Lightweight mirror technology using a thin facesheet with active rigid support

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ABSTRACT

The next generation of space telescopes will require primary mirrors that push beyond the current state of technology for mirror fabrication. These mirrors are large, up to 8 meters in diameter, have low mass per unit area, less than 15 kg/m^2 and must maintain diffraction limited performance at cryogenic temperatures. To meet these requirements, we have developed an active mirror that has a thin membrane as the optical surface, which is attached to a stiff lightweight support structure through a set of screw-type actuators. This system allows periodic adjustments with the actuators to maintain the surface figure as measured from star light. The optical surface accuracy and stability are maintained by the active system, so the support structure does not have to be optically stable and can be made using light weight carbon fiber laminates to economically provide stiffness. The key technologies for implementing this technology are now in place. We have performed two critical demonstrations using 2-mm glass membranes – diffraction limited optical performance of a 0.5-m diameter mirror and launch survival of a 1-m diameter mirror. We have also built and tested a prototype actuator that achieves 25 nm resolution at cryogenic temperatures. We are now building a 2-m mirror as a prototype for the Next Generation Space Telescope. This mirror will have mass of only 40 kg, including support structure, actuators, and control electronics. It will be actively controlled and interferometrically measured at 35 K.

Keywords: space optics, lightweight mirrors, active optics

1. INTRODUCTION

After years of successful operation of the Hubble Space Telescope (HST), NASA is now looking to a new type of observatory called the Next Generation Space Telescope (NGST).[1] This telescope will go in solar orbit and operate at cryogenic temperatures for near infrared performance, and it will be much larger than HST. Current designs call for an 8-m primary mirror that weighs less than 750 kg and must maintain diffraction limited performance over years of operation. Achieving such performance and low mass requires a new type of thinking about optical mirrors. Traditionally, large mirrors are made by polishing an accurate surface onto a glass substrate that is large enough to be rigid and stable on its own. Glass is used because of its stability and its ability to take an excellent polish and the mirror blanks are typically made to be thick, although often lightweighted, to achieve high specific stiffness. Other materials have not been demonstrated beyond 1 meter that can maintain optical tolerances over long times and large temperature changes. It would be extremely difficult to make all-glass mirrors several meters across with mass/area < 15 kg/m^2. This density corresponds to less than 7 mm thickness for a solid glass mirror. The fabrication of structured mirrors that use this small amount of glass, but are thick enough to provide rigidity, is prohibitive with current technologies.

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Table 1. Comparison of mirrors requirements of NGST with those from HST.

	HST	**NGST**
Collecting area	4.5 m^2	25-40 m^2
Mass	800 kg	600 kg
Mass/area	180 kg/m^2	15 kg/m^2
Operating temperature	293K	40 K
Focal ratio	$f/2.4$	$f/1.2$

We present a solution that uses closed-loop control of the surface based on wavefront measurements to maintain the optical figure and uses materials and fabrication technologies that are optimized for weight, stiffness, and economics.

2. DESIGN CONCEPT

For a telescope that is much larger and lighter than the HST and must produce excellent images while at cryogenic temperatures and out of thermal equilibrium, a new concept is needed. The HST solution was a mirror made as a thick, rigid, monolithic glass honeycomb sandwich, of glass with near zero coefficient of thermal expansion (CTE) at room temperature. The faceplate was thick enough and the honeycomb cells small enough so polishing forces did not deform the surface, and thermal distortion was avoided by operating the mirror at the fabrication temperature (~293K). The much lighter NGST mirror with inevitably thin sections is much more subject to deformation under gravity and stray forces, deformation under the polishing tool, deformation when cooled 250° C to the operating temperature because of CTE variations, and deformation because of large temperature gradients at the operating temperature.

Our approach to overcome these problems involves:

1. Making the mirror surface as a membrane of glass with the highest CTE uniformity and zero CTE at the cryogenic operating temperature.
2. Optical fabrication of the membrane in one piece while it is rigidly and uniformly supported in a condition of zero internal stress. Then aspheric figuring by methods already proven for large rigid monoliths is used, to produce a membrane whose natural shape in zero gravity and at low temperature is unchanged from the original figure.
3. To correct residual errors, and to raise the resonant frequency, the membrane is linked by position actuators to a rigid ultra-lightweight structure.
4. The actuators are adjusted to preserve the wavefront quality, as measured using star light, in the presence of deformation or creep in the support structure. The concept of using actuators to compensate for the motion of the support structure is shown below in Figure 1.

Our implementation of these concepts, optimized for NGST, uses a 2-mm thick glass membrane, supported with 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 will be made from paper-thin laminated sheets of composite carbon fiber, similar to ultra-lightweight microwave reflectors with mass density < 5 kg/m^2 that are regularly put into space.[2] These structures achieve excellent stiffness for their weight and they are proven to be stable over short time scales (days to months), minimizing the number of times that mirror shape needs to be re-adjusted.

