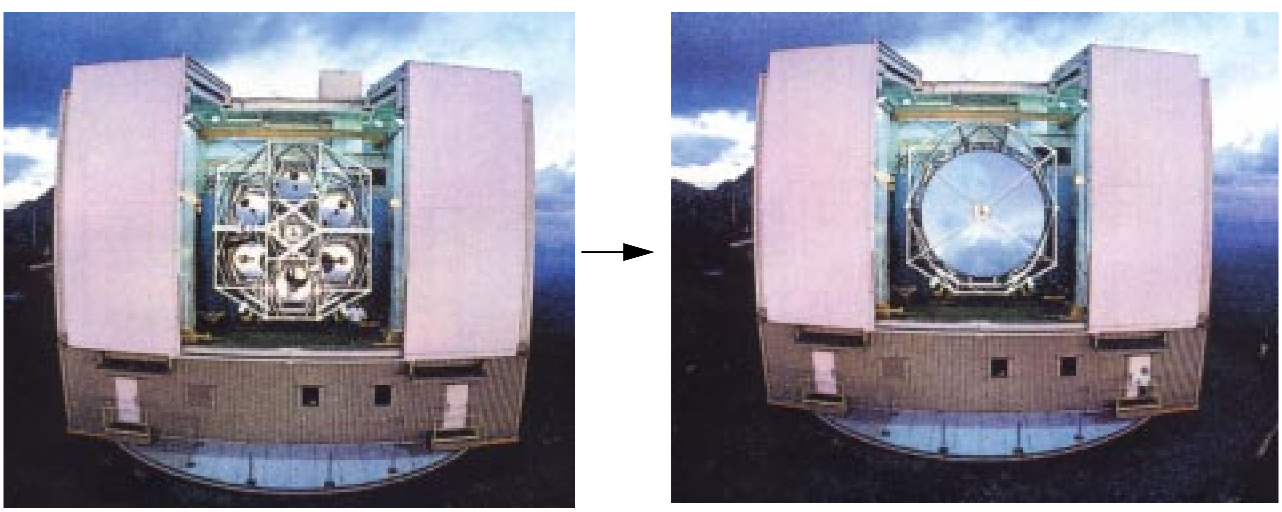


FIGURE 1. Artist's concept of the conversion of the Multiple Mirror Telescope into one incorporating a single 6.5-m primary mirror. (Courtesy of Serge Brunier/Ciel et Espace)

2.0 Optics

The 6.5-m f/1.25 diameter honeycomb borosilicate primary mirror was spun-cast, generated, and is currently being polished at the Steward Observatory Mirror Laboratory.[1-2] As shown in Figure 2, the MMT 6.5-m will support 5 Casseg-

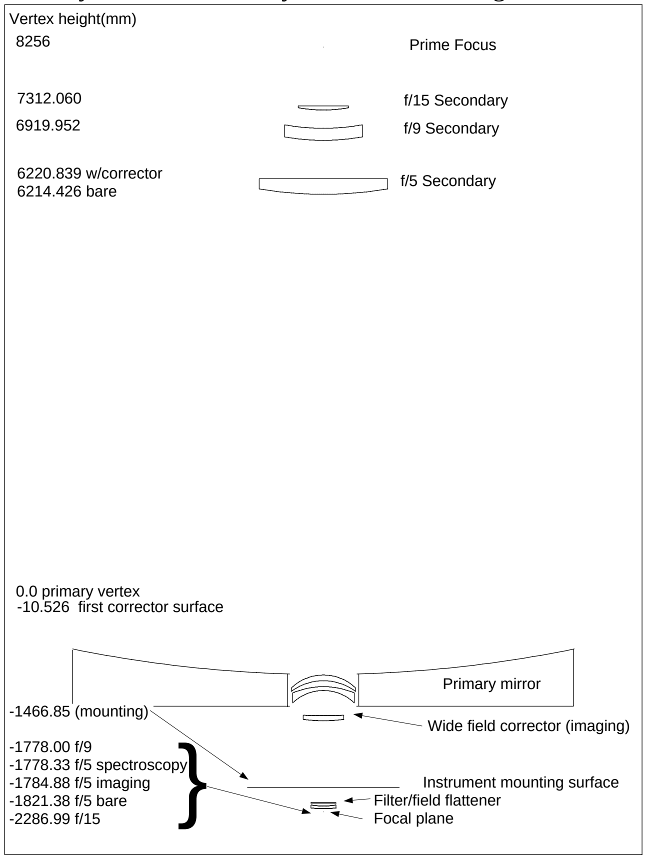
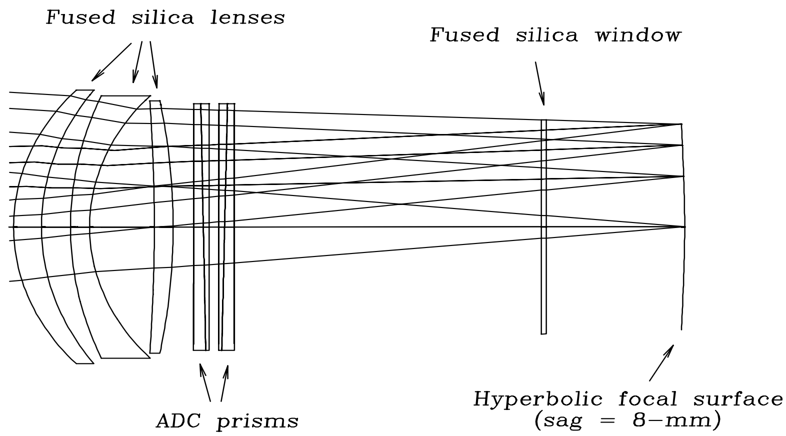


