Active mirror technology for large space telescopes

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ABSTRACT

Future space telescopes rely on advances in technology to enable fabrication of primary mirrors with orders of magnitude more area, yet similar mass as current mirrors. This requires a shift of paradigm from the concept of the mirror as a rigid, stable unit, to the idea of the mirror as a system that uses active control to maintain the figure of a flexible surface. We discuss issues for this new class of optics and present status on a 2-m prototype mirror for NGST.

Keywords: space optics, lightweight mirrors, active optics

1. THE RIGID MIRROR PARADIGM

The conventional way of making high quality optics for ground and space-based telescopes relies on the mirror substrate to provide the rigidity and stability to maintain the mirror's shape over the operating environment and lifetime. This is typically accomplished by making the mirror out of a rigid glass blank that has low coefficient of thermal expansion (CTE). Glass is ideal because of its low CTE, incredible stability, and its ability to take a fine polish. The blanks are made thick enough that they are rigid to bending. (Bending stiffness goes as the 3rd power of thickness.) The mass of these stiff mirrors can be reduced by shaping the blank to optimize it for rigidity. A common geometry, used for 8.4-m diameter mirrors for the Large Binocular Telescope and the for the 2.4-m Hubble Space Telescope (both shown below) incorporates a monolithic glass structure with a facesheet and backsheet that are connected by ribs. This gives good stiffness to bending in the same way an I-beam does.
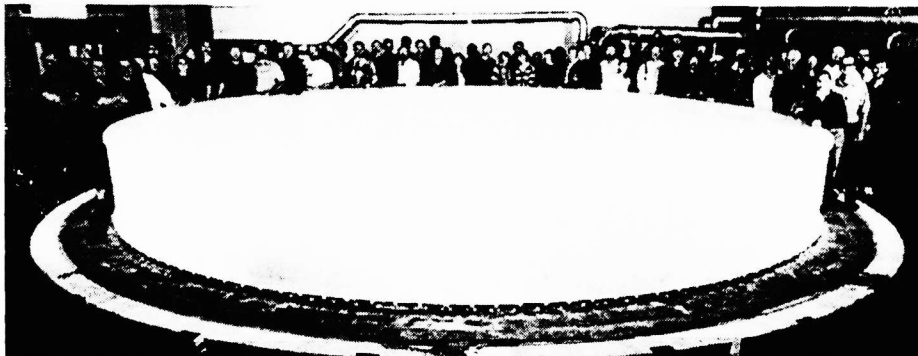

Figure 1. 8.4-m borosilicate glass mirror blank for the Large Binocular Telescope.
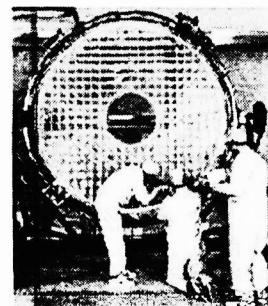

Figure 2. 2.4-m ULE glass blank for the Hubble Space Telescope.

Since the mirrors are stiff and stable, they will tend to hold their shape unless external forces are applied to distort them. So by limiting forces that act on the glass, the shape is maintained. Obviously, the stiffer the mirror, the less sensitive it is to inevitable, small force errors. This stiffness eases the requirements on the mirror support for polishing, testing, integration, and operation.

Stiff mirrors can be held using a force-type support, or one that controls the forces that are applied to the glass. This has the great advantage that it de-couples the mirror shape from deflections in the cell. If the cell moves, the actuators accommodate by changing their length, but maintain the applied force on the glass. So the mirror surface is not affected. All large ground based telescopes use this type of support.

The needs for ground based telescopes and space telescopes are of course different. Both types benefit from stiffness. Mirrors for space are driven to low-mass solutions to keep launch costs down. The mass for mirrors for ground based telescopes is much less important.

Due to the high launch costs, mirrors for space telescopes are highly optimized. The mass is minimized, while attempting to maintain stiffness. Mass of the mirrors is critical for space applications because it drives the mission cost. Stiffness for space telescopes is needed for two reasons – the mirror is made and tested in the presence of gravity so it must maintain its shape on the ground, and the dynamics of the pointing could potentially couple into the mirror.