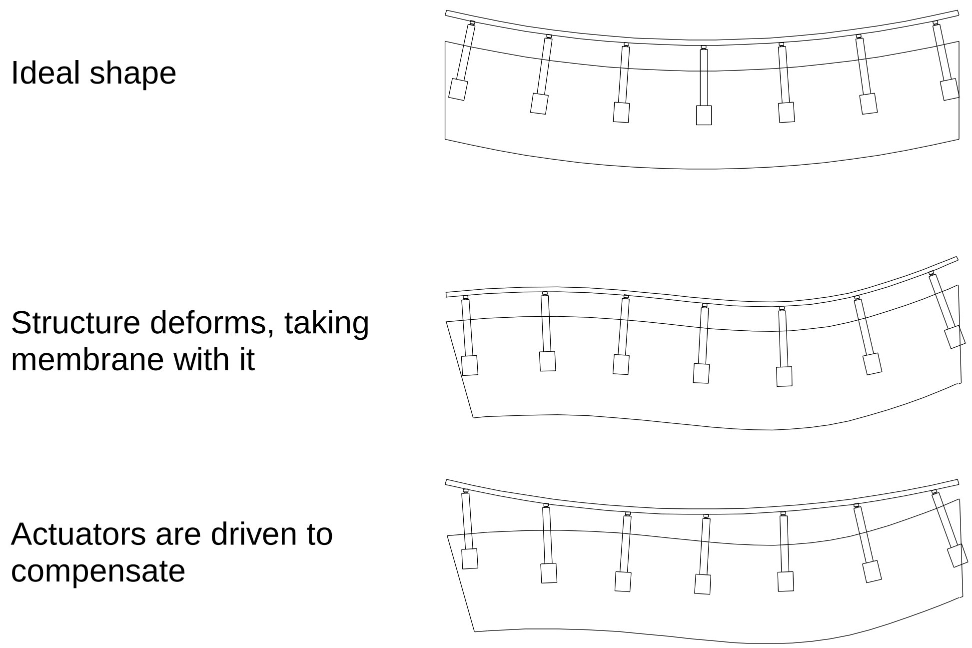


Figure 1. Use of position actuators to maintain the optical surface.

The actively controlled mirror has several important advantages over a fixed mirror. It eases requirements for thermal stability of the structure while the temperature drops hundreds of degrees and may have variations across the mirror of tens of degrees. It also accommodates changes in shape due to material instability over the life of the observatory. The membrane does not have to be made 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. (This technique is now quite common and it was used to measure the error in the Hubble Space Telescope primary.) Actuator commands are calculated and the mirror is automatically adjusted. The hardware requirements are minimal. The wavefront measurements need no additional imaging array. The calculation of phase and actuator commands can be done by an on-board computer, or the data can be transmitted to the ground for this computation.

The technology that makes this concept feasible is the fabrication of the 2-mm thick glass membrane. At the University of Arizona, we have already developed a method of making these membranes as part of a program funded by the Air Force Office of Scientific Research.[3] We use membrane mirrors with a high density of fast actuators for compensating the atmospheric turbulence that limits ground-based telescopes. We are now fabricating a 64-cm adaptive secondary mirror for the MMT that uses a 2-mm facesheet supported by 330 actuators driven at 1 kHz.[4]

Our fabrication method is designed to take advantage of the stressed lap method already proven in the figuring of large aspheric mirrors. It calls for the membrane to be “carved out” from a relatively thick disc of glass of known high quality. We start with two thick disks; one will become the membrane and the other for the stiff blocking body to which the membrane is attached during fabrication. A spherical convex surface that will become the back of the membrane is first ground and polished. The second thick substrate is prepared as a rigid blocking body, with an accurately matching concave surface. The two pieces are then warmed and bonded together with a thin layer of pitch, an ideal adhesive for this purpose because it has the stiffness required for polishing, but it relaxes during the blocking operation to provide a low-stress bond. Once rigidly attached, the upper disk is machined away, down to the desired curvature and near final thickness, then ground, polished and figured. On completion of figuring, the assembly is warmed to melt the pitch, and the membrane is released by sliding off the substrate. In this way, the manufacturing process is reduced to the well-understood process of figuring a rigid mirror, and the techniques already proven for 6.5-m diameter mirrors at the University of Arizona are directly applicable.

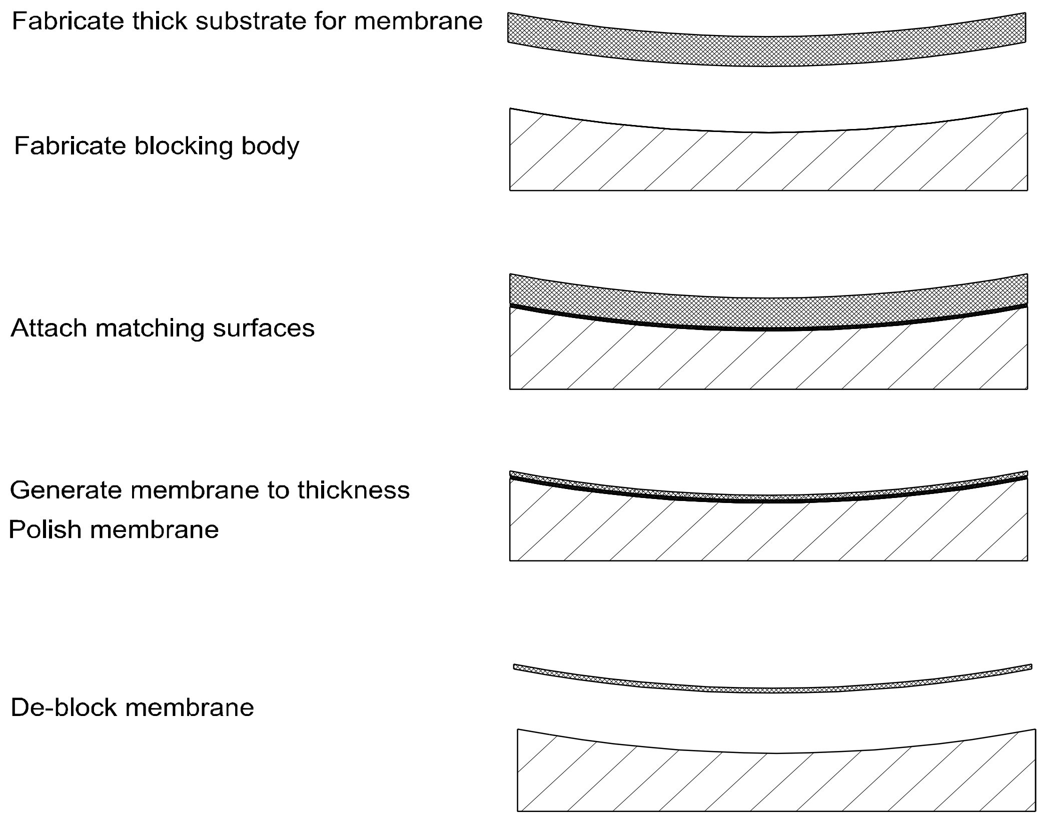


Figure 2. Concept for fabricating thin glass membranes.