FIGURE 2. Cassegrain optical configurations for the 6.5-m MMT .

rain optical configurations: 1) f/9 with a 13-arcminute diameter FOV -- to make use of existing instrumentation, 2) f/5.25 with a 5-arcminute FOV, 3) f/5.4 with a corrected 1-degree FOV, 4) fixed/chopping f/15 with a 20-arcminute FOV, and 5) a fully adaptive f/15. More information on the optical specifications, design and manufacture of these secondaries is found in these and other proceedings.[3-7]

The large field of view of the converted MMT at the f/5.4 focus is made possible by a large refractive corrector designed by Harland Epps. All optical surfaces in the corrector are either spherical or flat, and all elements with optical power are fused silica. The corrector has two optical configurations, one intended for spectroscopy and the other intended for imaging with large CCD arrays. The spectroscopic configuration incorporates atmospheric dispersion compensation (ADC) prisms, and allows a $1°$ diameter field. The counter-rotating ADC prisms correct for atmospheric dispersion between 1 and 2 airmasses. The spectroscopic focal surface is hyperbolic (sag 8-mm), yet highly telecentric to allow efficient spectroscopy with optical fibers. The imaging configuration is formed by replacing the ADC prisms and the rearmost fused silica lens of the spectroscopic configuration with another fused silica lens (see Figure 3). The imaging focal surface is flat. The (0.33--1.0 μm) polychromatic RMS image diameters are less than 0.50-arcseconds with the spectroscopic configuration and less than 0.15-arcseconds with the imaging configuration.

Instruments are under construction at SAO to make use of the wide fields for spectroscopy and imaging. The Hectospec is an optical fiber-fed spectrograph with 300 optical fibers that are reconfigured with tandem high-speed robots.[8] The Megacam is a large imager that will use 32 2048 x 4096 pixel CCD's to cover a 22 x 22 arcminute^2 field.[9] Other instru-



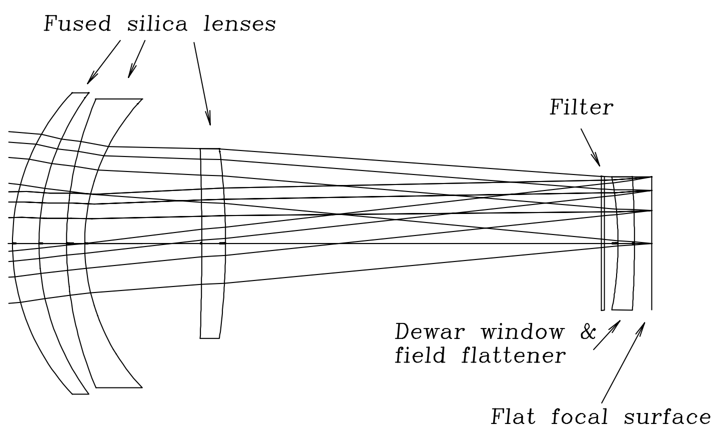


FIGURE 3. The two f/5.4 wide field imaging modes of the 6.5-m MMT. The top view is for wide-field spectroscopy and the bottom for imaging.

ments to operate at the f/5 focus include: a high resolution version of the Hectospec, the Binospec (a large areal spectrograph addressing dual 6' x 17' fields of view), and a triple-beamed (J, H, and K) infrared imager.

3.0 Major steel structures

3.1 Optical support structure and vacuum chamber

The firm of Simpson Gumpertz & Heger (SGH) designed the major steel components for this project. TIW Fabrication and Machining, Inc. of Albuquerque NM built the cell, OSS (Figure 4), and primary mirror vacuum chamber (Figure 4) and delivered them to Tucson on November 1, 1995. The cell was moved into the Steward Mirror Lab nadir-pointing to facilitate metrology and installation of the actuator support brackets. After installation, the cell was turned zenith-pointing for the installation of the static supports and ventilation nozzles (Figure 5).