Ground based telescopes see a different set of operating conditions. The mass of the mirror for ground based telescopes is less important by itself, but the mass must be limited to control the self-weight deflection and thermal inertia of the mirror. The mirrors for ground based telescopes obviously need to maintain their shape in the presence of gravity, even as the telescope changes its elevation angle. The effect of gravity is predictable and can be controlled using an open loop set of actuators. Wind loading, however, is random and must be controlled by the stiffness of the system. The mirrors for ground based telescopes must also maintain thermal equilibrium with the air around them to avoid "mirror seeing" or aberrations in the image due to motion of air with different temperature , this refractive index. This thermal equilibrium can be maintained using mirrors that have sections less than about 1 inch.

Actively controlled rigid mirrors use force actuators to control only the lowest few modes of the mirror. This is seen in the influence functions from force actuators in a 6.5-m honeycomb primary mirror.[1] It is apparent from the figure that the net effect of any single actuator is dominated by a few low order modes.
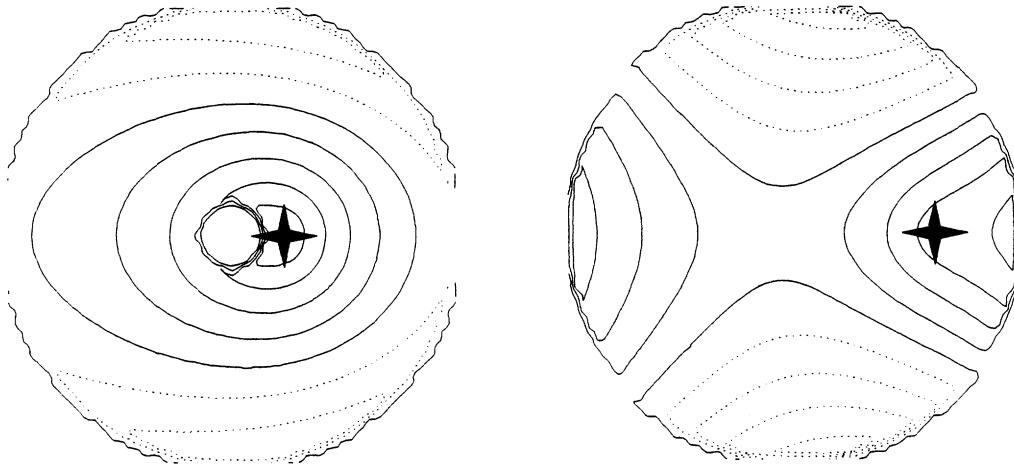

Figure 3. Shape change for a single actuator exerting 1 N of force on a 6.5-m honeycomb primary mirror from the University of Arizona. The surface contours are shown at 5 nm..

2. THE FLEXIBLE, ACTIVE MIRROR

The opposite extreme from thick rigid mirrors described above are optics that use very thin flexible shells or plates as the optical surface. These "rubber mirrors" are used as the active element for adaptive correction for the atmosphere.[2] Here the flexibility enables the mirror to be set to an arbitrary shape, by only controlling the actuators. The actuator spacing is driven by the needs of the application, and the facesheet thickness is selected to allow sufficient dynamic range with acceptable deflection from gravity.

These very thin mirrors use rigid *displacement-type* supports. The actuators are driven to a certain length, independent of the force applied to the glass. The thin glass has very little stiffness, so it takes the shape commanded by the actuators, rather than maintaining its own natural shape. This rigid coupling then means that any distortion in the backing structure holding the actuators will show up in the mirror surface. System performance is maintained by sensing the wavefront and applying a real time correction to the optical surface, via the actuators.

Unlike the rigid mirrors, the thin mirrors are controlled using the local influence from actuators, rather than the large scale bending modes. Figure 4 shows the influence of a single actuator for the 336-actuator adaptive secondary mirror for the MMT.[3] The effect of a pushing actuator is simply a bump at the location of the actuator, with a slight low ring around it. Most of the mirror's surface is not affected.

Figure 4. Shape change for a single actuator exerting pushing the 1.8-mm facesheet of the 64 cm adaptive secondary mirror for the 6.5-m MMT.

