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Analysis and verification of Hobby-Eberly Telescope 1 m mirror deflections due to edge sensor loading

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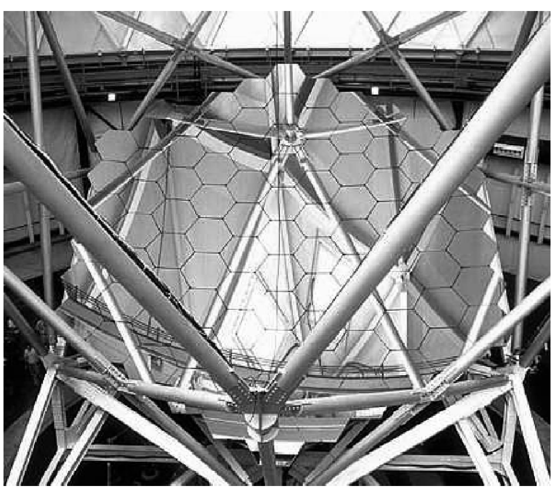
ABSTRACT

The ninety-one 1 m mirror segments which comprise the McDonald Observatory Hobby-Eberly Telescope (HET) primary mirror have been observed to drift out of alignment in an unpredictable manner in response to time variant temperature deviations. A Segment Alignment Maintenance System (SAMS) is being developed to detect and correct this segment-to-segment drift using sensors mounted at the edges of the mirror segments. However, the segments were not originally designed to carry the weight of edge sensors. Thus, analyses and tests were conducted as part of the SAMS design to estimate the magnitude and shape of the edge sensor induced deformations as well as the resultant optical performance. Interferometric testing of a 26 m radius of curvature HET mirror segment was performed at the NASA/Marshall Space Flight Center using several load conditions to verify the finite element analyses.

Keywords: finite element analysis, testing, mirror alignment, segmented mirror, edge sensors

1. INTRODUCTION

The McDonald Observatory Hobby-Eberly Telescope[1] (HET) primary mirror is composed of 91 hexagonal Zerodur mirrors (each 1 m flat-to-flat, 51.2 mm thick) which are arranged to form a hexagonal parent mirror 11 m point-to-point (Figure 1). The HET operates at a fixed zenith angle of 35 degrees and rotates in azimuth. Thus, the mirror segments are subjected to a constant gravity loading vector which simplifies the design and analysis. Each mirror segment has three actuators attached to its support structure which allow movement of the segment in piston, tip, and tilt.



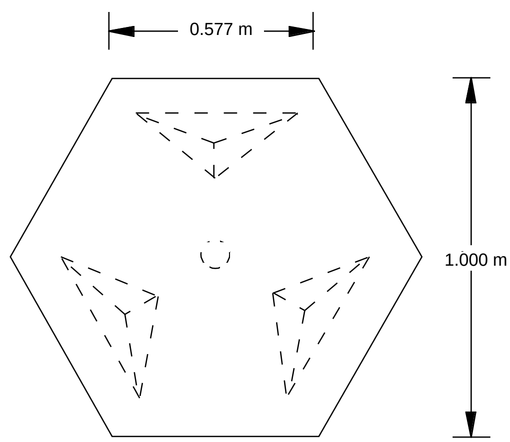


Figure 1. Hobby-Eberly Telescope primary mirror array (left) and one segment (right)

Over time, the mirror segments have been observed to drift out of alignment. The Segment Alignment Maintenance System[2,3] (SAMS) will detect the relative segment-to-segment drift and send the measurements to the HET primary mirror control computer (PMC). The PMC will analyze the data and issue commands to the actuators to bring the segments back into alignment without going through the normal segment alignment procedure.

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Experience has shown that the deflection of a mirror under load is highly dependent on the type and placement of its mounting system. Each HET mirror segment rests on a modified Hindle mount which supports the segment at nine places. A series of analyses and tests were undertaken to characterize this mirror/mount system to be able to predict the effects of the SAMS system on the mirror segments.

The mirror-mounted components of the current SAMS design include twelve inductive edge sensors mounted on the back of each segment. Two sensors are mounted near each of the six corners of the segment, no closer than 50 mm from each corner. One SAMS option also includes inclinometers mounted near the centers of four of the 91 segments, however, this configuration was not tested.