3.2 Building modifications

In order to accommodate the increased swing radius of the new OSS, the existing building lateral and vertical clearance each needed to be increased by about 2-m (Figure 6). TIW implemented the SGH-designed modifications. Following

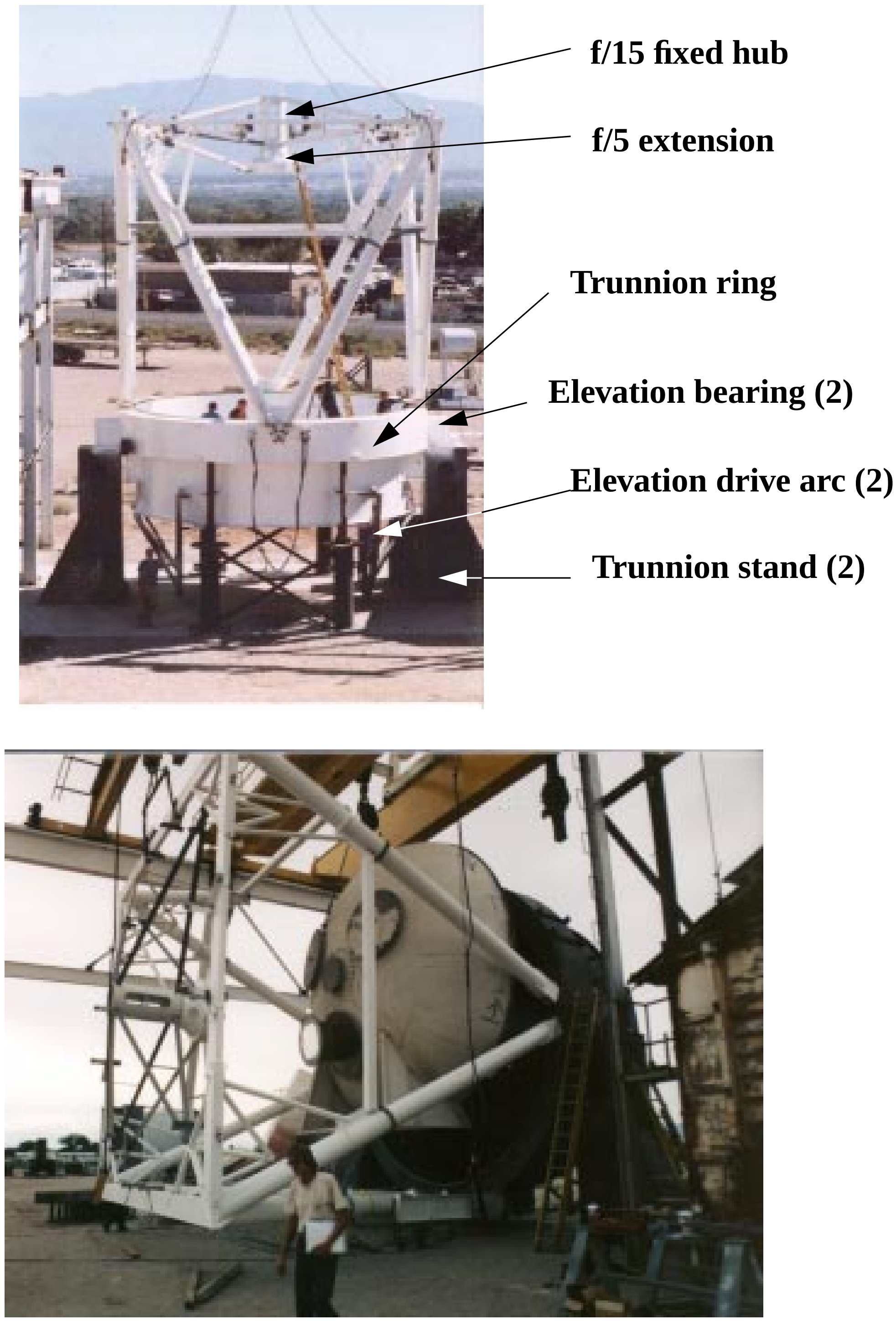


FIGURE 4. The completed cell, OSS, and primary mirror vacuum chamber. The f/15 hub remains attached for all Cassegrain modes. The removable f/5 extension is supported with an extra set of compression beams which increase stiffness and support the cantilever. The elevation bearings are an integral part of the trunnion ring. There are two elevation arcs with friction-wheel drives. The lower figure shows the vacuum chamber being fitted to the cell with the telescope horizon pointing. Aluminization will occur *in-situ* so that the primary mirror need never be removed from the telescope. Photos by S. Criswell.