Mirrors for space applications can benefit from the use of this concept to reduce overall mass, yet maintain performance with the active system. We are now manufacturing a 2-m NGST mirror system demonstrator (NMSD) that will prove out this method for space optics. The NMSD achieves low mass with a 2-mm thick polished glass shell membrane, supported by 50 actuators per sq. meter. The glass provides an excellent optical surface and will maintain its shape over scales too small to be corrected by the actuators. The actuators are remotely driven fine pitch screws that achieve 6 nm rms resolution and require no power to hold their position. The support structure is made from paper-thin laminated sheets of composite carbon fiber.
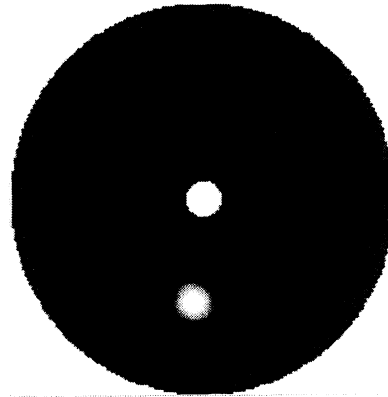

Ideal shape

Structure deforms, taking membrane with it

Actuators are driven to compensate

Polished glass shell
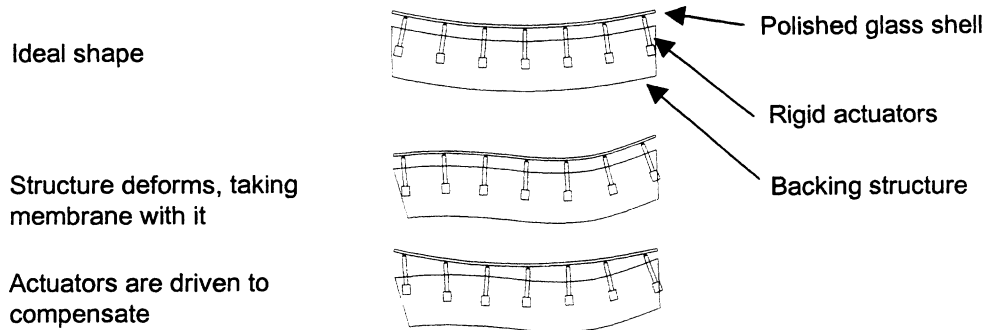
Rigid actuators

Backing structure

Figure 5. Use of position actuators to maintain the optical surface.

The actively controlled mirror has several important advantages over a fixed mirror. It eases requirements for thermal stability of the structure, which can be driven by large temperature changes or by thermal gradients.. It also accommodates changes in shape due to material instability over the life of the mirror. Also, the membrane does not have to be initially polished accurately on large scales because it can be deformed into shape.

The system is made to be fail-safe by including more actuators than are necessary. If an actuator fails, it can be disengaged and retracted from use. The loss of any one actuator, or even pairs of adjacent actuators, does

not significantly affect the mirror shape. Also, the actuators require no voltage or command to hold their positions, so if the carbon fiber structure is stable for weeks, then the surface shape will not need to be adjusted for weeks. When an adjustment is required, the error in the mirror can be measured using images from a bright star and applying phase retrieval algorithms.[4]

3. DESIGN AND OPTIMIZATION OF THIN FACESHEET, ACTIVE MIRRORS

To design a lightweight active mirror, we assume fixed mass budget and the we optimize for surface figure, high resonant frequencies, and launch survival by allocating this mass optimally to actuators, support structure, and membrane thickness. A basic tradeoff in the design involves the number of actuators. Ideally, the membrane will be perfectly manufactured and will require zero force to maintain its shape in space. In reality, the membrane will have strain due to the fabrication process and the variations of the material properties within the blank. These tend to warp the membrane and require corrective forces to maintain the correct shape of the membrane. The actuators apply this force at discrete locations and can cause ripple in the surface at the period of the actuators. This effect can be minimized by making the membrane thicker, thus stiffer to the local forces, or by increasing the number of actuators.