2. ANALYSIS

2.1 Analysis considerations

Although gravity must be taken into account in mirror and mount design, the HET mirror segments are polished and mounted in such a way that gravity causes no degradation of their optical performance when they are mounted at their standard 35 degree inclination. The purpose of this analysis and testing was to characterize the effect of mounting the SAMS edge sensors on the mirror assuming the mirror was perfect under the normal gravity environment. Thus, no gravity loads were applied to the model during these trade studies, only the forces due to the edge sensors.

The original SAMS specification[4] required the sensors to be no heavier than 25 g unless analysis could show that a system with heavier sensors would not cause degradation of the segment figure exceeding the required $\lambda/15$ RMS. In discussions with the developer of the edge sensors, Blue Line Engineering, it became clear that the sensors and their supporting brackets would likely weigh more than 25 g. As a result, trade studies needed to be performed with various edge sensor weights to determine the effect on the mirror segment. In addition, the maximum allowable moment of an individual sensor unit was required to be less than the moment generated by a 25 g mass suspended 25 mm below the segment backplane. Since the edge sensors had not reached final design, several analyses were performed using the MSC/NASTRAN and ANSYS finite element codes to determine the mirror figure error caused by sensors and inclinometers of various weights.

Calculations of root mean square (RMS) and peak-to-valley (P-V) deflections from the mean optical surface were made for all load cases. In order to verify the finite element model for these trade studies several deflection tests, which are described in Section 3, were performed on a spare mirror segment. Analyses were performed to predict the behavior of the mirror prior to the tests.

2.2 Model details

The model of the mirror is composed of 18,996 eight-noded solid brick elements arranged in three layers through the thickness (Figure 2). The 26.165 m radius of curvature of the optical face is accurately modeled. For the sensor sizing trade studies, forces representing the sensor weights (resolved into X, Y, and Z components) are applied to shell elements representing twelve brackets extending 25 mm beyond the back face of the mirror. Multi-point constraints are used to connect the shell elements to the solid elements of the mirror body.

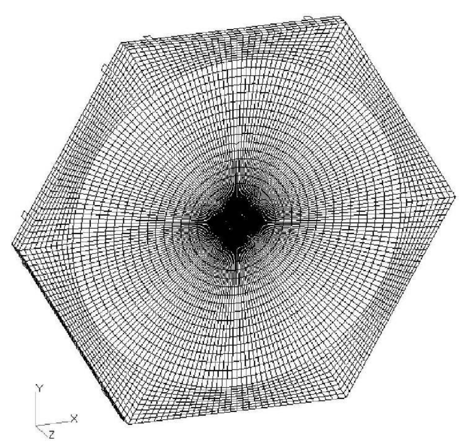

Figure 2. Mirror model front

Each mirror segment is supported by three tetrahedral frames. Each frame is comprised of six circular-cross-section Invar bars and pivoted at its center of mass. The tetrahedra are represented in the model by circular-cross-section beam elements attached to the back of the mirror via multi-point constraints (Figure 3). These constraints defined the motion of a tetrahedron corner as the weighted average of the X, Y, and Z motions of four nodes on the back of the mirror. Since the tetrahedra are pivoted, they are designed to follow the mirror as it deflects so

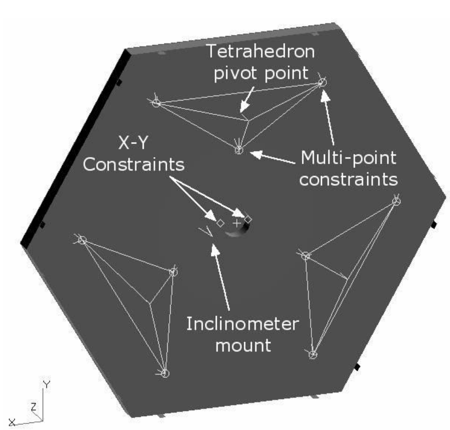

Figure 3. Mirror model rear, shaded

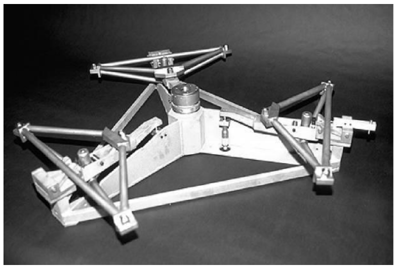

Figure 4. Support structure for one mirror segment

that all corners of each tetrahedron are constantly in contact with the mirror. The multi-point constraints are configured to properly model this behavior.