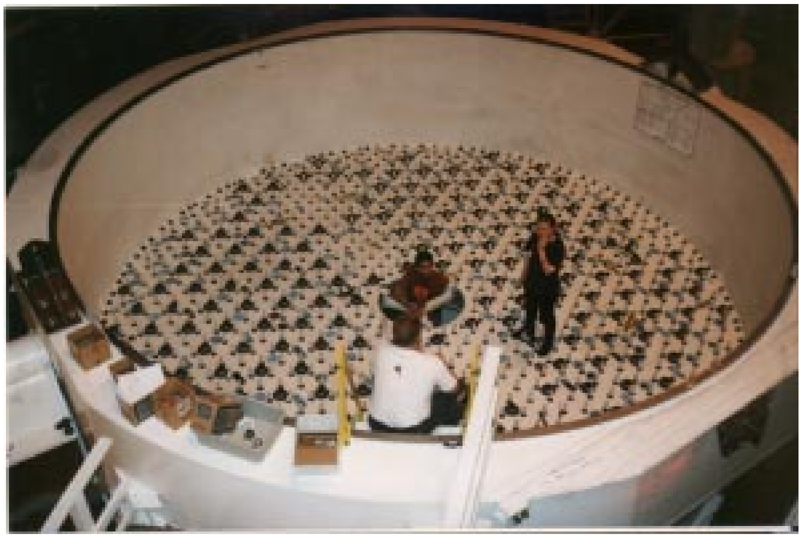


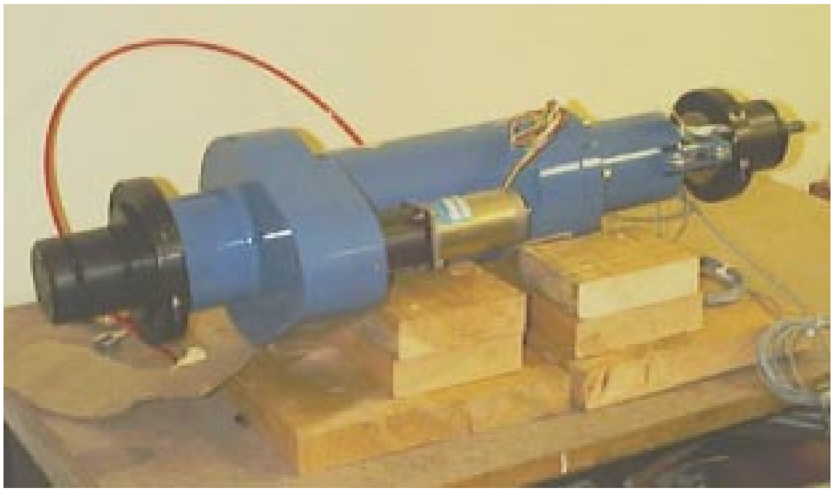
FIGURE 5. The zenith-pointing 6.5-m mirror cell in the Steward mirror lab. Seen are most of the 200 static supports (they define the set of axial and lateral resting forces for the mirror when the active support system is turned off) and the 1100+ ventilation air nozzles which squirt air into the interiors of the mirror honeycombs and around the mirror periphery. The vacuum seal flange is visible near the ID of the top of the trunnion ring.

FIGURE 6. An aerial view of the MMT building modifications. The shutters are lying on the ground, and the slit is being enlarged. The telescope is cocooned with plastic tarp and a wooden top in order to protect it from the modifications and the monsoons. Also seen is the storage location for the primary mirror aluminizing chamber on the roof of the adjacent building. The modifications were completed in October 1995.

the lead of the NTT, we also decided to have a 6-m high door put into the rear observing chamber wall in order to improve air circulation and reduce the effects of local seeing. Although the amount of modification was significant, it was far less expensive than simply replacing the entire rotating building which incorporates machine and electrical shops, an elevator, and many other facilities.

4.0 Primary mirror supports and thermal control

The primary mirror is positioned in its cell with a Stewart platform type parallel manipulator consisting of six adjustable very stiff struts (hardpoints) that connect the back plate of the cell to the back plate of the mirror. The hardpoints were designed and built by Studio Technico Tomelleri (Verona, Italy), and were tested at Arcetri Observatory by Luciano Miglietta.[10] One of the struts as well as the geometrical configuration of the Stewart platform is shown in Figure 7.