3.1 Optimization of facesheet support

The very thin facesheets have little tolerance for extraneous loading. The facesheet support must constrain the surface normal displacement without applying lateral forces or moments of any significance. Space based systems must also have a capability to withstand launch loads. For the very light mirrors we have chosen to utilize much the same load paths for launch restraints and operational supports. The weight of a structure strong enough for the launch restraint would be comparable to that of a structure stiff enough for the operational support. Our analysis of cryogenic designs based on a 2 mm glass facesheet have indicated that we need 450 support points, each no more than 6 mm in diameter to enable us to withstand 30 g quasi static loads with a factor of safety of 3. The 6 mm diameter limit is based on analysis of the effects of CTE mismatch between the facesheet and the bonded on buttons and the effects of the contraction of an 0.013 mm layer of PR-1564 adhesive. We require far fewer supports to maintain figure during operation, 50 actuators/m^2 coupled to the facesheet through a 3 point loadspreader would be adequate.

It was stated above that the facesheets have little tolerance for extraneous loading. What is required to provide surface normal restraint at 450 point/m^2 while limiting extraneous loads to acceptable levels? First we couple each loadspreader to its actuator through a magnetically preloaded ball bearing. This prevents lateral forces and moments from being applied to the loadspreader. The loadspreader assembly is described in detail below. It is attached to the facesheet by being loosely fitted over nine buttons bonded to the back of the facesheet. It is captured in this position by caps bonded onto the buttons. Compliant O-rings between the buttons and loadspreader transmit lateral launch loads but there is sufficient clearance to prevent anything more than incidental lateral contact during operation. Surface normal loads are transmitted by lightly preloading the loadspreader to each of the button caps. The preload must be about 25 grams and it is essential that the clamping force on the underside of the button cap be closely aligned with the reaction on the top of the cap.

This design meets the often conflicting requirements of cryogenic operation with excellent surface figure while providing a stiff constraint to surface normal motion and adequate strength to withstand launch loads. Lateral positioning during operation must be provided by a separate system of three tangent rods coupling the facesheet to the cell. This system must include a breakaway mechanism and auxiliary actuators to prevent overstress during launch and excessive distortion during maneuvering accelerations during operation.
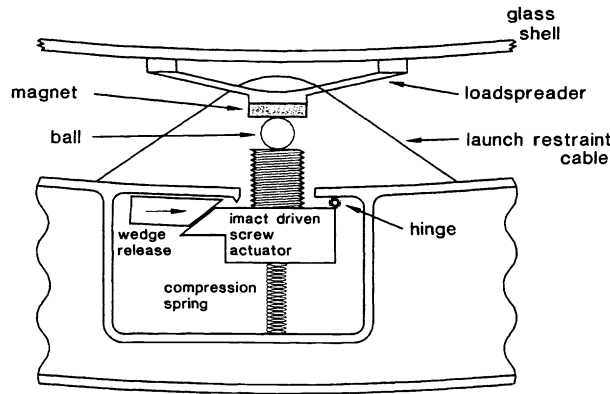
Figure 6. Conceptual design of actuator coupling to the glass. In operation, the actuators are adjusted in length to control the surface figure. The launch loads are taken by cables. There exists a separate mechanism to retract any actuators that fail.

