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GLASS MEMBRANE MIRRORS BEYOND NGST

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Glass Membrane Mirrors beyond NGST

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Much of the technology and hardware are in place for manufacturing the primary mirror for the Next Generation Space Telescope as a glass membrane with active rigid support. We are now pursuing advances in this technology, beyond NGST, to provide mirrors that are lighter and less expensive. The evolution of the technology, going to thinner facesheets, more optimized structures, and lighter actuators, can extend the concept to mirrors with 5 kg/m^2 areal density, approximately 3 times more lightweight than for NGST.

The concept

We have developed a type of mirror that achieves high quality and low mass using a glass membrane as the optical surface, coupled to a stiff, lightweight support structure through an array of actuators. The optical quality of the system is maintained by an active system that uses periodic adjustment of the actuators based on wavefront measurements (as shown in Fig. 1). The actuators themselves are simple fine pitch screws that are driven in small steps using electromagnets. The backing structure, optimized for stiffness and mass, is made from thin sheets of carbon fiber reinforced plastic. Any instability of the backing structure will be compensated with the actuators. Glass is used for the membranes because it is extremely stable, can be made in large, highly homogenous pieces, and it takes an excellent polish.

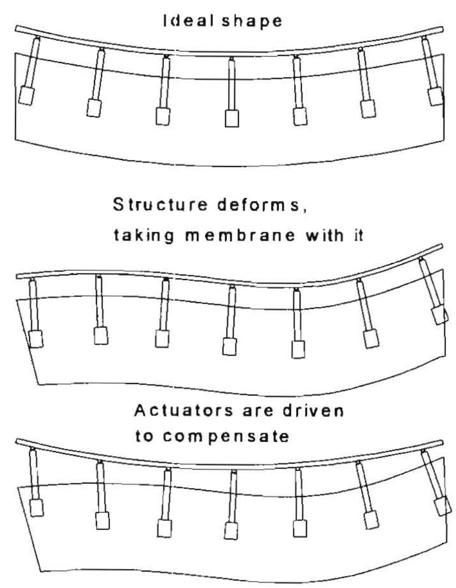

Figure 1. The mirror shape is maintained by making adjustments with actuators, based on wavefront measurements.

Implementation for NGST

The need for increasingly lightweight mirrors in space has led to an evolution of glass technologies. The Hubble Space Telescope used a primary mirror that achieved 180 kg/m^2 using a honeycomb construction. Further evolution of this method has made smaller mirrors as light as 30 kg/m^2. Also, large glass shells 2 cm thick (40 kg/m^2) have been developed for flyable laser projectors such as LAMP. These mirrors were stiff enough to allow support by traditional actuators that control the force applied to the glass.

For the still lighter mirrors, thinner glass shells are sufficiently flexible that the traditional flotation (force actuated) support is no longer desirable. However, as we have demonstrated, glass membranes as thin as 2 mm can be made into high quality mirrors, provided they are attached rigidly to a stiff back-up structure. This structure need not be stable to optical tolerance, provided the actuators can be adjusted to compensate for thermal or other deformations. The advantage of making a mirror in this way is that the attributes of a smooth, polishable surface and a rigid lightweight structure are separated. The choice of materials and structural designs for each can be separately optimized, and a great reduction in density obtained. We first demonstrated this concept with a 52-cm mirror with a 2-mm thick Zerodur and 36 actuators. This mirror system weighed 20 kg/m^2 in total, including the glass membrane, actuators and carbon fiber composite support. We are currently making a 2-m NGST Mirror System Demonstrator (NMSD) that weighs only 12 kg/m^2. Further refinement of the NMSD design can achieve optical quality performance with a mass density of only 5 kg/m^2.

