The MMT f/5 secondary support system: 
design, implementation, and performance

S. Callahan a, B. Cuerden b, D. Fabricant c, B. Martin b

a MMT Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ, USA 85721
b Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ, USA 85721
c Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA, USA, 02138

ABSTRACT

The 6.5m Multiple Mirror Telescope Observatory (MMTO) installed a new f/5 secondary system in April 2003. We describe the design and performance of the mirror cell and supports for the 1.7 m diameter Zerodur mirror. Pneumatic actuators divided into one lateral and three axial zones support this 318 kg mirror. The control feedback for the high bandwidth pressure transducers for these four zones is obtained from six load cells attached to rigid positioning rods. The mirror cell includes thermal control, force limiters, passive supports, installation and handling, and alignment metrology. Optical test results are described and compared to the original design specifications.

Keywords: mirrors

1. INTRODUCTION

1.1. MMT Optical Configurations

The converted MMT has a 6.5m f/1.25 primary and three interchangeable classical Cassegrain secondaries with focal ratios of f/5, f/9, and f/15. The f/9 secondary matches the focal ratio of the original multiple mirror telescope, allowing use of the original instruments. The f/15 secondary is an innovative adaptive secondary1,2,3 that allows infrared adaptive optics corrections with a low emissivity two mirror optical system.

The f/5 secondary is designed for wide-field optical and near infrared observations. With the addition of a large refractive corrector4, the f/5 focus offers a telecentric 1° diameter field of view for spectroscopy or a flat 0.5° diameter field of view for imaging. The f/5 secondary was placed into service in April 2003 and is now in routine operation. Currently, the secondary is used with three wide-field instruments: Hectospec (an R~1000 optical spectrograph fed with 300 robotically positioned optical fibers), Hectochelle (an R~40,000 optical spectrograph fed with the same fibers), Megacam (a 340 megapixel, 36 CCD optical imager). Three additional f/5 instruments will be placed into service during the next three years.

1.2. Description of the f/5 Mirror

The f/5 Zerodur secondary mirror is 1.688 m in diameter and weighs 316 kg. The mirror blank5 was cast and machined in Germany by Schott. The Steward Observatory Mirror Laboratory generated and polished the highly aspheric surface. The excellent polishing test results6,7 set high performance goals for the support system.

Laboratory measurements were made with the mirror facedown, i.e. as it is when the telescope points at the zenith, with support forces equal to those in the telescope. The raw surface accuracy on the polishing cell is 34 nm rms, much of which is astigmatism and spherical aberration that are corrected in the telescope. With these terms removed the surface accuracy is 17 nm rms. In perfect seeing, the 80% encircled-energy (EE) diameter of the MMT primary mirror is 0.14″ at a wavelength of 500 nm. For the primary and secondary mirrors combined, again in perfect seeing, the 80% EE diameter increases to 0.20″. In 0.25″ full-width-half-maximum (FWHM) seeing, the 80% EE diameter is 0.54″ for the

* scallahan@as.arizona.edu
primary alone and 0.56" for the primary and secondary combined. This compares with a 0.49" 80% EE diameter for perfect optics in 0.25" seeing.

Figure 1. The optical layout of the three MMT secondaries.

Figure 2. The f/5 secondaries shown with a fresh coat of aluminum. The mirror was aluminized at the Steward Observatory Sunnyside facility in November 2003.
1.3. Design Specifications for the f/5 Secondary Support System

An error budget was determined for the entire optical configuration. The specification for the mirror and support system is given as a structure function: an rms wavefront difference between points in the aperture as a function of their separation. The structure function has the same form as the seeing-induced wavefront structure function, and its magnitude is defined by an equivalent seeing-limited image FWHM. The specification for the mirror support system

![Graph showing structure function](image1)

**Figure 3.** Bottom curve: the structure function due to support errors predicted by finite element analysis for a zenith pointing telescope. Top curve: the structure function specification allowed by the error budget for a zenith pointing telescope.

![Graph showing structure function](image2)

**Figure 4.** Bottom curve: the structure function due to support errors predicted by finite element analysis at 60° from zenith. Top curve: the structure function specification allowed by the error budget at 60° from zenith.
corresponds to 0.017″ FWHM (corresponding to 0.026″ 80% EE energy diameter) at zenith and 0.017″ \cos(\theta)^{-0.6} FWHM at zenith angle \theta.

