Demonstration of a 0.5-m ultralightweight mirror for use at geosynchronous orbit

Dave Baiocchi [a], J. H. Burge [a,b] and B. Cuerden [b]

[a] Optical Sciences Center/Univ. of Arizona
[b] Steward Observatory/Univ. of Arizona

ABSTRACT

Future space telescopes will require apertures that are larger than the current state of the art, yet fit within the exiting launch restrictions on size and mass. The mass can be reduced by using a thin flexible substrate for the optical surface and a rigid, lightweight frame with actuators for support. The accuracy of the optical surface is actively maintained by adjusting the actuators using feedback from wavefront measurements. We have designed, built and tested a 0.5-m demonstration mirror for use in geosynchronous Earth-imaging systems. The mirror has an areal density of 5 $\frac{\mathrm{kg}}{\mathrm{m}^2}$ and is the lightest mirror we have made using the thin substrate design. This paper discusses the design, fabrication and performance of the 0.5-m mirror.

Keywords: Space mirrors, lightweight mirrors, thin glass membranes, gossamer optics

1. INTRODUCTION

1.1. The University of Arizona lightweight mirror design

Conventional monolithic mirrors are made from stiff, glass blanks. These optics generally have an aspect ratio of 6 or 7 to 1 – their diameter is six times greater than their thickness. These mirrors are usually made from low expansion glass, with a honeycomb-like structure inbetween the face and backsheet. The optics are stiff enough to withstand the polishing loads, handling operations and final operating conditions. Conventional mirrors use the substrate both as a high-quality optical surface and as a stiff support. These mirrors maintain their figure at the expense of being very heavy.

Conventional mirrors are limited in meeting the requirements for large space optics. First, the launch vehicle limits the payload in two ways: the rocket shroud limits the payload's volume, and the rocket's thrust limits the payload's mass. The launch process is also very rigorous; the payload must survive the trip into space. Finally, space is very cold, and the mirror must withstand the temperature extremes. In short, space mirrors must be lightweight, stiff and durable.

The University of Arizona has developed a lightweight mirror design that satisfies the requirements for large space optics. The design is shown in Figure 1, and it contains three key components:

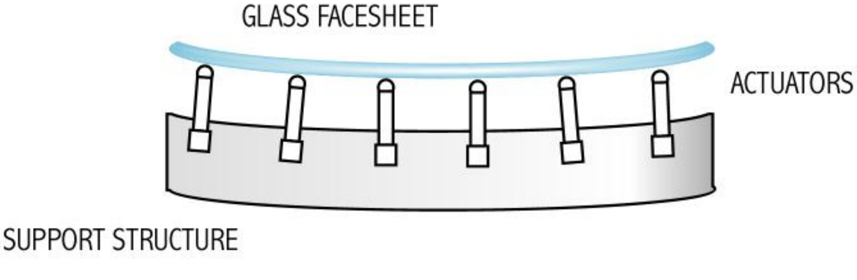

Figure 1. Active mirror design in use at the Univ. of Arizona. The optical surface is a thin, glass membrane. The actuators provide the surface accuracy, and a lightweight support structure provides the system stiffness.

Further author information:
Send correspondence to DB: baiocchi@optics.arizona.edu

Optical Manufacturing and Testing IV, H. Philip Stahl, Editor, Proceedings of SPIE Vol. 4451 (2001)

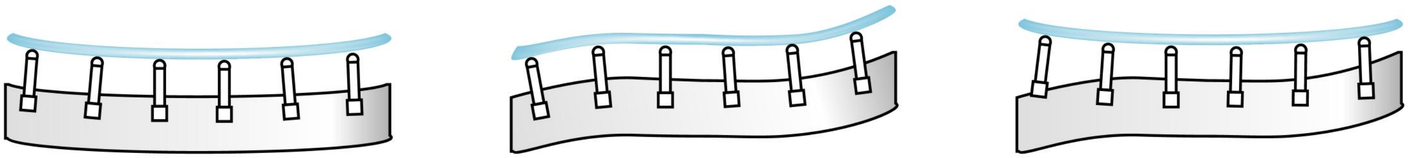

Figure 2. If the membrane deforms (middle), the actuators are driven to correct the figure (right).

- The optical surface is a thin, concave glass membrane. We use glass because it takes and holds an excellent polish. Also, we can fabricate glass into any shape with a minimal amount of internal stress. By using a glass with a low coefficient of thermal expansion (CTE), the figure will remain stable at the specified operating temperature.
- An array of actuators maintains the accuracy of the surface figure. Each actuator is remotely driven, and they do not require any current to maintain their positions.
- The stiffness is achieved with a lightweight, composite support structure.