3.2 Optimization of loadspreaders for the 2-m NMSD

Our system design uses load spreaders to distribute the load from each actuator to 9 points on the glass. This is driven by the requirement to minimize the stress concentrations at the glass attachment point during launch. The load spreaders also distribute the actuator forces to minimize the effect of the actuators on the optical figure. The glass attachment is difficult because this system must support high loads during launch and it must provide almost no load when it is operational at 35K. A diagram of the load spreader attachment is shown below in Fig. 7. We bond small glass pucks to the membrane surface to allow a rigid attachment and to minimize stress when the part is cooled.
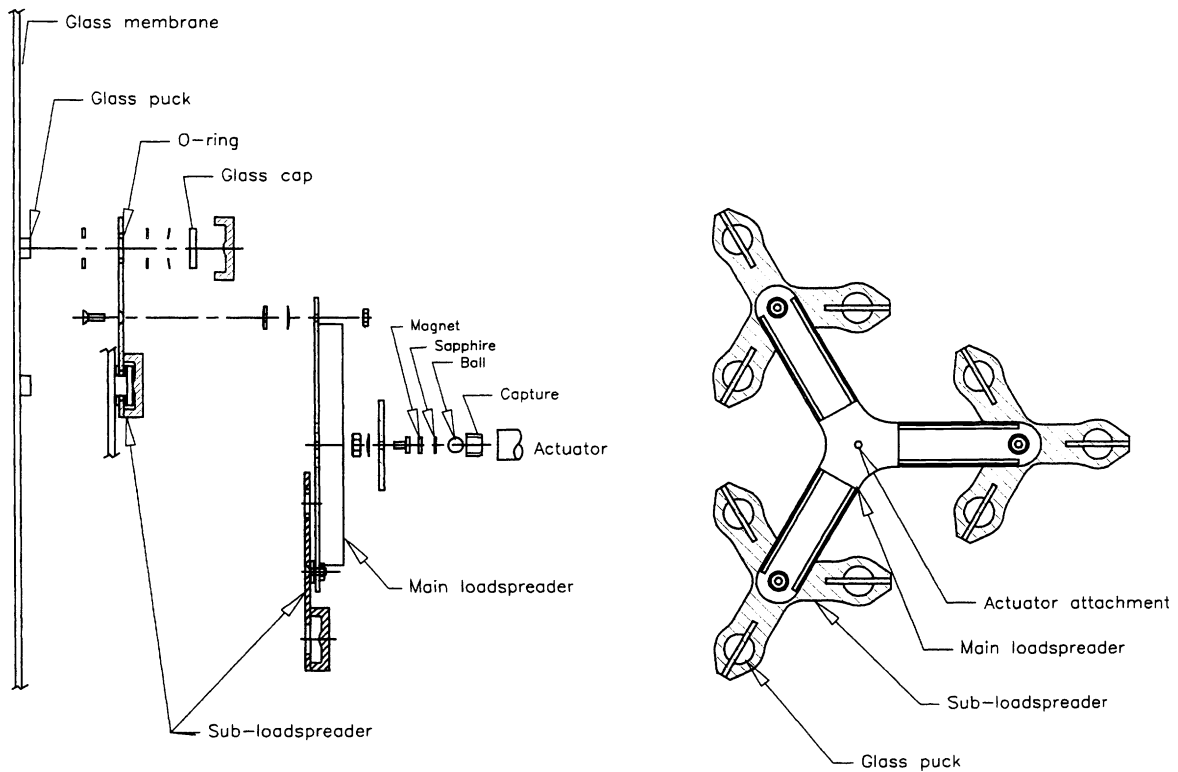

Figure 7. Exploded side view and assembly drawing showing the 9-point load spreaders and their attachment to the glass membrane.

644

A loadspreader assembly couples nine points on the facesheet to a single actuator. It consists of a main loadspreader that couples the actuator to three sub-loadspreaders. As noted above, the actuator to loadspreader interface is designed to transmit only surface normal forces, consisting of a magnetically preloaded ball bearing. The preload level ensures that adequate tensile forces can be transmitted to the facesheet but prevents the accumulation of tensile forces from becoming dangerous (if all the actuators but one pull back, the facesheet still cannot be damaged). For launch, the loadspreader is further restrained by extending the actuator until three cables (per actuator) are brought to full extension. This disables the tension breakaway and enable the transfer of lateral loads (through the cables) making the assembly capable of withstanding launch loads.

The connection between the main and sub-loadspreaders is a simple spherical joint. Frictional moments must be low across this joint and surface normal stiffness must be high. These requirements are satisfied by a lightly preloaded, dry lubed joint. The sub-loadspreaders themselves are complicated only by the demands for stiffness and the need to avoid applying moments at the button/cap interface to the facesheet. The moment is minimized by providing a sort of bridge piece that loops over the button cap and bears down against the middle of the cap. A curved spring washer on the underside of the cap pushes the loadspreader toward the facesheet. The resolved forces on both sides of the button cap are well centered. The bridge piece always bears against the middle of the cap, and the curved spring washer has a very low moment stiffness that keeps any applied moment low.

Subsequent loadspreader designs are further optimizing the stiffness of this assembly at the expense of complexity. The stiffness gains are being obtained by changing from rectangular and T sections to I section in both sub and main loadspreaders. Soon to be considered are modifications to the glass interface pattern from a uniform pattern to one formed by truncated loadspreader assemblies.