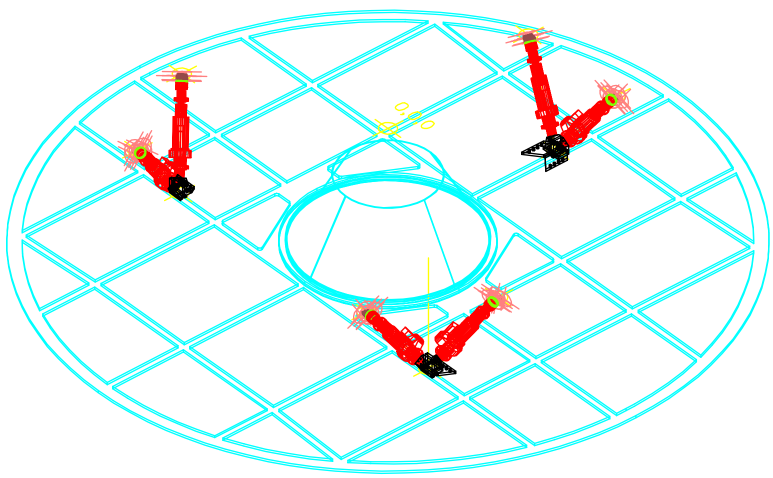
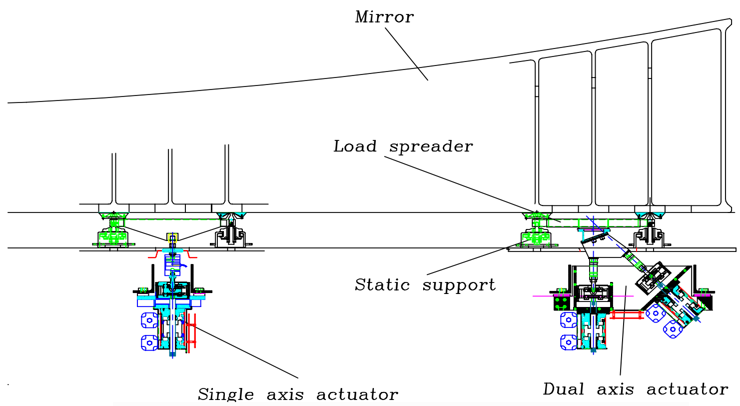
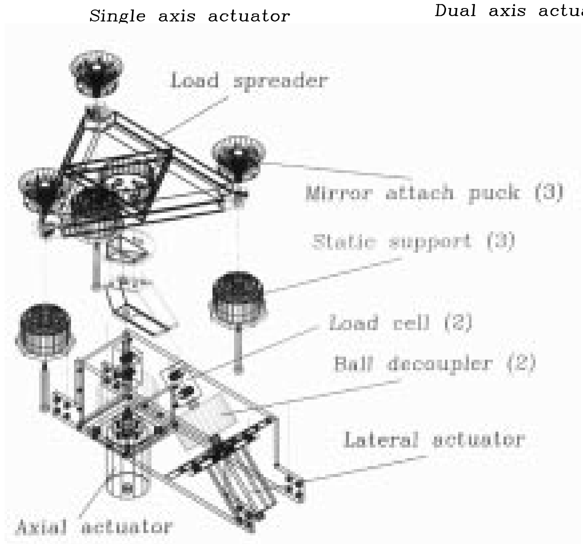


FIGURE 7. One of the six MMT hardpoints (top). They incorporate vane flexures at each end, an in-line load cell for force feedback of the servo system, tension and compression pneumatic high-force breakaways for protection of the mirror, 15-mm of stroke with a resolution of about 1-μm, internal length encoders, and they maintain a stiffness of over 90-$N/\mu m$. The lower figure shows the geometrical arrangement of the primary mirror Stewart platform. The hardpoints are connected at three locations to the cell back plate and extend upward to six locations on the mirror back plate (mirror not shown). Drawing by Eric Anderson.

Although the hardpoints define the precise positioning of the primary mirror and provide the stiffness of the support system, they operate near zero force. The weight of the mirror is supported with 104 pneumatic actuators whose individual forces are derived from a transformation required to null the six hardpoint forces against gravity and wind load.[11] Details of the pneumatic actuators are shown in Figure 8. The response of this support system to wind has been estimated and found to perform well even when pointing directly into a 7-m/s wind.[12]





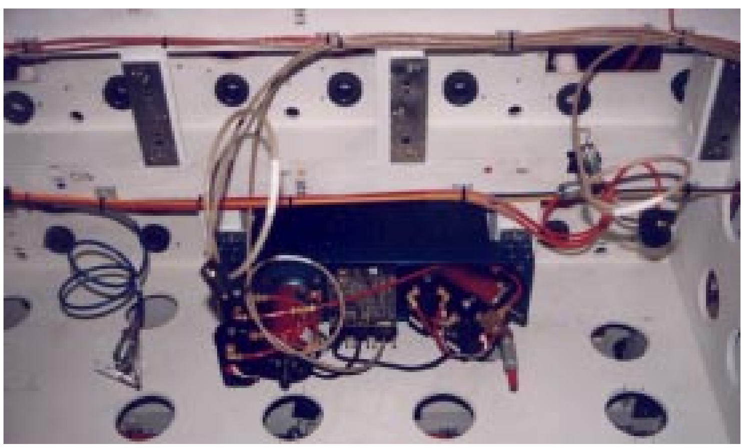


FIGURE 8. Several views of the pneumatic primary mirror support system. The top shows a side view of typical single and dual axis actuators. There are 50 dual-, 50 single-axis, and 4 cross-lateral actuators. The center view details how the actuators are connected to the mirror backplate through a triangular load spreader. It also shows the in-line load cells for servo control of the forces, and the lateral ball decouplers which insure that the actuators don't bind when the mirror changes position. The bottom picture shows one of the dual axis actuators attached under the cell top plate. Attachments for adjacent actuators can also be seen. (Drawings by Marion McEuen)