3. DEMONSTRATIONS OF TECHNOLOGY

We have made the critical technology demonstrations that prove this method to work. We manufactured a 53-cm prototype mirror and verified the performance using interferometry. We made a 1-m launch test to verify that the acoustic loading will not damage the mirror. We have demonstrated an actuator that achieves 25 nm resolution at cryogenic temperatures. We have also demonstrated wavefront sensing and mirror control technologies that can be implemented to provide the closed loop control.

3.1 Fabrication of a 53-cm mirror

As part of a study for NGST led by Lockheed Martin, we built a 53-cm prototype mirror shown below.[5] The glass membrane fabrication and system testing was performed at the University of Arizona. ThermoTrex performed the system integration and built the electronics that control the actuators, which incorporated Picomotors from New Focus. The lightweight graphite epoxy support structure was built by Composite Optics, Inc. This prototype verified the active system concept, as well as the fabrication and handling of a glass membrane. The use of screw-type actuators and a simple but effective interface from the actuators to the glass were also demonstrated. The optimization of the figure using the actuators was performed to achieve measured shape accuracy of 53 nm rms, which was calculated to reduce to 33 nm after subtracting the effects of gravity. With a total mass of 4.73 kg, the complete 0.53-m prototype mirror assembly, membrane, actuators and support, has a surface density of 21 kg/m^2.

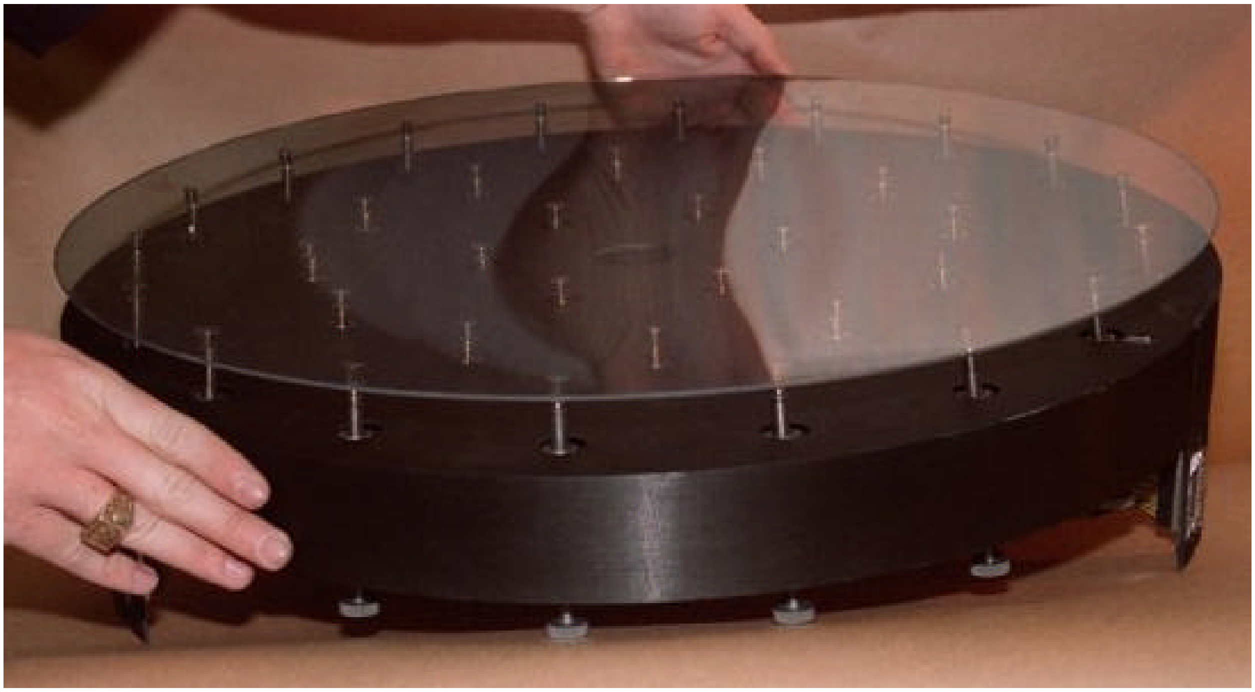


Figure 3. 53-cm prototype mirror with 2-mm thick uncoated glass membrane.

The membrane was made of Zerodur, provided by the Marshall Space Flight Center. The mirror was made to a spherical shape with 1.5-m radius of curvature, giving it a sagittal depth of 25 mm. The shell, which started out 7 cm thick, was generated and polished using conventional methods while it was blocked to an 8-cm thick Zerodur blocking body.

Commercial "Picomotor" actuators made by New Focus were used to for the prototype. Weighing only 40 g each, they consist of fine pitch screws driven by piezo actuators in a split nut. Based on the slip-stick friction principle, each action of the piezo results in a small rotation of the screw, causing it to advance or retract by about 20 nm, with no hysteresis. Travel of many millimeters is available, set only by the screw length. No power is consumed to hold the screw in fixed position.