3.3 Optimization of Reaction Structure

The reaction structure is a low thermal strain, lightweight, graphite reinforced composite assembly. Obtaining adequate stiffness and strength from this assembly using technology provided by Composite Optics has proven to be straight-forward. There is considerable latitude in selecting the thermal strain characteristics of the reaction structure. We select low CTE at the intended operating temperature. The actuators can accommodate any distortion of the cell so the only effect of concern is cell distortion between mirror face-sheet correction cycles. The thermal inertia of the reaction structure is very low, a direct result of hyper-aggressive lightweighting, so small heat inputs can induce optically significant distortion. Due to the rigid connection between the reaction structure and the face-sheet when the actuators are locked (the actuators are self locking, requiring no holding power) the facesheet distortion change almost exactly matches the reaction structure distortion change since the last correction cycle. There are therefore obvious benefits to having a reaction structure that is well insulated from external heat loads, is not burdened by internal heat loads, and has the lowest possible CTE at its operational temperature.
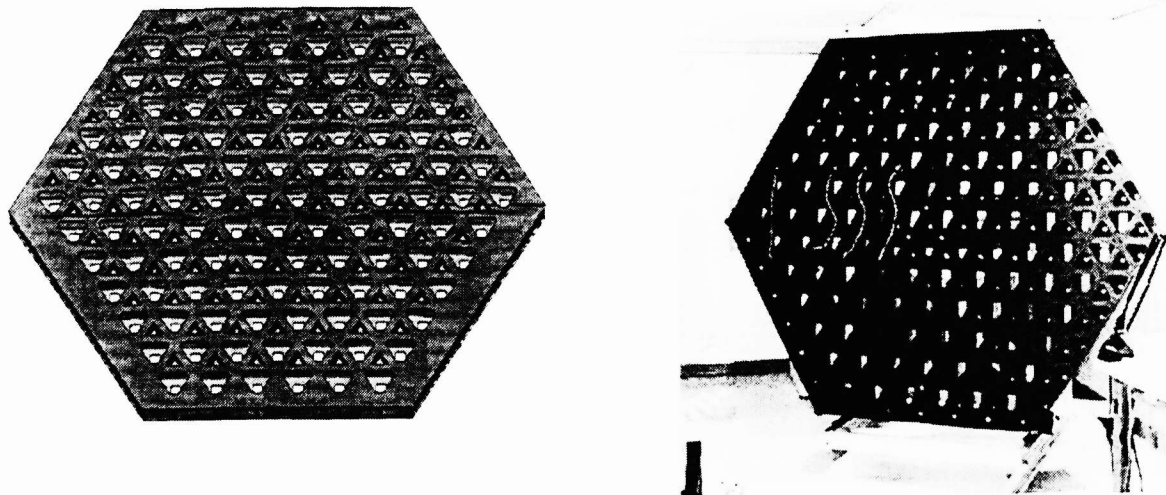