The three tetrahedra are mounted together on a rigid triangular frame (Figure 4) which is, in turn, mounted on the primary mirror support structure truss, neither of which are included in this model. At the center of each segment s triangular frame is a round hub mounted on a blade flexure. This flexure is designed such that the hub can freely translate in the Z direction (perpendicular to the plane of the mirror), cannot translate in X or Y directions (in the plane of the mirror), cannot rotate about Z, but is free to rotate slightly about X and Y. The hub contacts the mirror by extending into a blind hole in the back of the mirror.

3. TEST DESCRIPTION

A spare HET mirror segment and mirror support structure were provided to NASA for characterization and analysis verification testing. In order to find a suitable test environment, seismic dynamic measurements were taken throughout the Load Test Annex (LTA) in Building 4619 of Marshall Space Flight Center to evaluate its stability. A 200 ft path length interferometric test set-up was finally assembled inside the Controls, Astrophysics, and Structures Experiment (CASES) facility which occupied the southwest corner of the LTA. This enclosed vertical tent structure acted as a buffer to help reduce air turbulence during testing. The mirror segment was set up on the ground floor (Figure 5) with the optical test equipment located at the center of curvature of the segment more than 90 ft overhead, attached to one of the main structural columns of the LTA.

Figure 5. Mirror segment and weights on floor of test area

A 6 in diameter turning mirror and a Zygo f 1/25 diverging lens were used to align the output laser from a Wyko 6000 interferometer with the HET mirror segment. The 4 in diameter of the Zygo lens prevented full aperture analysis of the mirror, however, the optics were positioned to provide maximum mirror coverage. The beam was aligned to fully cover two corners of the hexagonal mirror segment. The Wyko wedge factor was set at 0.5, thus, the data reported represented the actual deviations in the surface figure of the mirror.

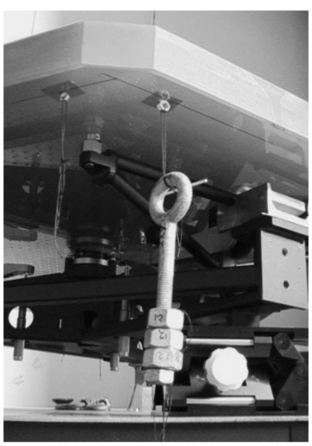

Figure 6. Load being applied to mirror segment

Vibrations from air movement, crane operations, test operations in adjacent areas, vehicular traffic, and other sources as well as thermally induced slip/stick motions of the LTA facility precluded data acquisition during regular working hours. To minimize vibrations of the support structure all data were acquired between 9:00 PM and 3:00 AM. Airflow disturbances and thermal shifts within the test area were far less disruptive at this time of day. To further reduce environmental effects on measurement accuracy, 15 to 25 averages were acquired for each loading condition. Optical Path Difference (OPD) data were acquired for five loading conditions simulating edge sensors weighing 0 g to 421.8 g.

The SAMS specification requires that the edge sensors not be attached within a 50 mm radius of each segment corner. Twelve test locations, corresponding to load locations in the finite element model, were chosen 69 mm from each corner and 32 mm from the nearest edge of the mirror segment. Kapton tape was applied to the back of the mirror then twelve 1/4-20 machine nuts were bonded to the Kapton tape providing a method to apply the loads to the mirror (Figure 6). A selection of eyebolts and machine nuts were used to simulate the weight of the edge sensors.

4. RESULTS

Finite element analysis (FEA) runs were performed for the various sensor weights. The out-of-plane deflections from the run with the heaviest load (421.8 g) are shown in Figure 7 (deflections are magnified to illustrate deflected shape). After removing rigid body motions the resulting deflections were 411.6 nm P—V and 103.2 nm RMS.Output from the FEA was also transferred to the Integrated Optical Design Analysis (IODA) program, which is being developed by SRS Technologies, to calculate Zernike coefficients (Figure 8). IODA has the ability to remove selected Zernike coefficients such as piston, tip, and tilt then plot the remaining Zernike fit. Once these rigid body motions were removed by IODA (Figure 9) it was clear that the largest effect was on focus.