The actuators are used to maintain the shape of the mirror, based on feedback from a wavefront sensor. This active control compensates for system instability, fabrication errors and deployment errors. The operation of our active mirror system is shown in Figure 2. The mirror exists in an initial state (left). If the support structure changes its shape, the glass will change, as well (middle). The actuators are adjusted to correct the figure (right).

1.2. Ultralightweight requirement for geosynchronous orbit

Geosynchronous orbit is an ideal location for an imaging system. A satellite in geo orbit will remain fixed over the same location as the Earth rotates. Geo orbit is much farther away than low-earth orbit. As a result, fewer satellites are necessary in order to image the entire planet. However, in order to provide the same imaging resolution as a low-earth orbit satellite, a telescope in geo orbit must be 100 times larger.

The immediate predecessor to this project is the 2 m Univ. of Arizona NGST* Mirror System Demonstrator (NMSD)[1,2] mirror, Figure 3. The mirror uses a 2 mm thick facesheet as the reflective surface. The composite support structure contains 166 actuators. The mirror is currently being assembled at the Optical Sciences Center. The completed NMSD mirror will have an areal density of 12.4 $\frac{\text{kg}}{\text{m}^2}$.

---

*Next Generation Space Telescope

Figure 3. The Univ. of Arizona NMSD facesheet.

We have determined that a successful geo telescope will possess an areal density of approximately 5 $\frac{\text{kg}}{\text{m}^2}$. Clearly, the NMSD mirror technology is not light enough for this project. However, the NMSD mirror served as an important starting point for our ultralightweight mirror.

This ultralightweight mirror starts with the same design philosophy as the NMSD mirror, but all of its parts have been miniaturized and aggressively lightweighted. Table 1 shows a comparison between the NMSD mirror and the ultralightweight mirror. This 0.5 m demonstration mirror represents the lightest (5.2 $\frac{\text{kg}}{\text{m}^2}$) mirror we have made using the Univ. of Arizona design.

	NMSD	NRO
Diameter of demonstration mirror	2 m	0.5 m
Glass thickness	2 mm	1 mm
Actuator mass	40 g	5 g
Reaction structure	3.2 $\frac{\text{kg}}{\text{m}^2}$	1.1 $\frac{\text{kg}}{\text{m}^2}$
Areal density	**12.4 $\frac{\text{kg}}{\text{m}^2}$**	**5.2 $\frac{\text{kg}}{\text{m}^2}$**

Table 1. Comparison of the NMSD and ultralightweight mirror.

2. MIRROR COMPONENTS

2.1. Lightweight support structure

The support structure is shown in Figure 4. It was designed at the Univ. of Arizona and fabricated at Composite Optics, Inc. (COI). The structure is made by sandwiching several layers of carbon fiber and epoxy together. Carbon fiber is an ideal material for this project: the resulting structure is extremely stiff and very lightweight. The facesheet and backsheet are both 0.015" thick; the webs are 0.010" thick. The entire structure has been aggressively lightweighted by cutting holes into the face/backsheets and ribs. The actuators are mounted in the 31 reinforced holes. The structure is concave such that the actuators are mounted normal to the glass. The completed shell is shown in Figure 5.

2.2. Actuators

The actuators are a miniaturized version of the NMSD actuators. A schematic of the actuators used for this project is shown in Figure 6. The actuators are an impact-driven model designed and built at the Univ. of Arizona. There are two advantages to using an impact-driven actuator. First, the design works at cryogenic temperatures. Also, the actuators are “set and forget”: they do not require a power source to maintain their position. This is an important requirement because space vehicles have limited power resources.

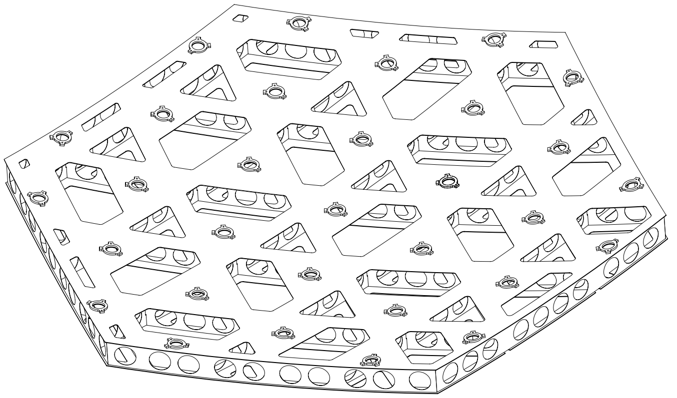

Figure 4. The support structure. It was designed at the Univ. of Arizona and fabricated at COI.

