Metrology results and lessons learned from the Univ. of Arizona NGST Mirror System Demonstrator

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ABSTRACT

The University of Arizona has built a 2-m lightweight active mirror prototype for the next generation of space telescopes. This paper briefly reviews the mirror's opto-mechanical design, and it describes the three different metrology systems that were used to measure it during the actuation process. We also present a list of lessons learned while working on this project. We conclude by discussing one of the successful projects that has come out of this technology.

Keywords: Lightweight, space, active mirrors, Arizona, NMSD, NGST, JWST

1. INTRODUCTION

The University of Arizona (UA) has built a 2-m lightweight prototype mirror initially designed as a technology demonstration for the Next Generation Space Telescope (NGST) project. The 6 meter NGST (recently renamed the James Webb Space Telescope) is scheduled for launch in 2011 to replace the aging Hubble Space Telescope (HST). Building large (6-m class) aperture space telescope presents some unique fabrication challenges. Because the large mirror will not fit within any of current launch vehicles, the mirror must be comprised of smaller segments. These segments will be assembled into a complete mirror once all of the pieces are launched into space. Conventional monolithic mirrors are much too heavy for the NGST's mass budget, so the segments must be light enough to be lifted into orbit. Finally, the NGST will be placed in solar orbit at an operating temperature of 35 K, and the materials used in construction must be able to perform at this temperature.

The UA 2-m prototype meets all of these design requirements. The mirror uses a design derived from the Univ. of Arizona's extensive experience in fabricating adaptive optics for ground-based telescopes.[1,2] The design concept is shown in Figure 1. A thin, glass substrate serves as the optical surface. However, because this surface is so thin, it is very flexible. The accuracy of the glass membrane is maintained by an array of precision actuators. These "set and forget" actuators set and maintain the substrate's accuracy. A lightweight, composite support structure provides the stiffness for the system.

This UA mirror concept represents a new paradigm in space mirror design.[3] The HST's primary mirror uses a conventional monolithic design made from a solid piece of ULE glass. The mirror depends on its rigidity in order to maintain the figure that was originally applied in the optics shop. The UA concept frees the mirror from this constraint. Because the mirror's figure is actively controlled by the actuators, the mirror can be adjusted once the optic is placed into orbit. This feature is especially valuable when temperature fluctuations may cause mechanical disturbances in the mirror's structure.

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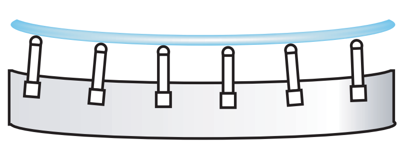

Figure 1. The Univ. of Arizona lightweight mirror design. A thin, flexible glass substrate serves as the reflective surface. The actuators maintain the surface accuracy, and a lightweight support structure provides stiffness.

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The f/5 mirror is 2 meters in diameter (point-to-point), and it uses a 2 mm thick borosilicate glass shell as the optical surface.[4] The mirror has an areal density of 13 $\frac{\text{kg}}{\text{m}^2}$, including the glass, actuators, loadspreaders, support structure and all of the onboard wiring. (By comparison, the Hubble's primary has an areal density of 180 $\frac{\text{kg}}{\text{m}^2}$.) The entire 2-m NMSD mirror weighs only 86 pounds!

A lightweight support structure contains 166 actuators for adjusting the mirror's figure. The support structure was designed at the UA and fabricated at Composite Optics, Inc. The structure has three components: a facesheet, a backsheet, and a honeycomb-like structure sandwiched in between. All of the pieces are made of a lightweight carbon fiber laminate. The actuators were designed and fabricated at the UA. They use an electromechanical drive to increment an 80 pitch screw in 20 nm steps. The 44 gram actuators work at ambient temperature and 35K, and they do not require any power to maintain their positions. Each actuator is interfaced with the glass via a nine point whiffletree, or loadspreader.

This paper will not concentrate on the fabrication details of this mirror, as they have been described elsewhere.[3] Instead, we will describe the metrology systems used to measure the mirror after it was assembled. We will also describe some of the lessons learned from this project. We conclude by listing some of the projects that have benefited as a result of this work.