A finite element model of the mirror and the support system was made to calculate support errors and cell deflections at various telescope elevations. The model results were then converted to a structure function and compared to the error budget structure functions. Figures 3 and 4 show the final design results.

1.4. Description of the Mirror Support System

The mirror support system consists of 36 pneumatic cylinders that apply axial force to the back of the mirror. These actuators are designed in two sizes with pneumatic diameters of 33.7 mm and 31.8 mm. The 30 lateral actuators apply force perpendicular to the elevation axis of the telescope. The force is transmitted to a puck bonded inside the honeycomb structure of the mirror near the center of gravity. Six load cells determine force feedback. Three load cells are attached tangent to the mirror perimeter, and three are attached perpendicular to the back of the mirror. The load cells are mounted on rigid columns known as hardpoints. To protect the mirror against excessive stress, a spring-loaded mechanism limits the force applied by each column to a maximum of 60 N.
Figure 6. Exploded view of a lateral support actuator

Figure 7. Exploded view of a locating hardpoint that is attached to the back of the mirror
The axial actuators are divided into three equal zones covering 120° sectors. A separate pneumatic control valve controls each zone. A fourth control valve controls all 30 lateral actuators. This arrangement allows rapid correction of wind-induced errors for four of the six degrees of freedom. The remaining two degrees of freedom, rotation about the optical axis and translation parallel to the elevation axis, are constrained by the hardpoints. All of the actuators are mounted in a 160 kg aluminum cell.

Figure 8. Exploded view of the mirror support system
1.5. Ventilation system

The mirror is ventilated with 273 nozzles. Each nozzle injects air into a hollow hexagonal core machined into the back of the mirror. A balanced blower transports air through the heat exchanger before circulating 0.7 liter sec\(^{-1}\) through each nozzle. This liquid-to-air heat exchanger is connected to a remote refrigeration unit to provide temperature control. At this time the ventilation system has not been completed.

![The f/5 secondary with mid baffle](image-url)
2. PERFORMANCE

The performance of the f/5 optics in the telescope is measured with a Shack-Hartmann wavefront sensor. These Shack-Hartmann measurements are used to actively correct the telescope collimation and primary support forces. Adjustments are not made to the secondary mirror supports or the f/5 refractive corrector. Following corrections to the secondary mirror position and primary support forces, a final Shack-Hartmann measurement is made. Figure 9 is a scatter plot of the Shack-Hartmann wavefront sensor spot positions obtained during seeing of ~0.32" FWHM with the f/5 secondary and the imaging configuration of the wide-field corrector. The data are extracted from an average of four 5-second exposures on a bright star. The spot fluctuations from seeing should be largely averaged out for an exposure of this length. Figure 10 is an encircled energy plot derived from the data plotted in Figure 9.

![Spot Diagram](image)

Figure 9. scatter plot of the position deviations of the Shack-Hartmann wavefront sensor spots
3. CONCLUSIONS

The error budget for the optical system and telescope, excluding seeing and tracking errors, is 0.36" 80% EE diameter. The measured number derived from Figure 10 is 0.32" 80% EE diameter, corresponding to an image FWHM of 0.21". While we cannot extract the performance of the secondary supports alone, it is clear that the complete f/5 optical system is meeting its performance goals with margin to spare. We conclude that the secondary supports are, at worst, performing close to the specified level, although we expect that the level of performance predicted in Figures 3 and 4 is being achieved. Overall, the performance of the f/5 optics is superb.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the many people who made this project successful, including: Eric Anderson, Steve Bauman, Dusty Clark, Brian Comisso, Creighton Chute, Robert Fata, Craig Foltz, J. Duane Gibson, Ron James, Bill Kindred, Cory Knop, Greg Landis, Tim Pickering, Alberto Ramos, Gary Rosenbaum, Gary Schmidt, Bryan Smith, Pete Spencer, Tom Trebisky, Court Wainwright, Steve West, and J.T. Williams.

REFERENCES