The coupling of the screw to the membrane must be rigid. But to prevent damage to the glass, it should break away if the force gets too large. It must also constrain only the axial motion, allowing the glass freedom to move parallel to its surface, and must apply no significant bending moment. All this was accomplished through magnetic attraction, as shown in Figure 4. Permanent magnets of neodymium-iron-boron were attached to the glass with a thin layer of RTV, which is stiff axially but yields in shear to avoid surface dimpling. These are attracted to the hardened steel ball on the lead screw tip with a force of about 1.5 N, five times the local weight carried by each actuator. To maintain the high resolution of the actuators, thin sapphire plates were glued to the magnet face next to the screw.

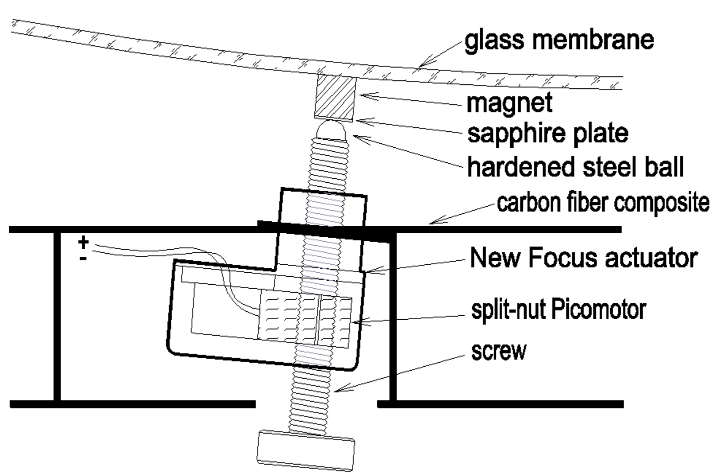
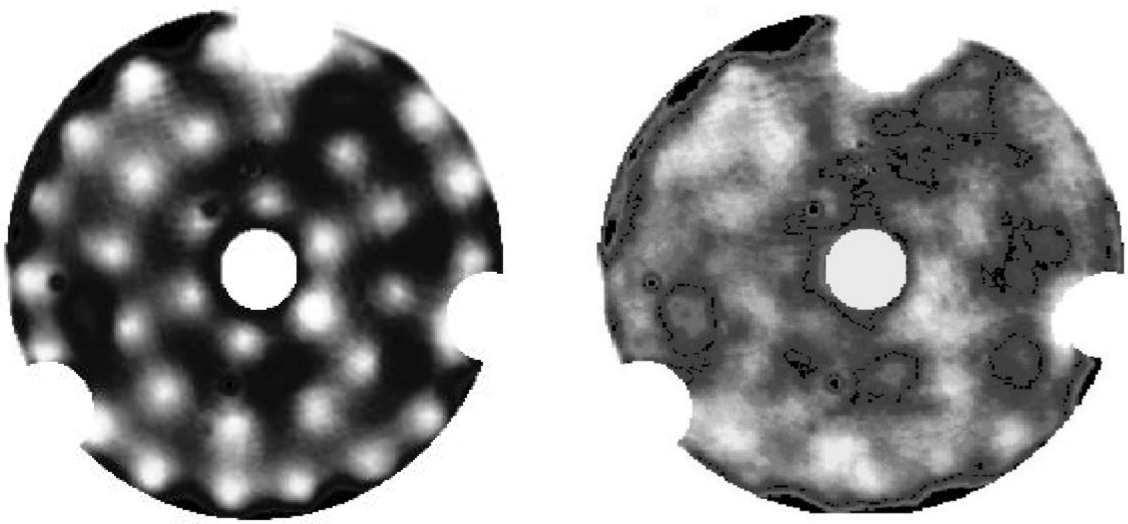


Figure 4. Attachment of membrane to composite support structure using Picomotor actuators

The prototype was assembled on its back in the optical shop, and the surface figure measured directly above the center of curvature. First, a Ronchi test was used to guide rough alignment, then a phase shifting interferometer with 633 nm light was used to measure the surface with accuracy of a few nanometers. Surface adjustments were made manually based on the figure measurements. The figure error at each actuator was measured, and a correction entered by sequentially stepping each actuator. This cycle of measurement and correction was then iterated to obtain the most accurate surface. The surface measurements are shown in Figure 5 as a) the raw measurement showing 53 nm rms which is mostly the print through of the support points due to gravity loading and b) the calculated figure after subtracting the static effects of gravity. The three bites removed from the edge data are regions where the surface was distorted during manufacture by shims in the pitch bond that were not removed soon enough. Subsequent tests have shown the problem is easily corrected by removing the shims directly after the pitch has hardened.



a) Raw measurement showing light shaded bumps where the actuators push on the glass. The overall surface is 53 nm rms.

b) Calculated figure after subtracting self-weight deflection, leaving 33 nm rms.

Figure 5. Gray scale plots of measured surface for 53-cm prototype mirror.

3.2 Demonstration of a cryogenic actuator

The 0.5-m prototype demonstrates the ability to make accurate, lightweight active optics, but its Picomotor actuators fail to operate at cryogenic temperatures. In order to demonstrate the technology at cryogenic temperatures, we require actuators that function at 35K with 10 nm resolution and large dynamic range. To keep the average operating power low, these mirror figure actuators must maintain their positions with zero hold power.

A prototype cryogenic actuator, shown in Fig. 6, was designed, built, and demonstrated by TTC with assistance from the U of A. The prototype, although not yet optimized to be light weight, weighs 72 grams – nearly reaching the goal of 50 grams. Initial tests at cryogenic temperatures indicate that it performs well and will satisfy the dynamic range and precision requirements for the NGST mirror figure actuators.