2. METROLOGY SCHEDULE

Because the surface figure of an active mirror is determined by the array of actuators, the reflective membrane does not assume the proper figure when it is initially assembled. The procedure for actuating smaller mirrors is rather simple: we support the membrane by three actuators, and we illuminate the mirror with a point source at the center of curvature. We adjust the three initial actuators until the image at the center of curvature displays three-fold symmetry. We continue this process of engaging additional actuators and adjusting them to achieve a corresponding symmetry in the return image. Once the majority of the actuators are engaged, we can start using a visible interferometer, and the surface is usually good enough to start making progress using interferometry. Because this mirror is larger than our previous mirrors, it was not possible to support the membrane by three support points because the stress involved would risk fracturing the glass. In addition to this, the loadspreaders contained a mechanical system that decoupled the actuator from the glass if too much self-weight was loaded onto each support points.

Because we weren't able to initially support the glass on only a few actuators, we weren't able to use our previous procedure and move immediately to using visible interferometry. Instead, we developed a metrology schedule that involved three different tests. The first of these tests had a high dynamic range and low accuracy for doing rough mirror figuring, and the two proceeding tests had increasingly smaller dynamic ranges with better accuracy. The following three subsections summarize each test and show the results that each method was able to obtain.

2.1. The Hartmann test

We used a Hartmann test because it afforded us virtually an unlimited dynamic range. The Hartmann screen was a simple paper mask with 216 holes that were 0.25" in diameter, Figure 2. The mask's hole geometry was chosen such that six spots, arranged in a hexagonal geometry, surround every actuator. We placed this mask directly onto the mirror's surface, and we used a thin lens to image the mask onto a CCD.

This test was very useful as an initial measurement scheme because it provided an efficient, qualitative measurement tool for quickly identifying and correcting actuators that were severely out of place. For example, Figure 3 shows two images that represent the before and after images of a portion of the mirror under test. The left side of Figure 3 shows that the southeast corner of the mirror isn't properly actuated. The Hartmann spots are visible, but they are not in the correct locations. The right side of Figure 3 shows the results after the actuators in the southweast corner were all moved up by hand. Using this information, we were able to manually turn each actuator and watch the resulting spot motions in real time. This proved to be a very effective procedure for quickly moving all of the actuators to their nominal positions.

We were also able to use this scheme to determine the actuator heights relative to one another. Because the Hartmann spots form a hexagon around each actuator, the relative size of the hexagonal spot pattern provides

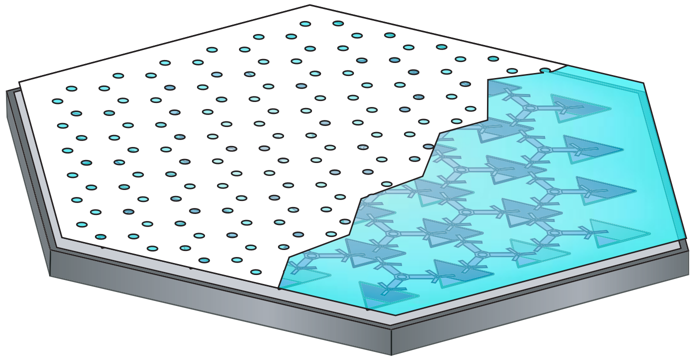

Figure 2. The Univ. of Arizona 2-m prototype space mirror with a Hartmann mask. Each actuator location is surrounded by 6 apertures in a hexagonal geometry.

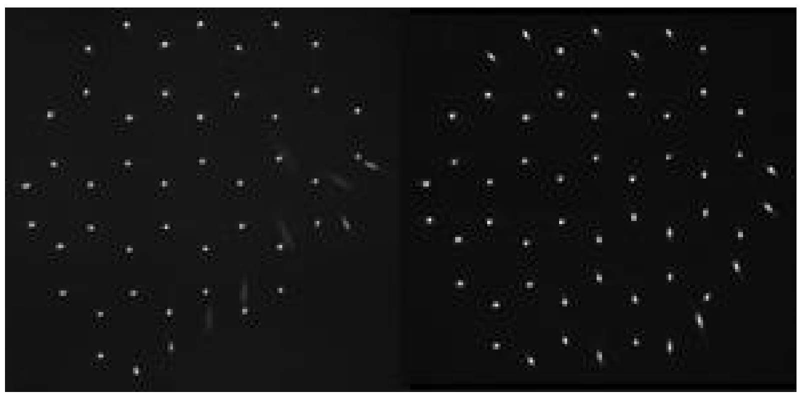

Figure 3. Hartmann data for the 19 inner-most actuators. There is an actuator inside each of the hexagons. Left: the spot pattern indicates that the southeast corner is too low. Right: the improved surface after adjusting the actuators.