Figure 5. Paul Gohman holds the completed shell. The structure is 0.5 m in diameter (tip-to-tip) and 25 mm thick. The mass is 300 g.

The operation of the actuator is similar to whipping a tablecloth out from beneath a set of dishes. Both depend on overcoming the static friction within the system. Figure 6 shows the important components necessary for operation. There are two solenoids; one turns the actuator clockwise and the other turns the actuator counterclockwise. When a current pulse is sent to a solenoid, an impactor is accelerated into the nut. At the moment of sharp impact, the nut slips about the screw by one arcminute. The flexures then return the nut to the original position, and the screw remains advanced by one arcminute.

A picture of our 5 g actuator is shown in Figure 7. The average step size is 20 nm without any loading. Each step requires an average pulse amplitude of 700 mA for 1.5 ms.

2.3. Glass fabrication

Our glass fabrication process allows us to create a thin shell with an accurate figure using the existing tools in our shop. The fabrication process is illustrated in Figure 8. We started with a large blank of high-quality Zerodur glass (A). We generated and polished the optical (concave) surface using conventional tools and techniques. The remaining steps shown in Figure 8 are necessary for generating the glass down to its final thickness. We began by attaching the polished surface to a stiff, granite blocking body using pitch (B). The resulting piece was very stiff, and the excess glass was removed using a standard generating machine (C). We ground and polished the rear convex surface to eliminate any microscopic stress fractures caused by the generation process. Figure 9 shows the glass after optical figuring and before deblocking.

After we finished polishing the rear surface, we attached the loadspreaders to the convex side of the glass. A schematic and photo of the loadspreader are shown in Figure 10. The loadspreaders have three feet that are bonded to the glass with Dow Corning's Q3-6093 RTV adhesive. The feet are each connected to the triangular arm via a flexure. Initially, we were concerned that the feet would deform the glass at each attachment point. We developed a bonding

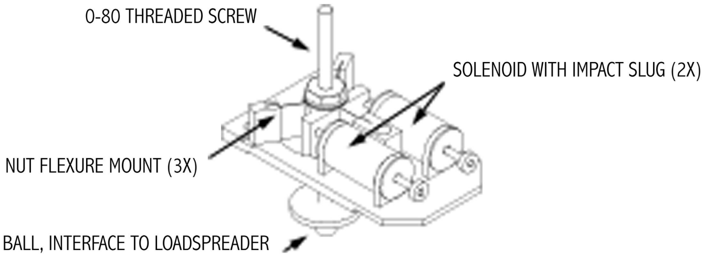

Figure 6. A schematic of the impact-driven actuator. These actuators are designed and built at the Univ. of Arizona.

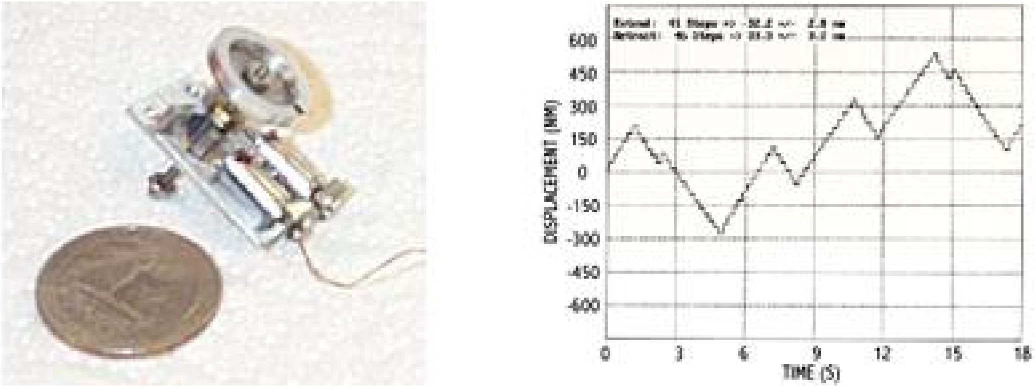

Figure 7. Left: An actuator. Right: Typical data. The horizontal axis represents time (sec), and the vertical axis shows displacement (nm). Because of the impactor mechanism, the actuator moves in discrete steps. The data shows that the performance is repeatable over the working range of the actuator.