Careful attention has been paid to the thermal control of the primary mirror. Past research has shown that a scheme of forced-air ventilation into the interiors of the honeycomb structures works well to maintain a very high quality optical surface.[13,14] In order to avoid figure distortion, the blank must be kept isothermal to within $0.1°C$, and in order to minimize local seeing effects, it must be kept to within $\pm 0.15°C$ of the ambient temperature. Temperature slew rates of $2°C/\mathrm{hr}$ must be attained and the thermal time constant of the mirror can be no more than 45-min. Figure distortion is controlled by allowing no more than 40-Pa pressure gradient across the mirror diameter. Lateral vibrations produce wavefront tilt, and therefore the thermal system cannot induce more than 75-nm of lateral vibration which is 10% of the diffraction limit at a wavelength of $0.5\text{-}\mu m$.

The MMT will use an array of non-supersonic jet ejectors to achieve this performance.[15,16] Approximately 150 jet ejectors similar to those shown in Figure 9 are attached to holes in the upper plate of the cell. Pressurized and thermally

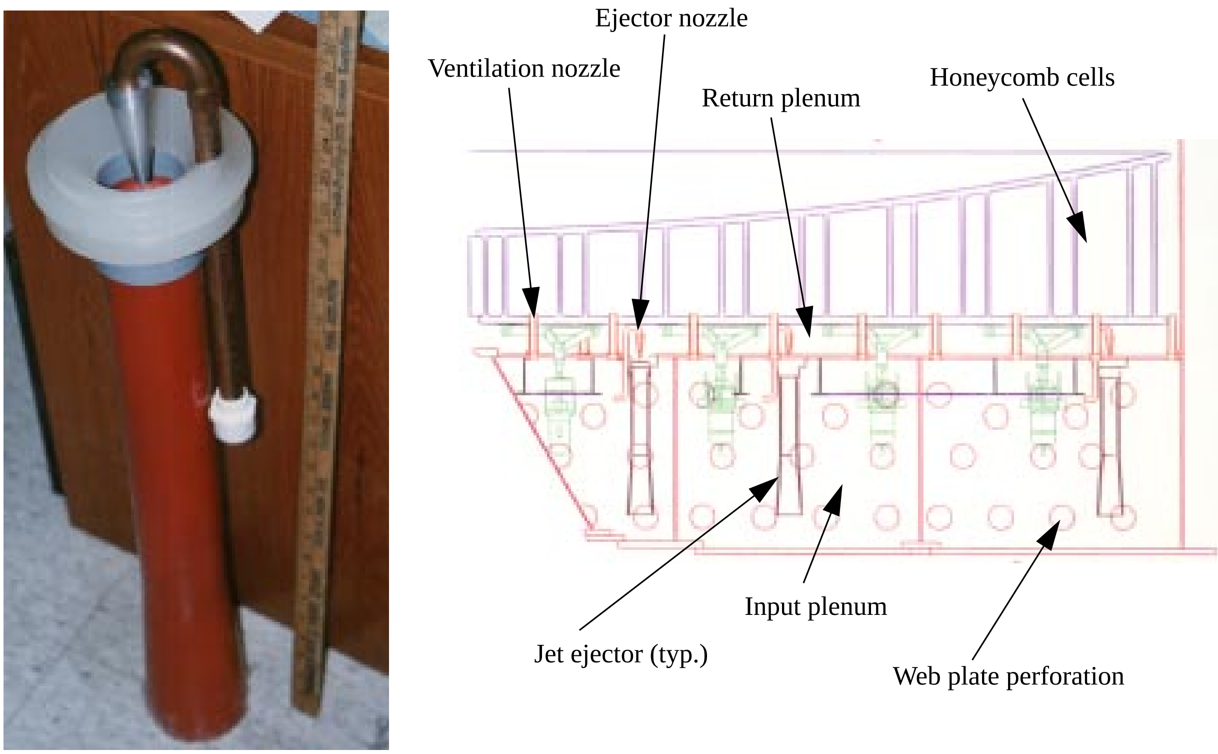


FIGURE 9. A prototype jet ejector for thermal control of the primary mirror (left). At right is a schematic of the thermal system contained in the primary mirror cell.

managed air is blown through the ejector nozzle which then draws air out of the mirror return plenum between the cell top plate and the mirror back plate (and hence out of the honeycomb cells). The two air streams mix in the long chamber and exit and pressurize the input plenum in the lower part of the mirror cell thus forcing air through the ventilation nozzles and back into the honeycomb cells. Ten-percent of total air volume circulated is pushed through the nozzles and must be “vented” out of the cell continuously. Another set of 15 jet ejectors exhausts this air into the telescope chamber and onto the telescope trunnion ring. The jet ejectors generate about 80-Pa of pressure difference across the nozzles and so supply about 8-l/s of air volume to each honeycomb cell. Air is supplied to the nozzles by an off-board chiller/blower unit.