some information about the relative height of all of the actuators. For example, if a particular hexagon is smaller than average, the actuator underneath it is too low. If a hexagon is larger than average, this actuator is too high. This concept is illustrated in Figure 4.

We were also able to use this method to gather quantitative data about the surface figure. To do this, we moved the CCD along the optical axis to take two frames of data. The first frame was taken at nominal focus, and this provided a reference measurement. The second frame was taken after the CCD was translated back away from the mirror*. These two frames provided enough information to define all 216 rays in three dimensions, and we used this information to calculate the slopes at the mirror. Finally, we used a least-squares fitting algorithm to calculate all 166 actuator commands at once.

This test scheme proved very successful. Figure 5 shows the initial and final qualitative measurements that we made using this scheme. The mirror's initial figure was approximately 25 microns RMS, and the final figure was less than 4 microns RMS. Thus, the Hartmann scheme proved useful on two fronts. First, we were able to efficiently move each actuator to within 3 to 5 microns of its ideal location. Once we positioned all of the actuators in this way, we were able to make quantitative measurements of the surface figure.

*The imaging system was telecentric in image space. We introduced defocus when we moved the CCD, but the magnification didn't change.

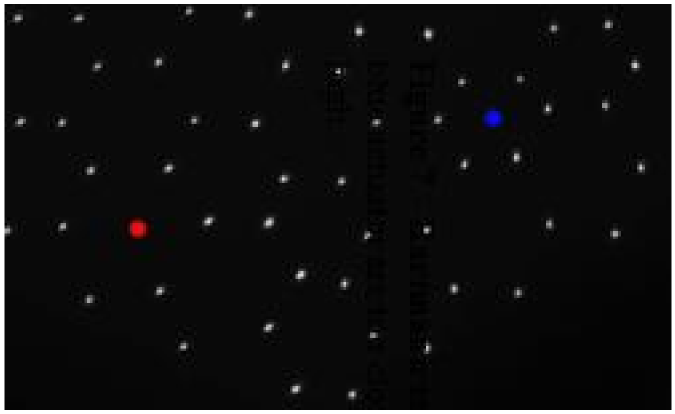

Figure 4. Quantitative Hartmann test data. The six spots surrounding the blue actuator (actuator indicated on the right side of the image) are too close together; the actuator is too low. By contrast, the red actuator (actuator indicated on the left side of the image) is too high.

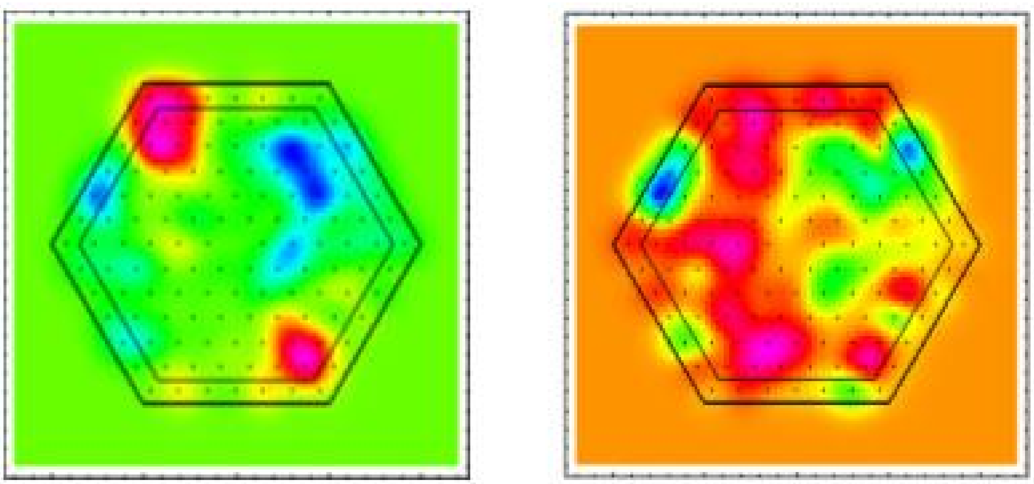

Figure 5. Initial and final surface maps from the Hartmann test. The surface on the left represents a surface figure of 25 μm RMS/125 μm PV. The surface on the right represents a figure of 3.7 μm RMS/23.1 μm PV. Colorscale: Violet is high, blue is low. Grayscale: dark areas are high.