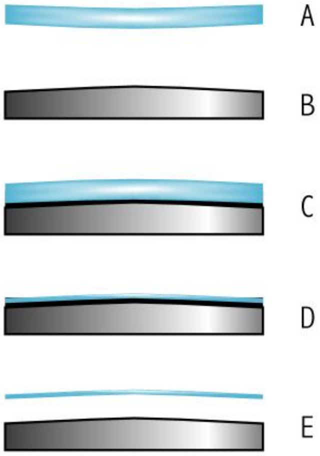

Figure 8. The glass fabrication process. A: The concave optical surface is figured while the mirror is still a thick, stiff blank. B: We create a stiff blocking body. C: The glass is attached to the blocking body using pitch. D: All of the excess glass is removed. E: The glass is removed from the blocking body.

Figure 9. Glass shell on blocking body. At this point, all of the glass figuring steps are complete. The next step is to attach the loadspreaders to the glass.

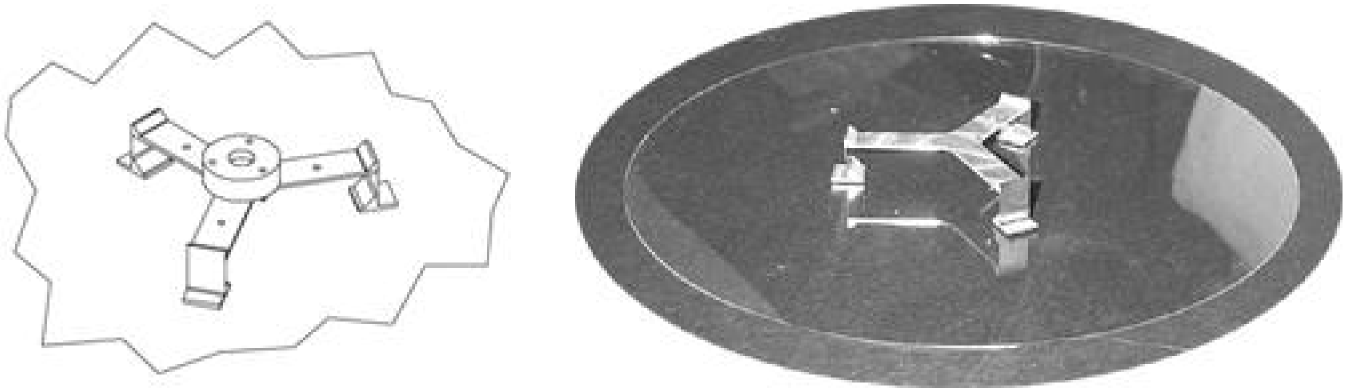

Figure 10. Schematic and photo of a loadspreader. Right: The sample loadspreader is attached to a test piece of glass.

Figure 11. This interferogram shows no visible distortion in the fringes around each foot.

technique that ensured a stress-free contact at each of the feet. An interferogram from one of our test coupons is shown in Figure 11. The loadspreader is attached to a sample piece of glass: the overall figure is not very good. However, there is no visible fringe distortion in the region around each foot.

Once the loadspreaders were bonded to the glass, we removed the glass from the blocking body. At 200 °C, pitch has the consistency of thick honey; we placed the part in a large oven at the Steward Mirror Lab. After sitting in the oven for 10 hours, we were able to slide the glass off the granite stone, Figure 12. The finished glass is shown in Figure 13.

Figure 12. Steve Miller removes the thin shell from the granite blocking body.

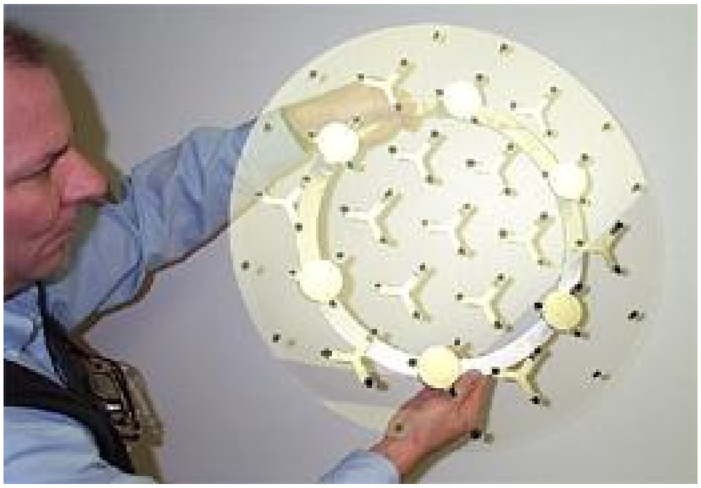

Figure 13. Finished glass, 0.5-m in diameter and 1 mm thick. The ring is just a handling fixture – it is not part of the finished mirror.