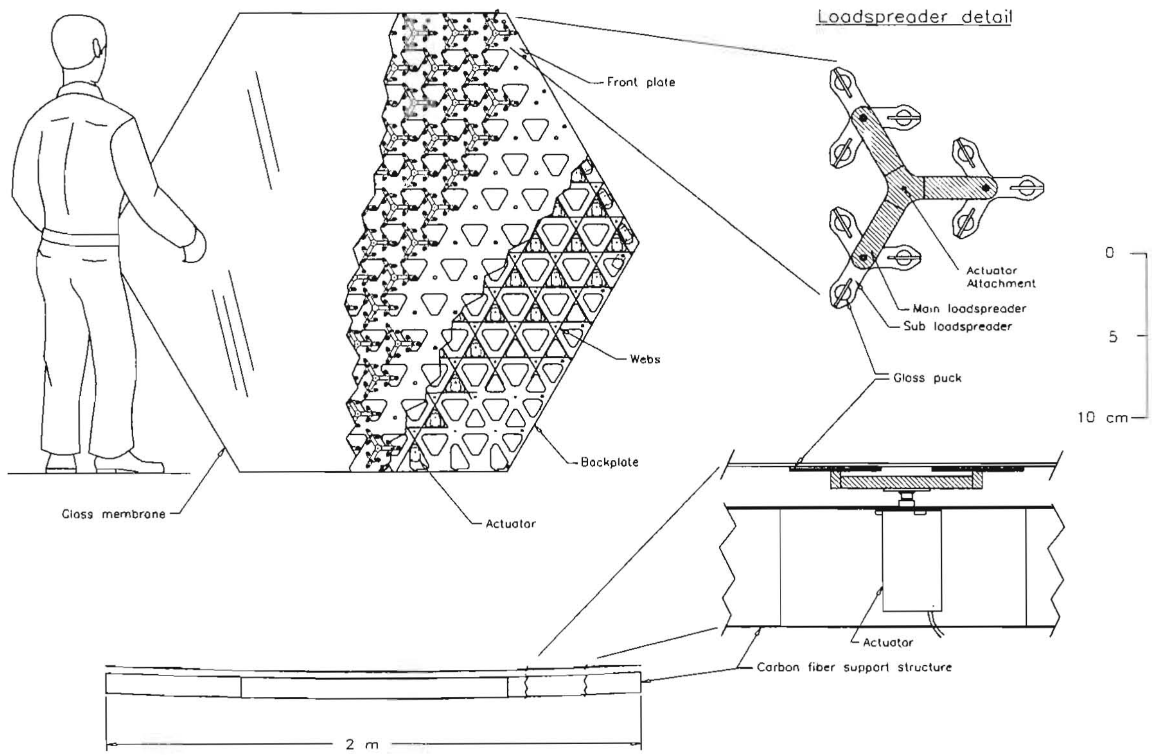

Figure 2. University of Arizona 2-m NGST Mirror System Demonstrator

The design and analysis of the 2-m NMSD form the basis for the 5 kg/m^2 design. This mirror, shown in Fig. 2, uses a borosilicate glass membrane (optimal for operation at 35 K), supported by 166 screw type actuators. The support structure was made by Composite Optics, Inc using laminate sheets of M55J carbon fiber/cyanate ester.

To manufacture glass membranes, we start with a relatively thick substrate, block it down, and thin and polish the membrane while it is blocked, as shown in Fig. 3. This allows us to work the optical surface of the membrane while it is rigidly supported, so we can use all of our polishing methods and equipment. The blocking is done using pitch to allow a low-stress bond. We perform the blocking by supporting the proto-membrane in a blocking oven, heat the system to about 100° C and slowly settle the membrane into the molten pitch. The final part is de-blocked by reversing this operation, with the membrane attached to a support fixture.

The performance expectations for the 2-m NMSD are high. Using the actuators to implement closed loop control of the mirror surface, we expect diffraction limited performance, even for visible wavelengths. Figure 4 shows the Strehl ratio calculated from a detailed model of the 2-m surface.