Figure 6. Prototype cryogenic actuator

Figure 7 illustrates the operation of the prototype actuator at liquid nitrogen temperature with the displacements measured by a Kaman eddy current sensor in the dewar, to an accuracy of a few nm. A sequence of 40 10-nm steps over a 50-second period is plotted. The desired linear motion is produced with an accuracy of 25 nm rms.

The performance of this early prototype demonstrates the feasibility of using lightweight actuators to control the mirror surface at cryogenic temperatures. ThermoTrex is now building on this success to manufacture actuators and control electronics that are lighter, more accurate, and more robust.

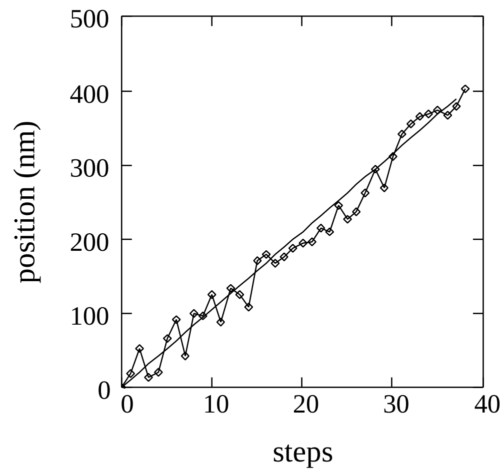


Figure 7. Measured motion of the actuator at 77 K

3.3 Demonstration of launch survival

For the glass membranes to be useful for space optics, they must be certain to survive launch. We have calculated that a properly manufactured 2-mm thick glass membrane would survive the stress of acoustic launch dynamics by a safe margin. U of A and Lockheed collaborated to demonstrate the survival of a 1-meter prototype mirror when subjected to the proto-flight acoustic testing for an Atlas IIAS launch. As the primary risk to the glass is the acoustic loading, we built a test sample that used a 1-m glass shell supported like the final mirror. The mirror was supported in a reverberant acoustic test chamber at Lockheed Martin and suffer no damage from acoustic loads 3 dB more than the launch loads of an Atlas IIAS launch for two minutes.

Figure 8. 1-m prototype mirror on 75 dummy actuators that survived acoustic launch testing

3.4 Other technologies in place

The development of the membrane mirrors follows a history of technology development that can be directly applied to the design and manufacture of active mirrors for space. The NGST will benefit from the rapid advances in technology for 8 m class mirrors for ground based telescopes over the last decade. These telescopes have helped to spawn new systems concepts for large optics, powerful new techniques for fabrication and testing, and novel methods and structures for active mirror support. The Steward Observatory Mirror Lab has played a major role in the development of methods to make and support large, lightweight mirrors. Among the innovations that have come out of the Mirror Lab are the direct casting of efficient structures up to 8.4 m in diameter, the stressed-lap polishing technique that has figured mirrors as fast as $f/1$ to the visible diffraction limit, manufacture and verification of null correctors for mirrors with up to 1 mm of aspheric departure, and fully active support of large mirrors. Many of these innovations have been demonstrated with the recent completion of the 6.5-m $f/1.25$ primary mirror for the Multiple Mirror Telescope Conversion. This mirror, shown in Fig. 8, is a lightweight honeycomb sandwich cast of borosilicate glass. It was figured to an accuracy of 25 nm rms surface error, and with active correction using its 104 supports is expected to maintain that accuracy in the telescope. The performance of this mirror is illustrated by Fig. 9, showing calculated interference fringes for 1 µm light. This 6.5-m mirror is diffraction limited at 0.7 µm, so the surface would meet NGST requirements.

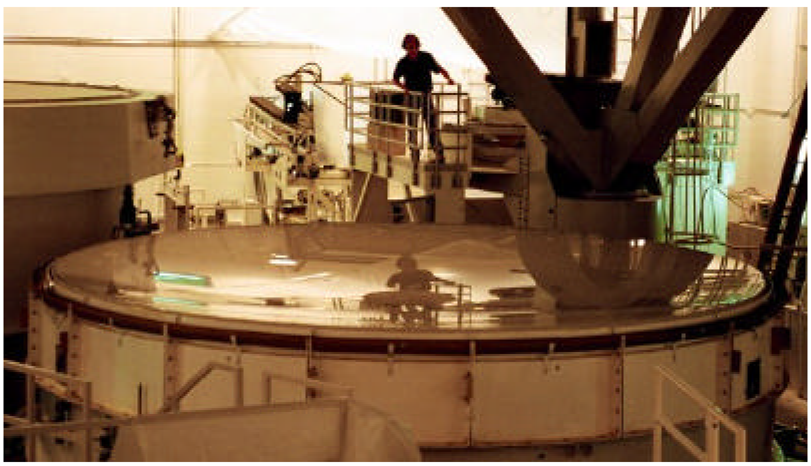


Figure 9. 6.5 m mirror for the MMT Conversion after completion of polishing at the Mirror Lab.

Figure 10. Interferogram, calculated from measurements for $\lambda = 1$ µm, showing the figure of the 6.5-m primary.

The Mirror Lab oven that casts the lightweight blanks, and the polishing and testing facility require no significant modification to make mirrors up to 8.4-m diameter and $f/1$.

Much of the technology for the lightweight active mirror has come from our experience building adaptive optics (AO) systems that compensate atmospheric aberrations. The membrane fabrication methods were developed and optimized for making large deformable mirrors for AO correction.[6] ThermoTrex and the U of A together developed new large-scale deformable mirrors, wavefront sensors, wavefront computers, and methods for using laser-beacons. The control of the membrane mirrors optimized for low-mass space application is similar to what we have already done for the adaptive optics systems, but much easier. The AO correction must run at frequencies above 100 Hz to correct the always changing atmosphere. The lightweight optics in space need only correct motion of the backing structure which will have day or even month-long time scales. So we have no difficulties from the dynamics of the system.