Figure 8. 2-m composite support structure for NMSD

4. FABRICATION OF 2-M NMSD

We are currently manufacturing the 2-m NGST mirror system demonstrator, shown below. The 2-mm glass shell is made of borosilicate glass because this material has zero CTE at the 35 K operating temperature. The backing structure was made by Composite Optics, Inc. The actuators are being manufactured at the University of Arizona. This mirror is expected to achieve < 30 nm rms performance at 35 K and the total mass of the 2 meter mirror, including glass, composite, actuators, and cabling is only 40 kg.
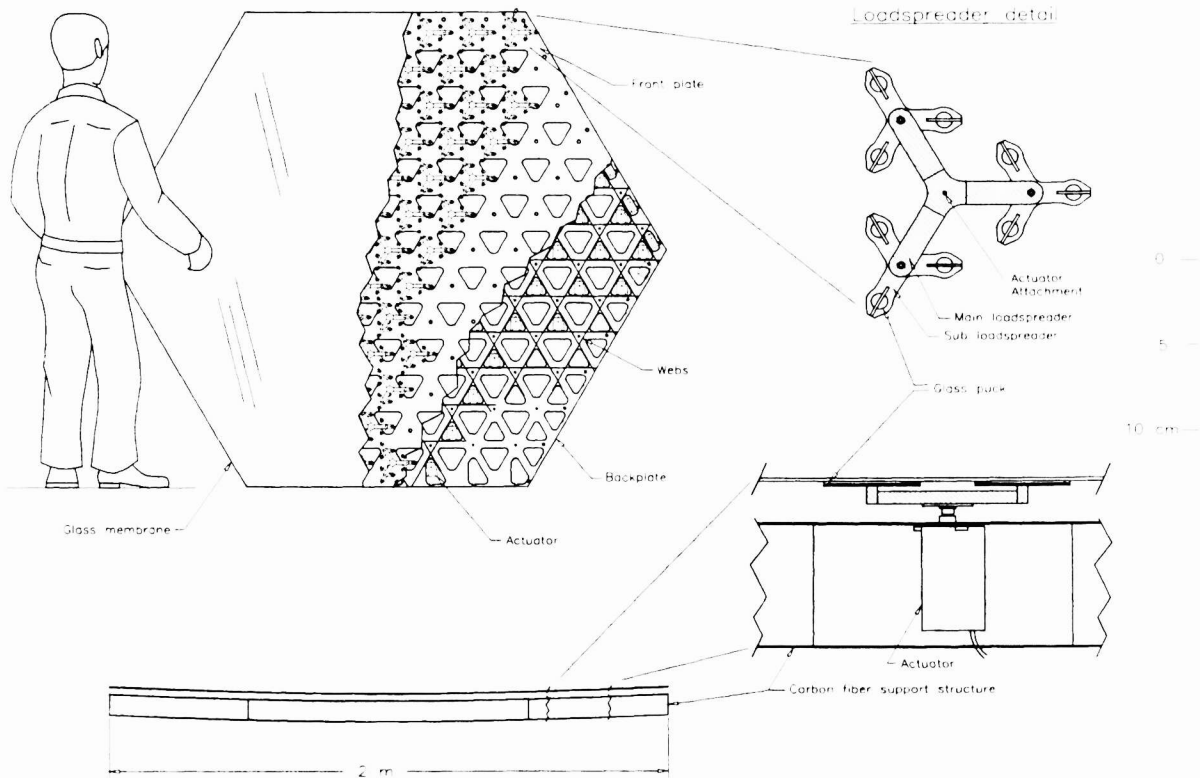

Figure 9. 2-meter NGST Mirror System Demonstrator.

We are making a second glass shell for this mirror. The manufacture of the first shell, described previously, suffered flaws in the initial casting that caused it to fail in subsequent operations. The basic manufacturing steps for the NMSD glass are shown below. We cast the blank from Ohara's E6 borosilicate glass using the 8-m rotating furnace at the Mirror Lab. This casting achieves high homogeneity because it starts from a complete block of select glass which was made in a single pot. It was then melted and flowed out to a 2.2-m blank.

Figure 10. Manufacture of the E6 blank for the NMSD shell, including mold construction, preparation to flow out glass, and final substrate.

Block to rigid
substrate

Generate to 3 mm,
grind and polish
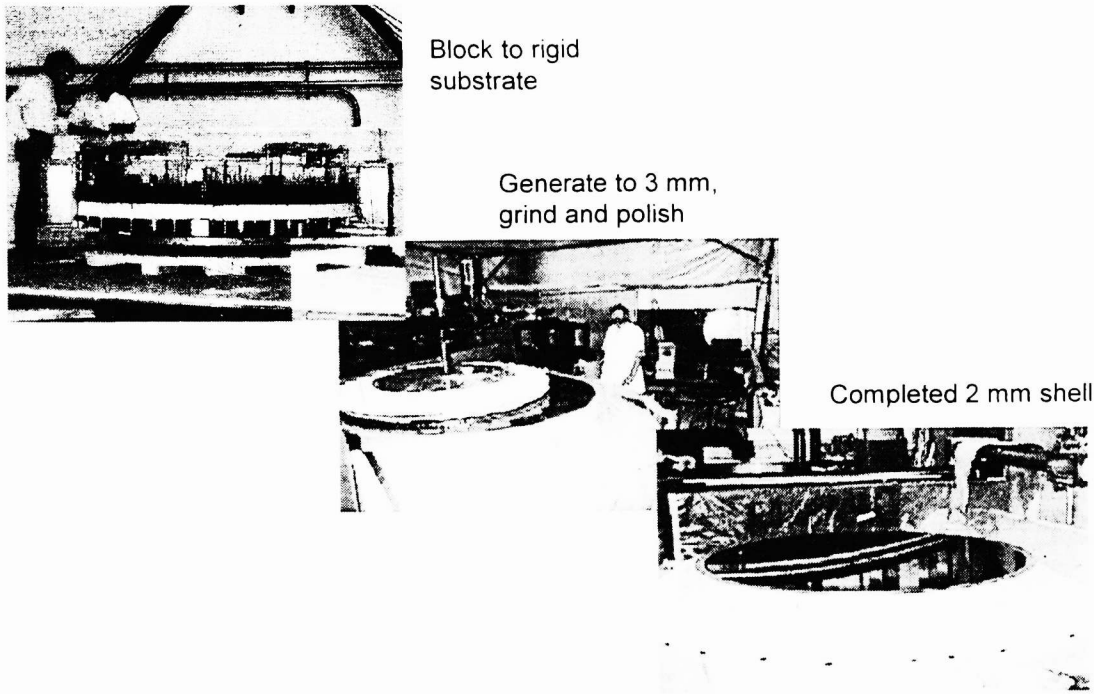
Completed 2 mm shell