Figure 6. Initial IR interferogram.

2.2. IR Interferometry

The Hartmann test worked well enough to prepare the surface figure for IR interferometry. The IR interferometer was based on a model initially built by Phil Stahl. The illumination source was a 10 W CO_2 laser operating at 10.6 microns. This interferometer was phase-shifted and connected to a computer running IntelliWave.

Using the IR interferometer was more straightforward than the Hartmann test because the IR interferometer was provided as a turnkey system. The initial interferogram is shown in Figure 6. Because the instrument was phase-shifted, we were able to generate surface maps and calculate an appropriate set of actuator commands to fix the figure. The final interferogram and surface map taken using the IR interferometer is shown in Figure 7. The surface statistics are 1.5 wvs peak to valley and 0.177 wvs RMS (10.6 μm). This surface represents a clear aperture that is 90% of the total mirror width.

We were not able to measure the entire clear aperture using this instrument because the slopes near the edge were too large. An example of this is shown under the arrow in Figure 7.

2.3. Visible Interferometry

The visible interferometer was a PhaseCam on loan from 4D Technology. The PhaseCam is a modified Twyman-Green interferometer. The PhaseCam uses a diffraction grating to image four frames of data onto a single CCD. These four frames are phased 90 degrees apart from each other. As a result, a phase map can be calculated from a single CCD frame. This system virtually eliminates the effects of vibration and air turbulence from the metrology setup. The illumination source is a HeNe (632.8 nm) laser. This interferometer was connected to a computer, and IntelliWave was used to generate a surface map.

The PhaseCam proved to be very effective at measuring the mirror, and it was particularly good at gathering data over regions of high slope errors. The initial and most recent surface maps are shown in Figure 8. We are currently working to improve the mirror's surface figure.

3. LESSONS LEARNED

An important by-product of every project are the lessons learned from it. While this mirror did not achieve the ultimate goal of diffraction-limited performance across the entire two meter aperture at visible wavelengths, it provided a wealth of information about designing, fabricating and operating lightweight active mirrors. This section outlines some of the important outcomes of this project. All of the difficulties involved with this project are related to the problems faced when scaling a mirror technology up to the next largest size.