4. DESIGN AND OPTIMIZATION

We have developed methods for optimizing the design of this type of mirror. The optimization assumes a fixed mass budget and we design for optimal 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, similar to the "bumps" seen in Fig. 5 for 1-G testing of the 53-cm mirror. This effect can be minimized by making the membrane thicker, thus stiffer to the local forces, or by increasing the number of actuators. We have found that for any given actuator mass, the optimal use of mass is for the membrane mass to equal the mass of the actuators plus attachments.

We use a statistical model of the fabrication errors in terms of a power spectral density. This is coupled with finite element analysis that simulates the effects of fabrication errors and material property variations as functions of spatial frequency.

We have chosen borosilicate glass for the cryogenic telescopes because of its zero CTE (coefficient of thermal expansion) at 35 K. Other glasses have better performance over a wider range, but the borosilicate is best in the NGST operating range, it is obtainable at moderate cost, and it is made with excellent CTE homogeneity. Schott's Zerodur glasses also have good cryogenic performance, although standard Zerodur has demonstrated some instability between 20 and 30 K. The cryogenic CTE, as measured by S. Jacobs at the University of Arizona, is shown below in Fig. 11. This data will be published shortly.

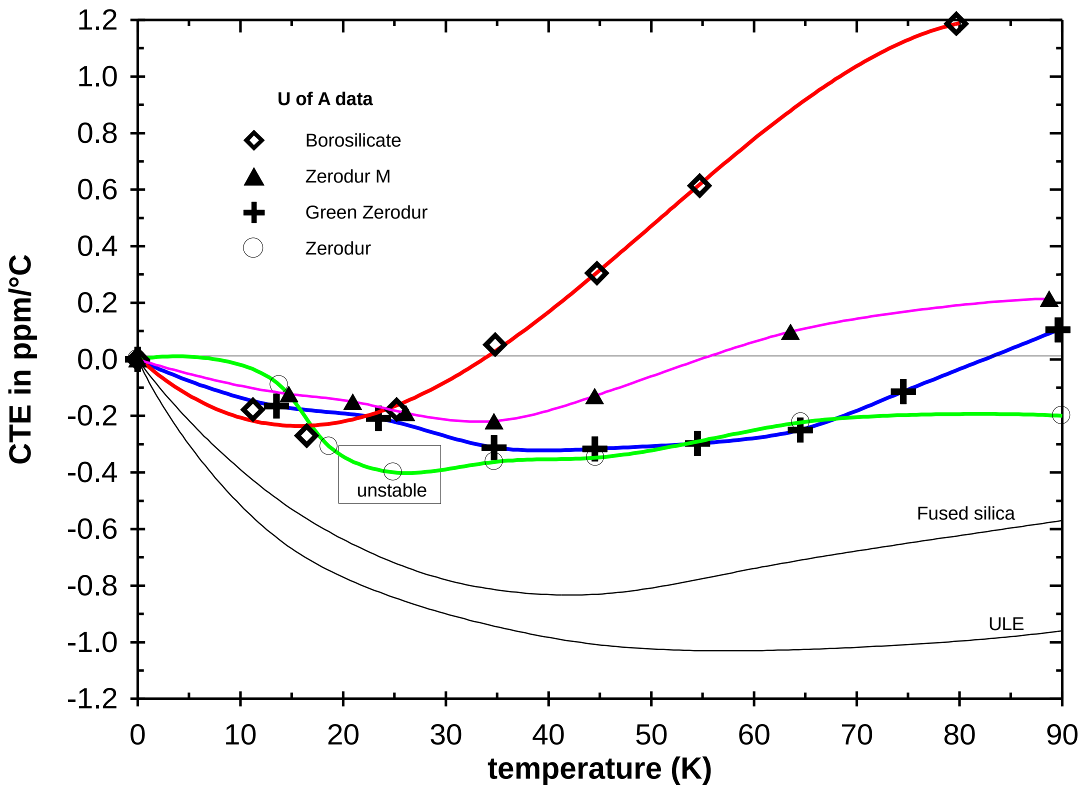


Figure 11. Cryogenic CTE for some candidate glasses

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 better distribute the actuator forces to minimize the effect of the actuators on the optical figure. The glass attachment is tricky because this system must support high loads during launch and it must provide almost no load when it is operational at 40K. A diagram of the load spreader attachment is shown below in Fig. 12. We bond small glass pucks to the membrane surface to allow a rigid attachment and to minimize stress when the part is cooled.