Figure 11. Completion of the 2-m diameter glass shell for the NGST Mirror System Demonstrator.

We are now preparing to remove the finished shell from its blocking body. This will be done by immersing the glass in oil and heating to 120 C. The pitch holding the shell down will melt, allowing the shell itself to be floated of the blocking body using hydrostatic forces.

The actuators and control electronics for NMSD are now being manufactured at the University of Arizona. The actuators have demonstrated repeatable performance at ambient and cryogenic temperatures. The actuator, and some data at 35K are shown below. The electronics are being built at the University of Arizona to enable robust operation of the actuators at both ambient and cryogenic temperatures.
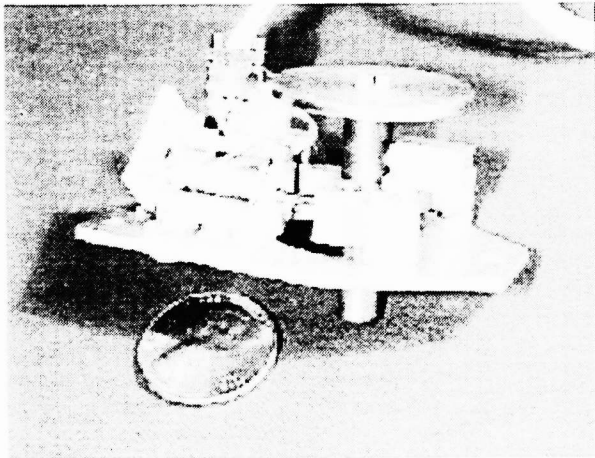

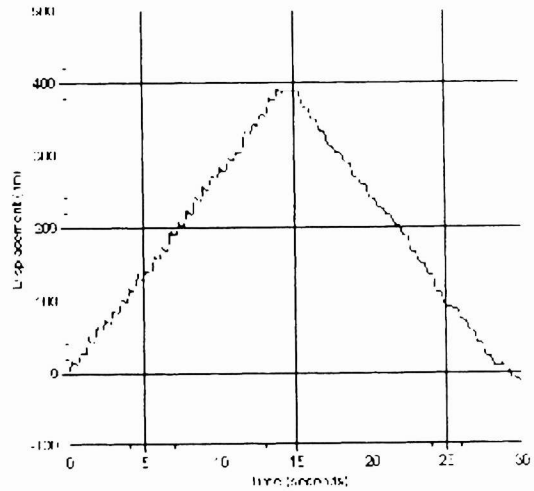
Figure 12. University of Arizona NMSD actuator

Figure 13. Measured actuator performance at 35K.

5. ACTIVE MIRRORS BEYOND NGST

The concepts presented here are not limited to cryogenic mirrors or mirrors with mass density > 10 kg/m^2 . We have designed and optimized a mirror for low earth orbit that can meet the dynamic and thermal requirements for Space Based Laser.[6] In addition, a mirror with 5 kg/m2 is now being manufactured at the University of Arizona.[7] This mirror uses 7 gram actuators and 1-mm thick glass, both developed at the University of Arizona. An ultralightweigh support structure is being built by Composite Optics, Inc. This advanced prototype will be tested at ambient temperatures in late 2000.

ACKNOWLEDGMENTS

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