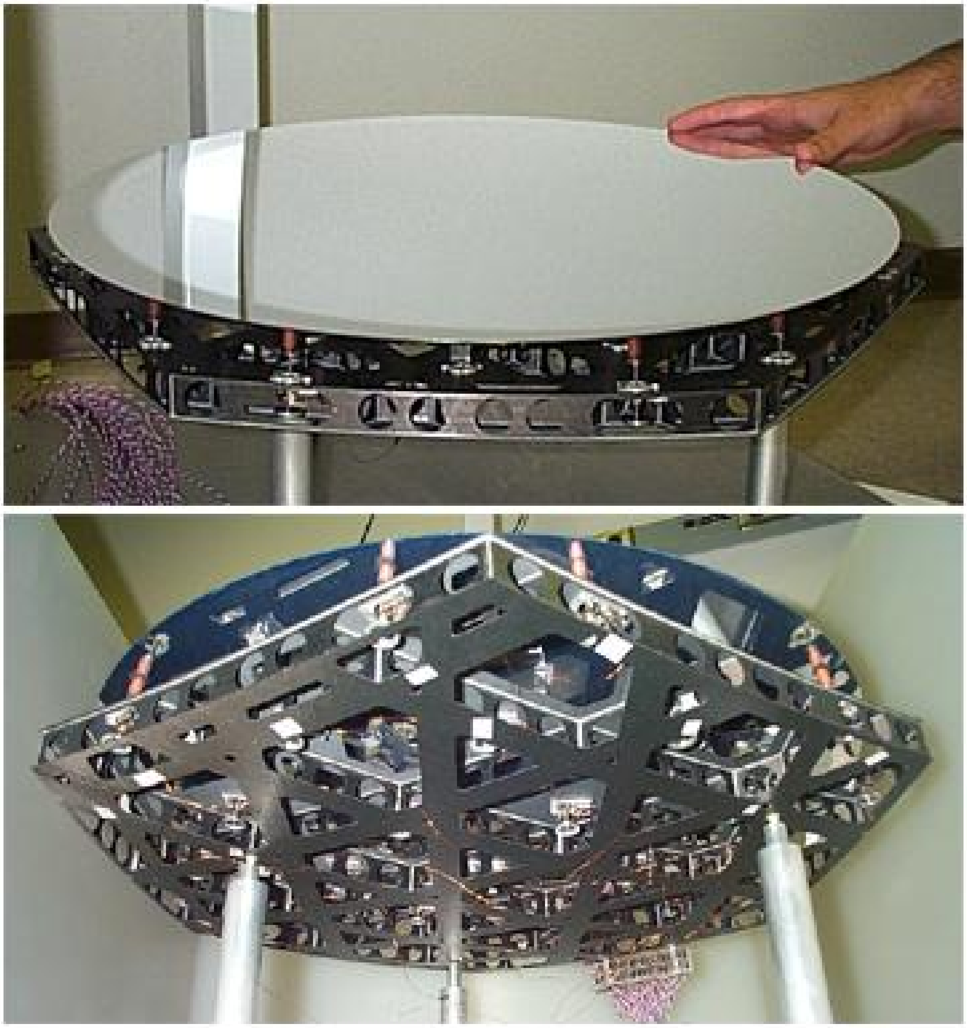

Figure 14. The completed mirror. The 0.5-m mirror has a total mass of 1.17 kg. The lower figure shows the three hardpoints used for supporting the mirror in a 1 g environment.

3. SYSTEM ASSEMBLY AND TESTING

The assembled mirror is shown in Figure 14. The mirror's mass is 1.17 kg; this includes the actuators, load spreaders, glass, reaction structure and all of the on-board wiring. The mirror was attached to a tilt/tip stand via the three hardpoints seen in Figure 14.

The mirror was tested from its center of curvature using a phase-shifting[3] Twyman-Green interferometer.[4] The actuators were controlled via a set of control electronics. The user adjusted the actuators using a simple Windows program running on a PC. Adjusting the mirrors's figure was an iterative process. We repeatedly took measurements and adjusted the actuators until we obtained the desired surface specification. Figure 15 shows the progression of interferograms during the actuation process. The final interferogram and surface map are shown in Figure 16. The surface quality is 0.248 wvs rms and 1.960 wvs P-V (HeNe).