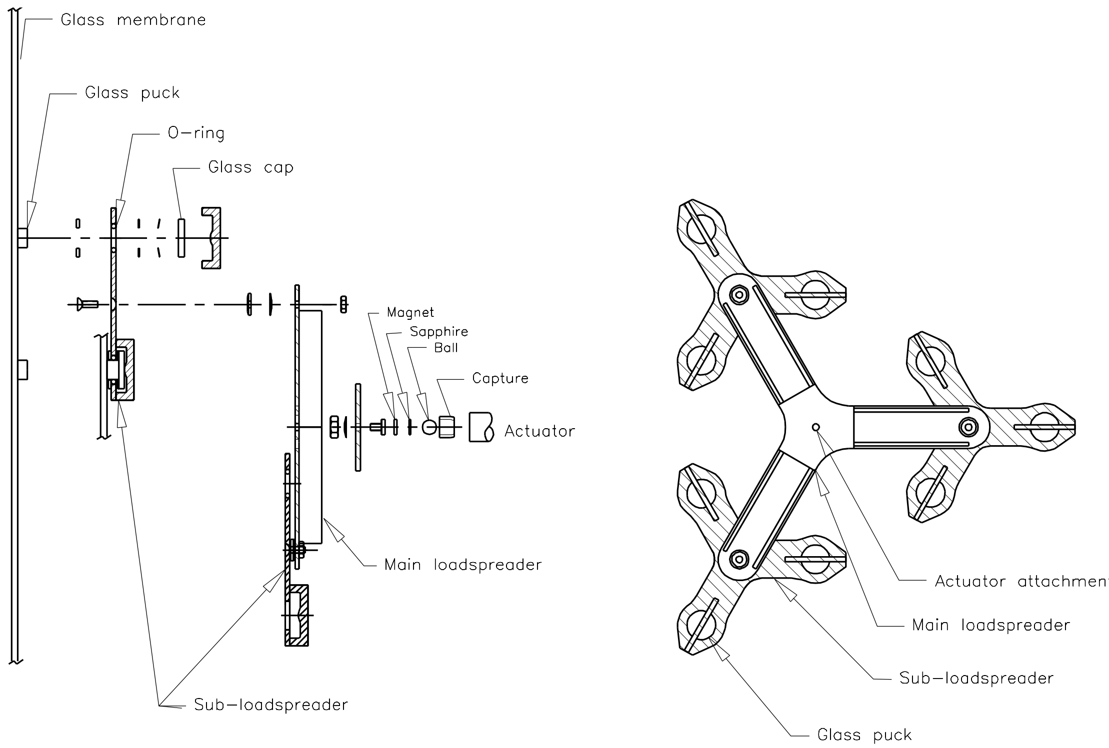


Figure 12. Exploded side view and assembly drawing showing the 9-point load spreaders and their attachment to the glass membrane.

In operation the actuators are attached to the load spreaders with a weak magnet. Since very little force is required, this allows us to control the shape, but to allow actuators to break away before any force gets large enough to damage the glass or load spreaders. Parasitic lateral forces are avoided by using a ball coupling at the magnet. The actuators also have remotely controlled retraction mechanisms that can remove any actuators that malfunction. The actuator density is sufficient to maintain surface control even if 10% of the actuators fail.

The launch loads of the glass membrane are taken through the actuators. This requires an additional set of attachments that keep the magnet-ball in compression and can take lateral loads. We solved this issue using cables that are pre-tensioned before launch to pre-load the actuator. This system was analyzed and shown to provide a safe support for the mirror.

As the actuators retract, the cables will go slack. The membrane is then supported only by the actuators the constrain motion normal to the surface and three tangent arms that prevent lateral motion and rotation.

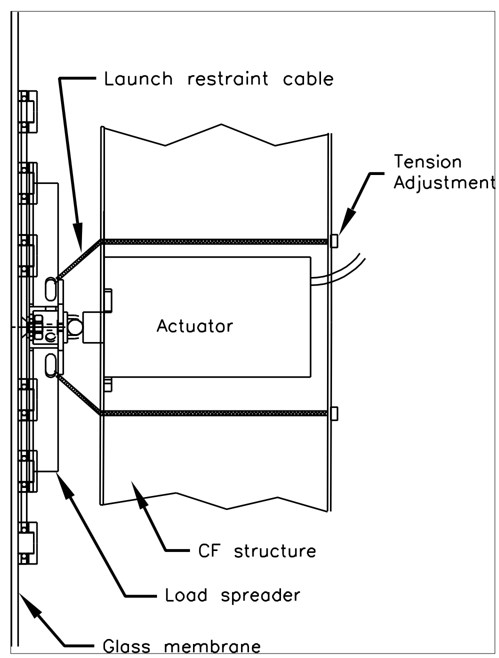


Figure 13. Side view showing launch restraint cables.

5. PROTOTYPE MIRROR FOR NGST

We are now under contract from NASA to build a 2-m mirror as a prototype for the Next Generation Space Telescope. This mirror, shown in Figure 14, will be demonstrated with closed-loop control at 35°K in mid-1999. Table 1 summarizes the design parameters. The system design and integration, and the membrane fabrication will be done at the University of Arizona. ThermoTrex will provide the cryogenic actuators and the electronics. The carbon fiber backing structure will be build by COI, and cryogenic and dynamic testing will be performed by Lockheed Martin.