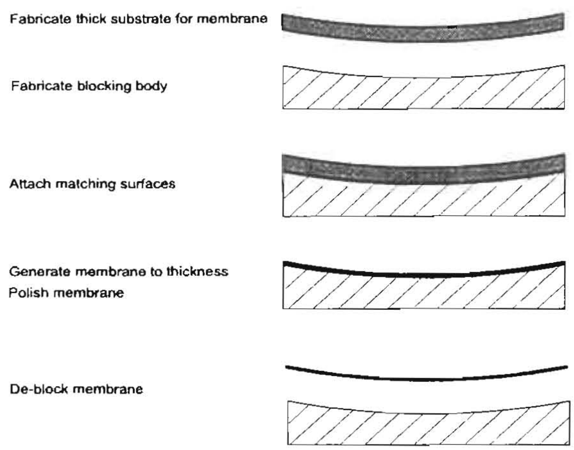

Figure 3. Membrane is carved out of a thicker glass substrate while held to a rigid blocking body with pitch.

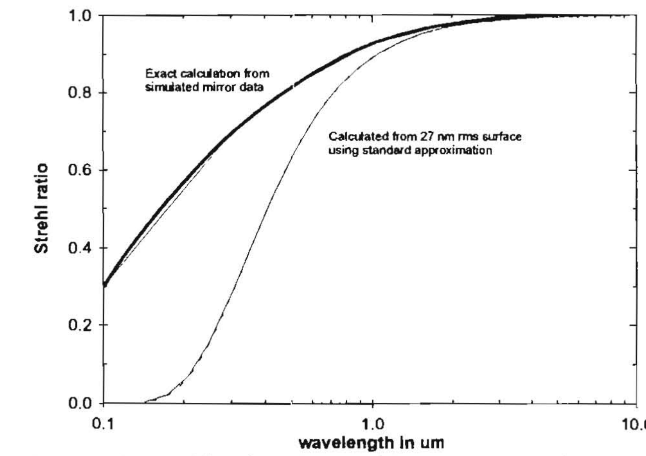

Figure 4. Strehl ratio calculated from simulated figure for the 2-m NMSD.

The next step beyond NGST

So far, our detailed mirror designs and optimizations have been based on NGST requirements, which are 15 kg/m^2 mass density, diffraction limited at 1 μm wavelengths, 35 K operating temperature, and launch in 2007. Since the current 12 kg/m^2 already exceeds NGST requirements, we have made no effort to decrease this ***for NGST***. It is imperative that NGST adopt a design and move forward aggressively to meet their schedule requirements. However, future missions could benefit from further refinement of this mirror design. For this reason, we have studied the next step that we can make to decrease the mass of our mirrors.

We believe that a flyable 5 kg/m^2 mirror can be made using existing technologies. Our strategy for taking this next step builds on the experience from the 2-m, 12 kg/m^2 mirror. We assume the same basic design, including actuator spacing, but we reduce the mass by making the following changes:

1. Decrease facesheet thickness from 2 to 1 mm
2. Reduce mass of glass attachment hardware by half
3. Reduce actuator mass significantly to 7 gm/actuator. (Electronics and cabling have not been reduced.)
4. Use highly optimized backing structure with mass ~ 1 kg/m^2

These steps, summarized in Table 1, were not made arbitrarily and we have good reason for believing that we can achieve such mass reduction. In most cases, we have already demonstrated improvement beyond that needed for the 5 kg/m^2 mirror.

Our design assumes a glass facesheet 1 mm thick. This is a modest change over the 2 mm thick membranes for the NMSD. However, we have already manufactured glass membranes as thin as 0.4 mm thick for high performance deformable mirrors. We have not made detailed designs for the hardware that is used to connect the actuators to the glass, but we can expect this to be at least 2 times lighter because it supports half the mass for the thinner membrane.

For the baseline design, we assume actuators of 7 grams. To verify the ability to make actuators this light, we built one and verified that it can make steps as small as 5 nm. This actuator and its much larger NMSD cousin are shown in Figure 5. These actuators, invented at the University of Arizona, use an impact driven nut to make small advancements of a fine pitch screw. By modifying the pulse width used for the impact, different step sizes can be made, as shown in Figure 6. For the 5 kg/m^2 mirror, the weight of the drive electronics and cabling are assumed to be the same as those for the NMSD.