The surface is limited by self-weight deflection – gravity causes the glass to sag about all of the support points. In the future, we plan to remove the gravity by inserting a computer generated hologram (CGH) into our optical test system. The CGH will contain the figure errors that result from a 1 g force applied to the mirror.

Figure 15. A progression of interferograms. Left: The initial measurement. Middle, Right: By manipulating the actuators, we can correct the figure. The middle figure shows 2 wvs surface rms, and the figure on the right shows 0.5 wvs surface rms (HeNe).

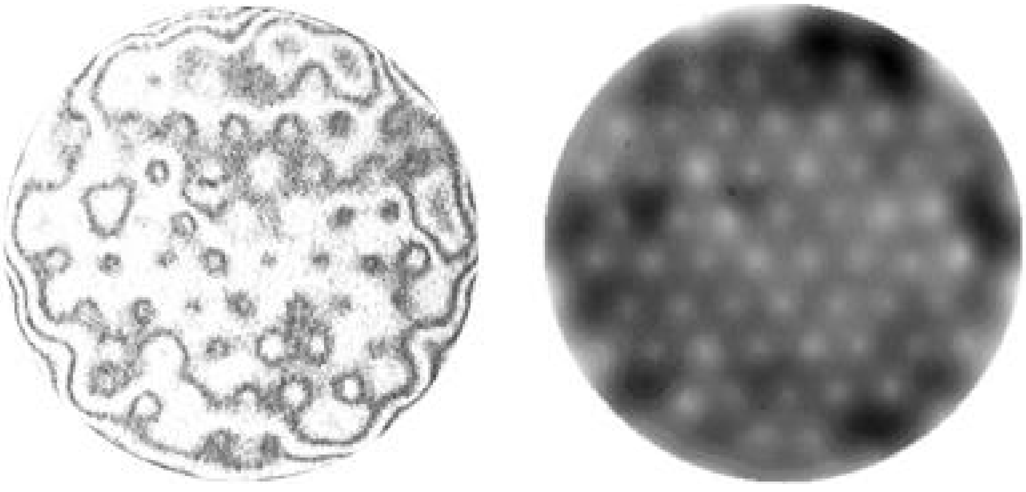

Figure 16. Final interferogram and surface map. The map represents a surface figure of 0.248 wvs rms (HeNe). The white areas are high and the dark areas are low.

4. CONCLUSION

This mirror represents an important milestone for the Univ. of Arizona active mirror design: we were able to achieve an areal density of 5 $\frac{\mathrm{kg}}{\mathrm{m}^2}$. In the future, we hope to build a 0.5-m flight-hardened version of this mirror to include on a future shuttle mission. A flight test will be an important part of our technology development. We will test the mirror's survivability, the transition from stowed to active mode, and the system performance in a zero gravity environment.

ACKNOWLEDGMENTS

A team of talented and diverse individuals are responsible for the success of this project. Brian Cuerden designed the support structure, load spreaders and actuators. Steve Miller oversaw the fabrication of the glass surface. Paul Gohman built and tested all of the actuators. Steve Bell designed and built the electronics for driving the actuators. Gil Rilvis wrote the actuator control software.

The University of Arizona gratefully acknowledges funding from the National Reconnaissance Office for work on this project.

REFERENCES

1. J. Burge, D. Baiocchi and B. Cuerden, "Ultralightweight active mirror technology at the University of Arizona," in *Optomechanical Engineering 2000*, M. A. Kahan, ed., *Proc. SPIE* **4198**, pp. 230–241, 2000.
2. J. H. Burge, B. Cuerden, S. Miller, R. C. Crawford, R. W. Wortley, D. G. Sandler, "Manufacture of a 2-m mirror with a membrane facesheet and active rigid support," in *Optical Manufacturing and Testing III*, H. P. Stahl, ed., *Proc. SPIE* **3782**, pp. 122–133, 1999.
3. J. E. Greivenkamp and J. H. Bruning, "Phase shifting interferometers," in *Optical Shop Testing, Second Ed.*, D. Malacara, ed., pp. 501–598, John Wiley & Sons, 1992.
4. C. Zhao and J. Burge, "Vibration-compensated interferometer for measuring cryogenic mirrors," in *Optical Manufacturing and Testing III*, H. P. Stahl, ed., *Proc. SPIE* **3782**, pp. 399–406, 1999.