For the testing, an initial no load condition (gravity only) OPD was acquired and subtracted from the OPDs taken with the mirror loaded, producing data that directly quantified the mirror deflection due to the test loads. The contour maps from the testing (Figures 10 and 11) clearly illustrate the change in mirror shape resulting from the weight of the simulated edge sensors. Within the resolution of the testing methodology, nearly all of the deflection can be characterized as a deviation in focus.

Figures 12 and 13 show that the model predicted larger deflections than those observed during testing. The intermediate load cases were run on the first night of testing and the maximum and minimum load cases were run on the second night. The peak-to-valley plot (Figure 12) indicates a nonlinear deflection response to load at the heaviest loading condition (RMS data was not taken at this load level). Even though the data were taken after hours there was sufficient vibration in the test setup that multiple readings had to be averaged together for each loading condition. Because of this averaging process it was clear that the small nonlinear deviations were not data artifacts but rather were an indication of time-variant hysteretic behavior of the test setup. After some investigation it was determined that the mirror support structure was being affected by small thermal variations in the test environment which had not been observed during earlier testing.

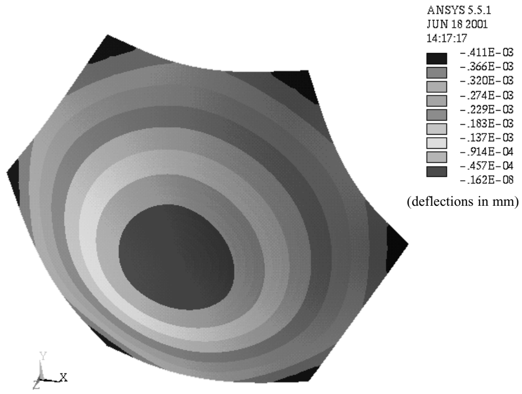

Figure 7. FEA deflections due to 421.8 g weights

Zernike	Coefficient	Aberration
1	-0.5253	Piston
2	-0.1402	Tip
3	0.0841	Tilt
4	0.0271	Astigmatism
5	-0.1582	Focus
6	-0.0315	Astigmatism
7	0.0043	Trefoil
8	-0.0067	Coma
9	0.0066	Coma
10	0.0602	Trefoil
11	-0.0040	
12	-0.0021	
13	0.0247	Spherical
14	0.0048	
15	-0.0103	