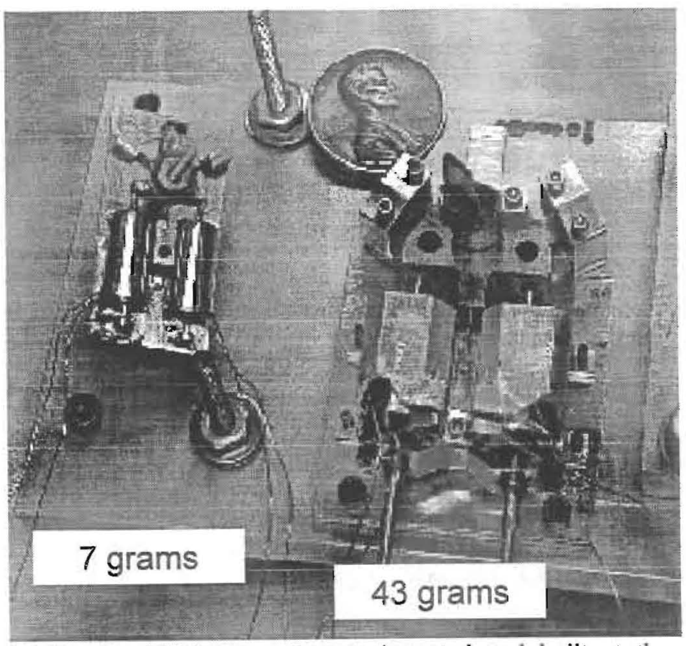

Figure 5. Miniature actuators invented and built at the University of Arizona.

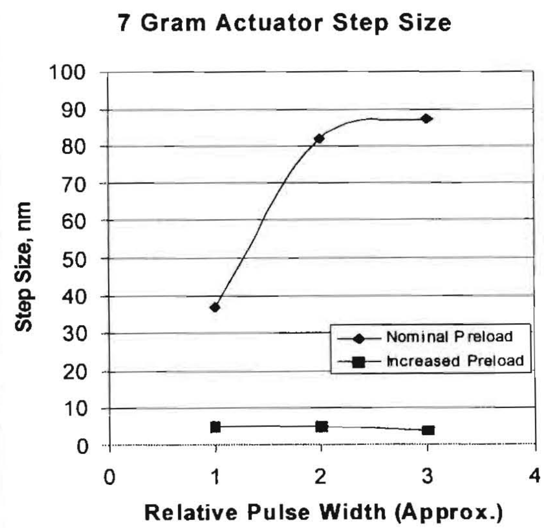

Figure 6. Measured step size for the 7 gram actuator.

We budget the support structure to have mass density of 1.1 kg/m^2. This is consistent with the state of the art for composite structures used as microwave reflectors. Composite Optics, Inc. has fabricated 1-m class structures with 0.56 kg/m^2 density, shown in Fig. 7. There is no doubt that the backing structure for our mirror can be made at 1.1 kg/m^2. The only open issue is the optimization, which depends critically on application and mounting requirements.