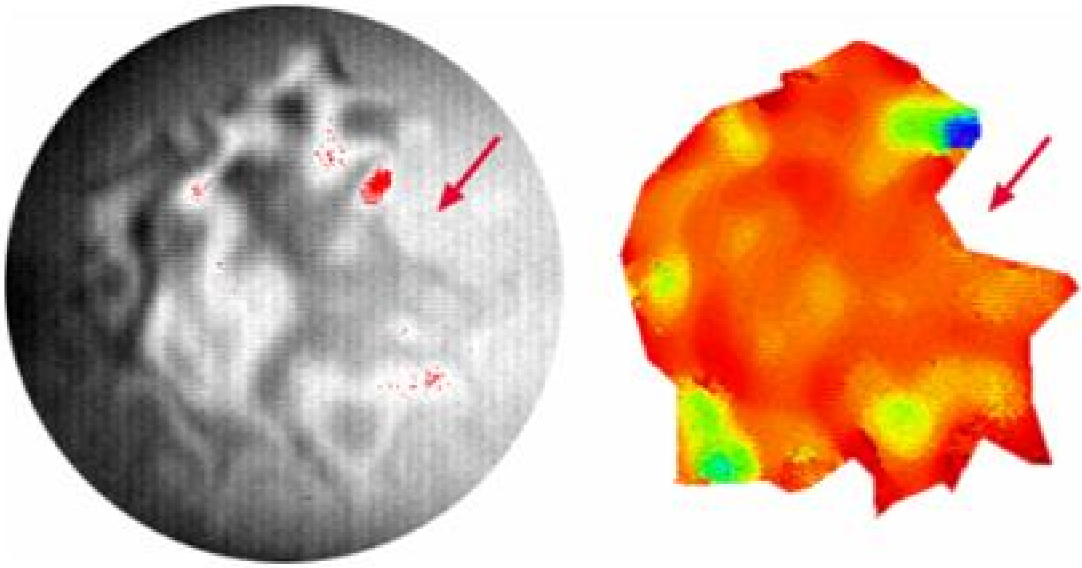

Figure 7. IR Interferometric test data. The interferogram is on the left and the surface map is on the right. The region under the arrow had a particularly large slope and was not measured by the instrument. The surface quality is 15.9 microns PV / 1.88 microns RMS. Colorscale: Red is high, blue is low. Grayscale: dark areas are high.

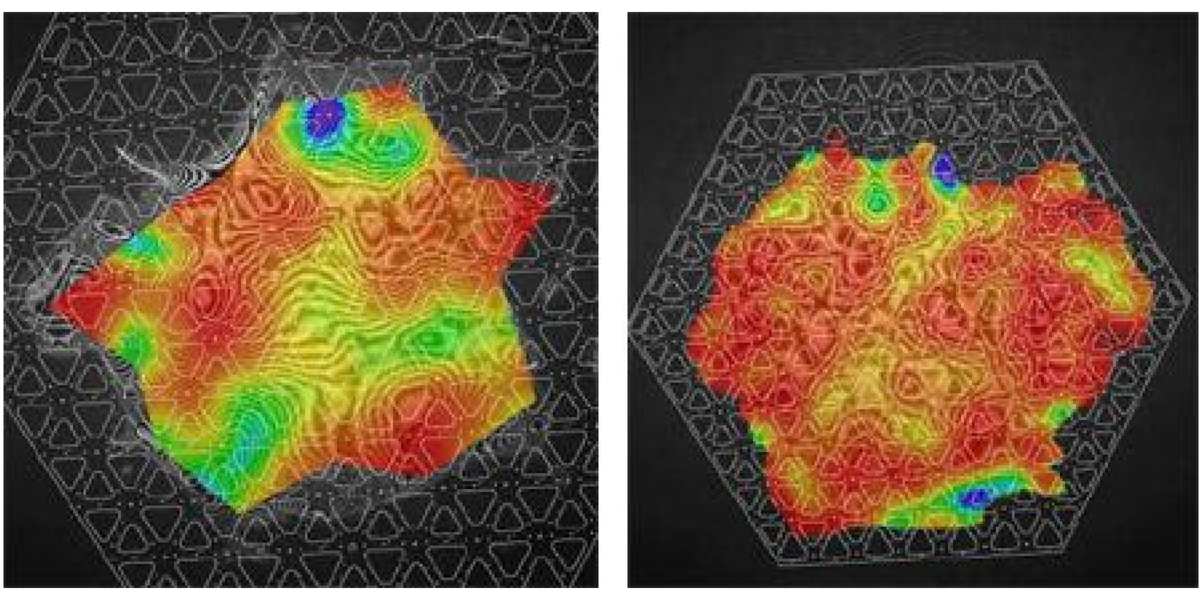

Figure 8. Initial and most recent measurements. Each image contains the interferogram, the surface map and a line drawing of the support structure to show scale. Left: initial visible measurement. The surface quality for the initial measurement was 14 wvs P-V / 2.0 wvs RMS (HeNe). Right: most recent visible measurement. The surface quality for the most recent measurement was 4.8 wvs P-V / 0.7 wvs RMS (HeNe). Colorscale: red is high, blue is low.

When the clear aperture exceeds a half meter, the seemingly simple task of handling the mirror becomes a serious engineering challenge. This becomes an issue even before the mirror blank is created. Most glass manufacturers have half meter blanks on hand, but finding a high quality piece of homogeneous, low CTE optical glass is a serious challenge. In fact, for this project, we opted to cast the blank ourselves at the Steward Observatory Mirror lab. Once the blank is cast, it cannot be lifted by hand and carried around the shop like a 0.5-m blank. We had to design special tooling to move the blank around the optics shop as it progressed through the figuring process. We also developed a new procedure for deblocking the glass facesheet once the polishing process was complete.[3] Finally, we needed to design and build a special vacuum lifting fixture for moving the 2-m, 2 mm thick membrane around the shop.