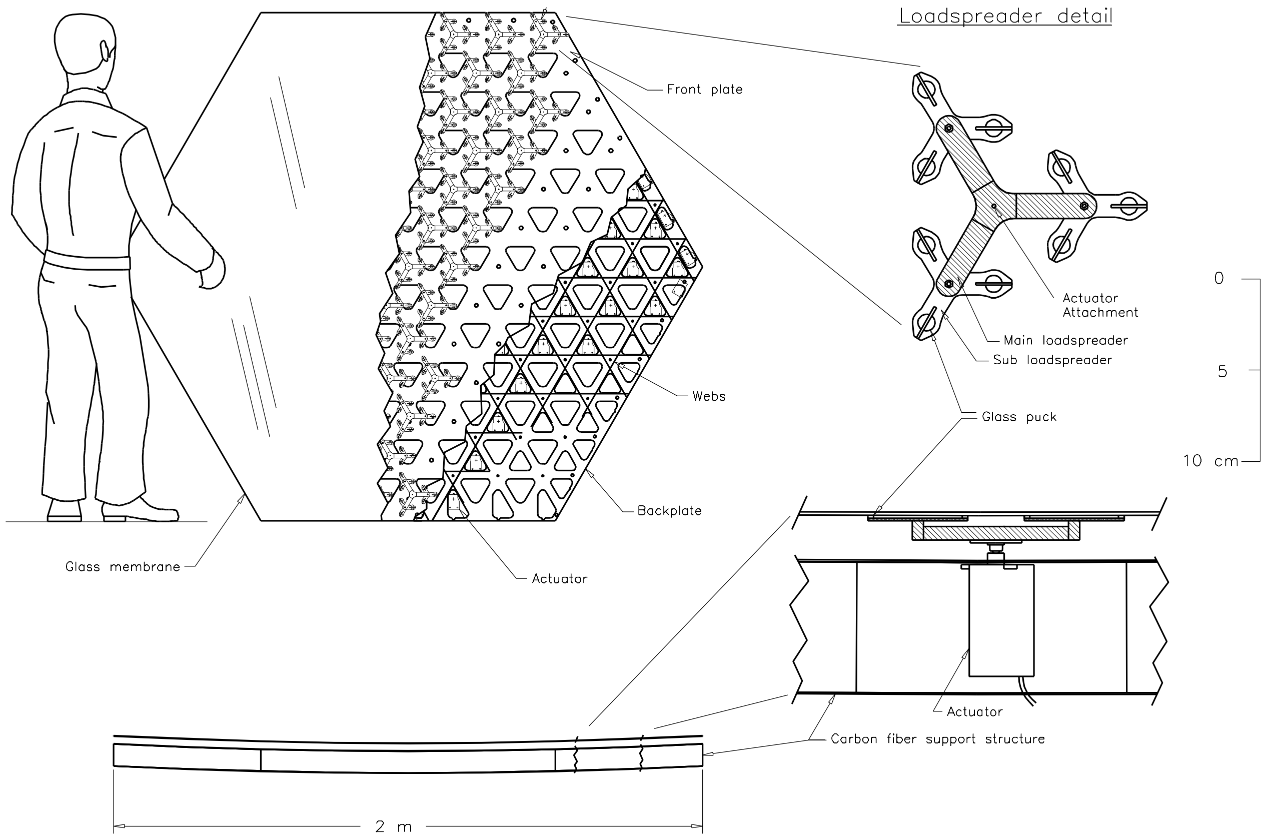


Figure 14. 2-meter NGST demonstration mirror

Table 3. Mass budget for the NGST demonstration mirror.

Item	**Kg/m^2**
Glass membrane, 2 mm thick borosilicate, 2.2 gm/cm^3	4.4
Actuators and cabling, 50/m^2, 50 gm per actuator	2.5
Load spreaders, 50/m^2, 27 gm per load spreader	1.4
Attachments to membrane, 450/m^2, 0.9 gm each	0.4
Launch restraint hardware, 6.2 gm per actuator	0.3
Carbon fiber support structure	4.0
Total mass per square meter	**13.0**

6. CONCLUSIONS

We present a robust method of making lightweight optics for space applications that use technologies we have demonstrated. We achieve accurate surface shape by actively controlling the reflecting surface of the mirror based on wavefront measurements. The mirror stiffness and low mass are achieved using advances in lightweight graphite epoxy technology. We have built and tested a 0.53-m mirror and are now building a 2-m demonstration optic that will achieve diffraction limited performance at cryogenic temperatures. Our fabrication procedures can be scaled up to 8-m optics within current facilities. We have identified several improvements in our fabrication and support that will improve on our results from the 53-cm. We estimate that we can achieve 19 nm rms figure accuracy for the NGST, as broken down below. Our analysis indicates we can achieve this with the same mass density as for the 2-m shown above in Table 3.

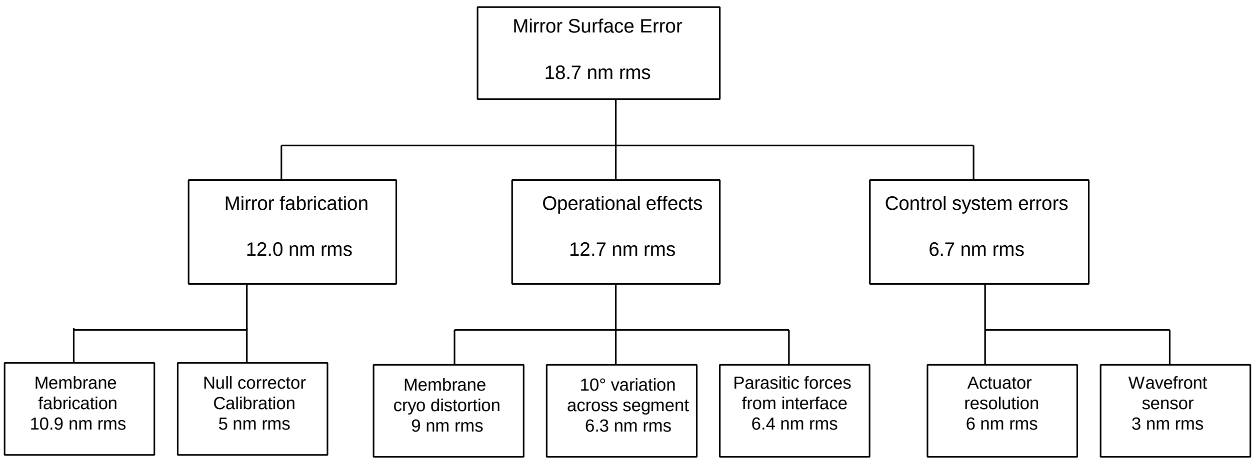


Figure 15. Error budget for a 3-m segment of the NGST primary mirror.

ACKNOWLEDGMENTS

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