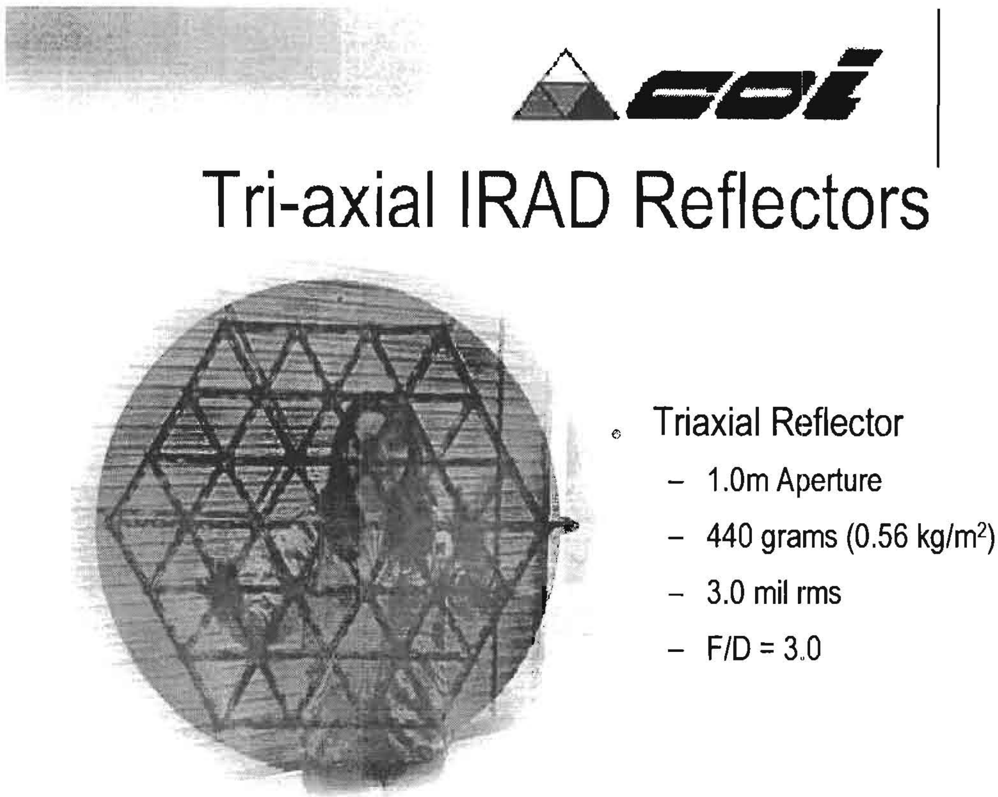

Figure 7. Lightweight reflectors built by COI demonstrate the technology for the backing structure. This mirror weighs 0.56 kg/m^2 including the mesh reflector surface.

In summary, we feel that all of the technologies are in place to build a mirror that matches the performance of our 2-m NMSD mirror, but with mass of 5 kg/m^2.

Table 1. Mass summary for 2-m NMSD currently being built and the proposed 5 kg/m^2 mirror.

	NMSD under construction (kg/m^2)	**Next generation mirror (kg/m^2)**
Glass membrane	4.4	2.2
Actuators, electronics, and cabling	2.5	0.5
Load spreaders	1.6	0.8
Attachments to membrane	0.4	0.2
Launch restraint hardware	0.3	0.16
Carbon fiber support structure	3.2	1.1
Total mass per square meter	**12.4**	**5.0**
Total mass for an 8-m mirror	**623 kg**	**250 kg**

Beyond the next step

The mirror described here achieves 5 kg/m^2 by applying existing technology to a fairly mature mirror design. This represents a natural evolution of today's advanced technology to serve the needs of tomorrow. But what about the day after tomorrow? It seems likely that this technology can be further refined for mass reductions by another factor of two or three. It is not clear, however, that further mass reductions make sense. The mirrors are made to be lightweight so they can be launched using moderately priced rockets and shrouds. At some point, the critical parameter for launch becomes volume, not mass. For example, a 30-m aperture could be made from 4-m segments, which fit inside existing launch vehicles. This mirror would require 60 of these segments, weighing 3500 kg. A single rocket could take the mass without difficulty, but this stack of segments is likely to be 10 meters tall, nearly filling the available volume.

Conclusion

We present a concept for lightweight mirrors that is evolutionary, not revolutionary. However, the advantages of this mirror must be considered:

- This mirror requires no new advances in materials or other technologies.
- We could build and fly one of these mirrors in as little as one year.
- Fabrication technologies and facilities exist to implement this design NOW for mirrors up to 8 meters across.