More than one measurement scheme is necessary for successfully actuating this mirror design. The Hartmann test allows for an efficient testing procedure for moving to visible interferometry as quickly as possible. The initial mirror figuring should be done using the Hartmann method described above. The Hartmann test allows the initial actuation to take place in less than a week. Using the quantitative Hartmann test, the mirror should be ready for IR interferometry after another week of computer-controlled actuation. If the mirror was mounted on isolated hardpoints, someone could get underneath the mirror and this fine-tuning process could be done efficiently by hand: one person manually adjusts the actuators while another watches the Hartmann spots. Once the Hartmann testing is complete, IR interferometry should be used to further improve the figure. Alternatively, the Hartmann test could be improved such that the IR testing is unnecessary. For example, we used a simple paper mask, a single imaging lens, and a simple centroiding algorithm to calculate the slope information. All of these elements could be optimized to enhance the accuracy of the test.

The actuation process would go much quicker if each actuator had a linear distance encoder. The success of this mirror design depends on repeatable, accurate actuator behavior. The actuators for this project were designed to be incredibly lightweight with very small step sizes; this design did not focus on consistent actuator behavior. However, we could have fixed this issue if we knew how far each actuator actually moved when we commanded it to do so. Although this would represent a large increase in the cost of each actuator, the time saved during the testing and actuation process would more than make up for this initial cost. A distance encoder would be particularly useful with the Hartmann and IR interferometric tests because these tests do not have the sensitivity to measure the smallest actuator motions.

The actuation process could also be improved by designing a control system that could move the actuators in either large or normal step sizes. When the mirror is initially actuated, the actuators must move large distances to correct the figure error. Under normal conditions, our actuators moved using step sizes of 15 nm. Some of the initial errors were as large as 200 microns; this is equal to 13300 steps! It took roughly 50 minutes to move an actuator this far using its normal settings. If the actuators had another mode for moving long distances quickly, we would have been able to converge on the final figure much quicker.

4. CONCLUSION

The experienced gained from working on this mirror has been used to benefit several areas of research at the Univ. of Arizona. The most noteworthy result has been the successful installation of the adaptive secondary mirror at the newly renovated Multiple Mirror Telescope (MMT) on Mt. Hopkins outside of Tucson, Arizona.

The MMT is the first large telescope in the world to incorporate an adaptive optics system directly into the secondary mirror.[5] The mirror is 64 cm in diameter, 2 mm thick, and it uses 336 actuators to affect the incident wavefront. This success of this project depended in part on the mirror handling and fabrication techniques gained while working on the 2-m prototype.

REFERENCES

1. H. M. Martin *et. al.*, "Optical fabrication of the mmt adaptive secondary mirror," in *Adaptive Optical Systems and Technology*, P. L. Wizinowich, ed., *Proc. SPIE* **4007**, 2000.
2. Steve Miller *et. al.*, "Fabrication of ultra thin mirrors for adaptive and space optics," in *Adpative Optics and Applications*, R. K. Tyson, ed., *Proc. SPIE* **3126**, 2000.

3. Jim Burge, Dave Baiocchi and Brian Cuerden, "Ultralightweight active mirror technology at the University of Arizona," in *Optomechanical Engineering 2000*, M. A. Kahan, ed., *Proc. SPIE* **4198**, 2000.
4. Jim Burge *et. al.*, "NGST mirror system demonstrator from the University of Arizona," in *Optical Manufacturing and Testing IV*, P. H. Stahl, ed., *Proc. SPIE* **4451**, 2001.
5. F. P. Wildi, G. Brusa, A. Riccardi, D. L. Miller, D. Fisher, M. Lloyd-Hart and H. M. Martin, "1st light of the 6.5m mmt adaptive optics system with deformable secondary," in *Adaptive Optical System Technologies II*, P. L. Wizinowich, ed., *Proc. SPIE* **4839**, 2002.