Figure 8. Zernike coefficients for 421.8 g weights

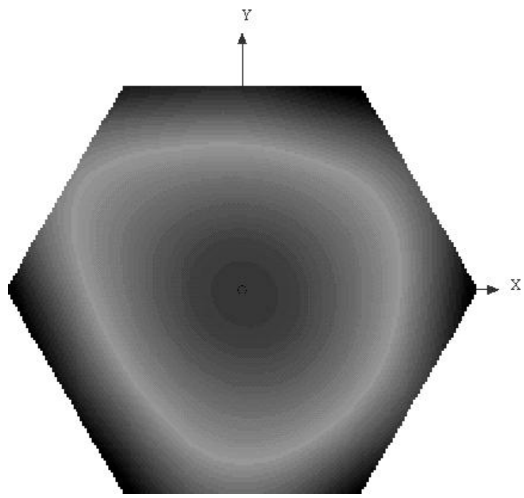

Figure 9. Zernike fit from IODA with piston, tip, and tilt removed

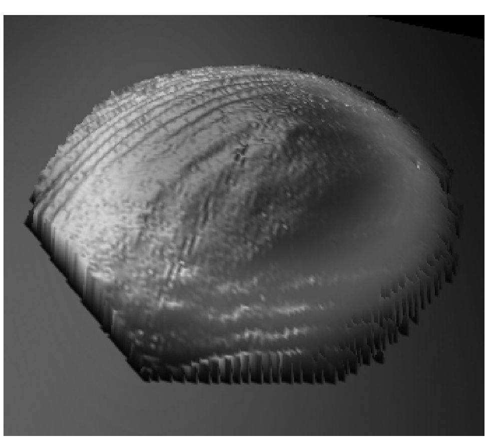

Figure 10. 3D contour map

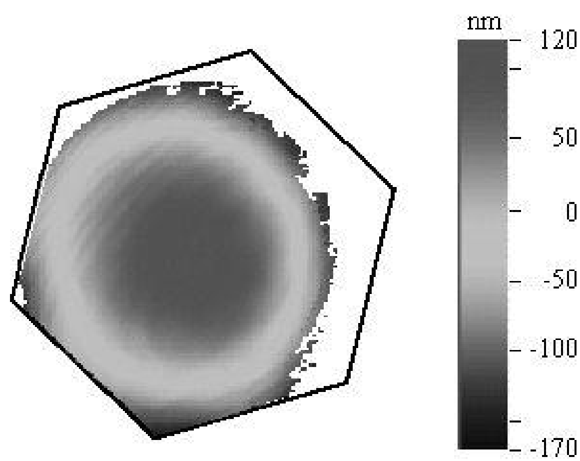

Figure 11. Contour map

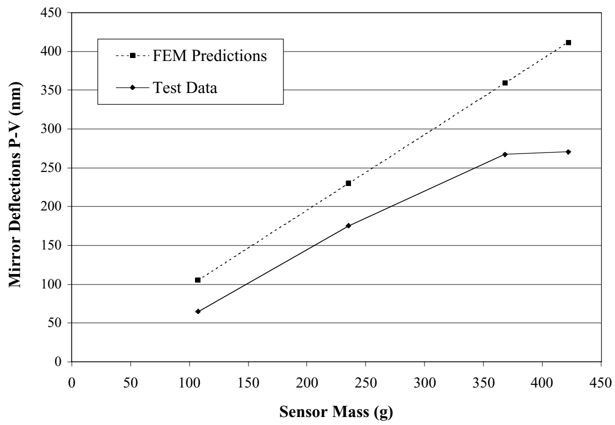

Figure 12. P-V deflections

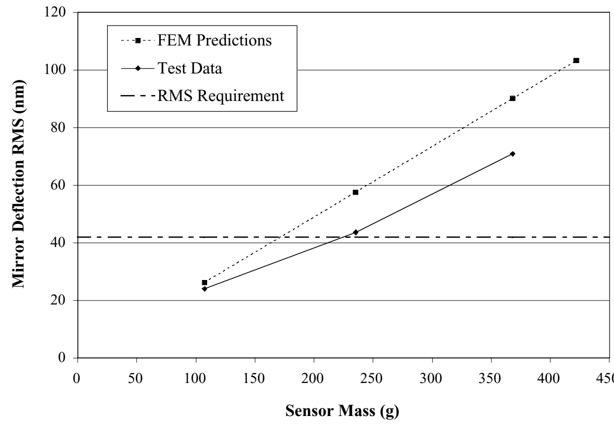

Figure 13. RMS deflections
(RMS test data not recorded at 421.8 g)

5. CONCLUSIONS

The purpose of this testing was to verify the finite element model so an assessment could be made of the effects on the HET mirror segment due to the addition of edge sensors. The requirement was that the edge sensors would not cause degradation of the segment figure exceeding $\lambda/15$ RMS (which translates to 42 nm RMS using λ=633 nm). Although the model tended to conservatively estimate the effects on the mirror, the expected weight of the edge sensors (50 g) was considerably less than the loads used during testing. Further adjustments to the model might provide better correlation with the test results. With the model now test verified it was clear that sensors weighing 50 g would be acceptable with some margin available to accommodate design changes, if necessary.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. L.W. Ramsey, M.T. Adams, T.G. Barnes, J.A. Booth, M.E. Cornell, J.R. Fowler, N. Gaffney, J.W. Glaspey, J. Good, P.W. Kelton, V.L. Krabbendam, L. Long, F.B. Ray, R.L. Ricklefs, J. Sage, T.A. Sebring, W.J. Spiesman, M. Steiner, The early performance and present status of the Hobby-Eberly Telescope, SPIE Vol. 3352, *Advanced Technology Optical/IR Telescope VI*, pp. 34-43, 1998.
2. E. Montgomery, G. Ames, J. Rakoczy, J. Weir, J. Lindner, A Proposal for a Segment Alignment Maintenance System, Hobby-Eberly Telescope, August 3, 1999.
3. J. Booth, M. Adams, G. Ames, J. Fowler, E. Montgomery, J. Rakoczy, Development of the Segment Alignment Maintenance System (SAMS) for the Hobby-Eberly Telescope, SPIE Vol. 4003, *Optical Design, Materials, Fabrication, and Maintenance*, pp. 176-187, 2000.
4. J. Booth, HET Segment Alignment Maintenance System Statement of Work, June 1, 1999.