5.0 Mount control system

The azimuth, elevation and instrument rotator axes of the telescope will be controlled by the MMT mount servo control system. Control of each axis is shown in the simplified schematic “Servo Loop Diagram” (Figure 10) . The outer posi-

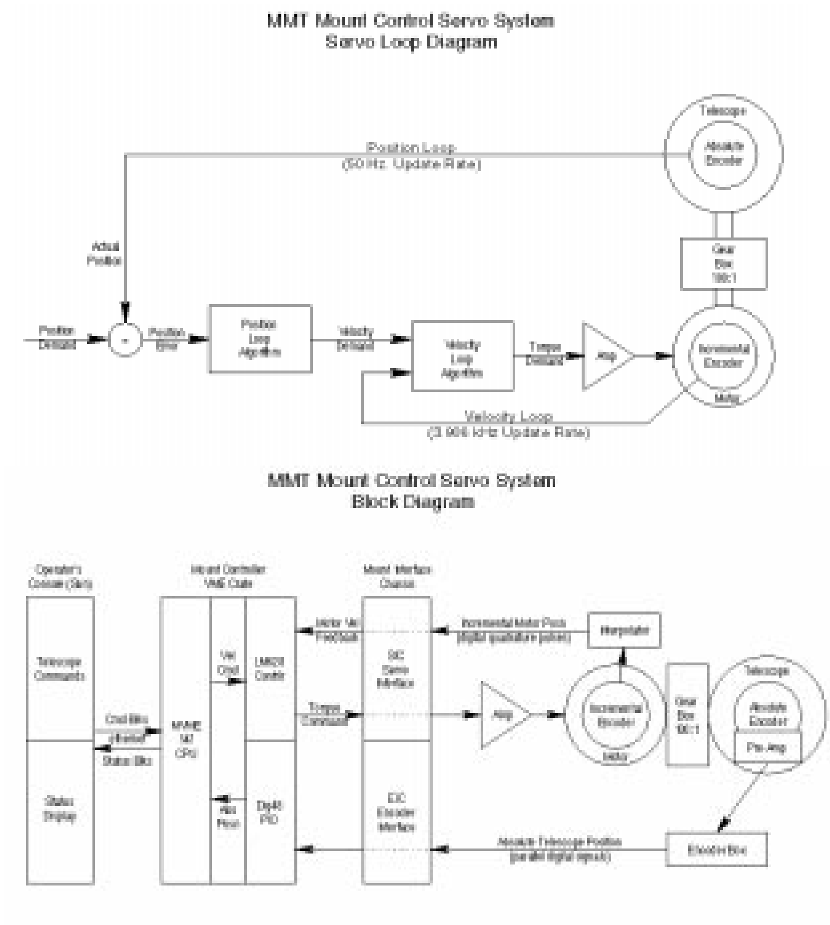


FIGURE 10. Schematics of the MMT servo control system. See text for details.

tion loop consists of an input position demand and a position feedback from an on-axis Inductosyn absolute encoder. The resultant position error signal is processed by the position loop algorithm to generate a velocity demand properly clipped so that maximum velocity, acceleration, and jerk are not exceeded. The command is then passed to the velocity loop. The position loop algorithm is implemented in software, using VxWorks on a Motorola CPU in a VME chassis. The absolute encoder is read and the is algorithm computed at 50-Hz.

The inner velocity loop consists of the velocity demand and velocity feedback derived from an incremental encoder mounted directly to the motor shaft. The signals of this digital tachometer are processed by the velocity loop algorithm to produce a torque demand. The algorithm is a classical PID control law performed in a hardware motor controller based on the National Semiconductor LM628 chip in an IndustryPack module in a VME carrier board. The P, I, and D parameters are loaded into the LM628 from software in the VME CPU and may be changed dynamically. The velocity loop operates at ~4-kHz passing the torque command to the amplifiers and hence to the motors.

Four motors are used on the azimuth drive -- each with its own amplifier driving a common bull gear through gearboxes. The motors are in two pairs, and the motors of each pair are biased against each other to minimize backlash. This provides a “stiff” system, and we anticipate that the velocity of all of the motors will be the same. Therefore, we can use an incremental encoder on just one motor as the velocity feedback, so the torque demand from one motor controller is fed to all the amplifiers.

In elevation however, the 6.5-m MMT will have two motors, each friction-coupled to a drive arc on opposite sides of the telescope. Anticipating the possibility of flexing between the arcs led us to design for incremental encoders on each motor, feeding back to two LM628 motor controllers. The position feedback is from one absolute encoder on-axis, so one position loop algorithm feeds the same velocity demand into both controllers.

The block diagram (lower part of Figure 10), shows the basic hardware layout of the mount control system. A Sun workstation provides a graphical user interface for the telescope operator. Position commands in the form of current-epoch RA and Dec coordinates are sent to the Motorola CPU in a VME crate, and status information is received and displayed on the Sun.

The mount control program, running under VxWorks in the VME computer, converts the RA/Dec input to demanded azimuth, elevation and rotator angles, reads the absolute encoders through parallel interface modules, and calculates the position loop algorithms. The demanded velocities are passed on the VME backplane to the LM628 controllers residing in the same crate. Between the VME crate and the telescope, we have a Mount Interface Chassis -- an in-house built unit to provide isolation and line-driving capabilities. This is physically close to the VME to minimize the effect of lightning-induced transients. The encoder box is placed close to the encoder in order to minimize noise degradation of the analog signals produced by the Inductosyn encoders. This box houses resolver-to-digital converters and the encoder excitation oscillators. The output from this box is then a parallel digital signal which is noise-immune.

6.0 Acknowledgments

We recognize the enormous efforts of the MMTO staff, the Steward Observatory Mirror Laboratory, the Steward Observatory technical division, Arcetri Observatory, Harland Epps, Bob Fata, Irwin Shapiro, and Peter Strittmatter.

7.0 References

1. B. H. Olbert, J. R. P. Angel, J. M. Hill, and S. F. Hinman 1994, “Casting 6.5-m mirrors for the MMT Conversion and Magellan”, *Advanced Technology Optical Telescopes V*, Proc. SPIE **2199**, 144-155.

2. B. M. Martin, J. H. Burge, D. A. Ketelsen, and S. C. West 1996, “Fabrication of the 6.5-m primary mirror for the Multiple Mirror Telescope Conversion”, Proc. this conference.

3. Peter Gray, S. C. West, and W. Gallieni 1996, “Support and actuation of six secondaries for the 6.5-m MMT and 8.4-m LBT telescopes”, Proc. this conference.

4. Jim Burge 1996, “Measurement of large convex secondary mirrors”, Proc. this conference.

5. D. Fabricant and B. McLeod 1996, “Optical specifications for the MMT conversion”, preprint of a forthcoming MMT Conversion Technical Report.

6. R. Fata and D. Fabricant 1994, “The design and support of the 1.7-m f/5 secondary mirror for the MMT conversion”, *Advanced Technology Optical Telescopes V*, Proc. SPIE **2199**, 580-592.

7. D. G. Bruns, T. K. Barrett, D. G. Sandler, H. M. Martin, and G. Brusa 1996, “MMT adaptive secondary mirror concave prototype”, Proc. this conference.

8. D. Fabricant, E. Hertz, and A. Szentgyorgy 1994, “Hectospec: a 300-optical-fiber spectrograph for the converted MMT”, Proc. SPIE **2198**, 251-263.

9. B. McLeod, D. Fabricant, J. Geary, and A. Szentgyorgy 1996, Wide-field CCD imager for the 6.5-m MMT telescope”, Proc. SPIE **2654**, 233-238.

10. L. Miglietta 1996, “The position actuators of the 8.4-m LBT primary mirrors”, Proc. this conference.

11. J. M. Hill 1995, “Mirror support system for large honeycomb mirrors II/R”, LBT Project Technical Memo, UA-95-02.

12. S. C. West and H. M. Martin 1995, “Approximate wind disturbance of the MMT 6.5-m primary mirror on its supports”, *Multiple Mirror Telescope Technical Report* #**28**, University of Arizona and the Smithsonian Institution.

13. J. R. P. Angel, A. Y. S. Cheng, and N. J. Woolf 1988, “Thermal stabilization of honeycomb mirrors”, in Proc. ESO *Very Large Telescopes and Their Instrumentation*, ed. M. H. Ulrich, 467.
14. M. Lloyd-Hart 1990, “System for precise temperature sensing and thermal control of borosilicate honeycomb mirros during polishing and testing”, *Advanced Technology Optical Telescopes IV*, Proc. SPIE **1236**, ed. L. D. Barr, 844.
15. L. Miglietta 1991, “Primary mirror temperature control system: feasibility study of an air-air ejector device”, *Arcetri Technical Report* **09-1991**, Arcetri Observatory.
16. L. Miglietta April 1992, “Air-air ejector for large mirror temperature control: numerical simulations and experimental data”, Progress in Telescope and Instrumentation Technologies, Proc. ESO, Garching, 361-364.