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NGST AS A FULLY ASSEMBLED 6M TELESCOPE, USING A MONOLITHIC MARS MIRROR

Roger Angel, Buddy Martin, Steve Miller, Jim Burge, Phil Hinz and Neville Woolf
Steward Observatory, Tucson
The University of Arizona

David Sandler and Don Bruns
ThermoTrex Corporation San Diego

Domenick Tenerelli
Lockheed Martin, Rancho Bernardo

NAME | ID No. | M.S.

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NGST as a fully assembled 6 m telescope, using a monolithic MARS mirror

Roger Angel, Buddy Martin, Steve Miller, Jim Burge, Phil Hinz and Neville Woolf
Steward Observatory, The University of Arizona

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Lockheed Martin

Abstract

A large space telescope could be built relatively quickly at moderate cost by taking advantage of a new mirror technology, Membrane with Active Rigid Support (MARS). The mirror would consist of a rigid, ultra-lightweight structure of carbon fiber composite, faced with a membrane of glass for diffraction limited imaging down to 1 micron wavelength (30 milliarcsec FWHM). To overcome long term or thermal instability of the supporting structure, the membrane would be rigidly linked via positioning screws at 10 cm intervals. These would be adjusted periodically to maintain the surface figure as measured by starlight. Using methods already proven in the fabrication of a very fast 6.5 m mirror, a 0.5 m prototype MARS mirror with a 2 mm thick membrane has been made at the Steward Observatory Mirror Lab. It demonstrates already the desired surface accuracy and extreme degree of lightweighting.

We outline an optics development program for the proposed Next Generation Space Telescope mission (NGST) that could lead to a 6 m flight mirror completed in 2004, at a full program cost of $60 M. Built with a monolithic MARS mirror, the telescope would be fully assembled before launch and tested with full aperture illumination, in vacuum and at the cryogenic operating temperature. The 6 m glass disc used to support the membrane during manufacture would serve double duty as the collimator mirror for the test. Through this test, and by eliminating the need for any subsequent folding and re-deployment of optics, high reliability should be realized. The spacecraft cost should be consistent with the $500M target set by NASA, and it should be lightweight; the complete spacecraft is projected to weigh less than 2 tons, compared to 11 tons for the Hubble. Launch will require the spacecraft to be housed in a 7 m fairing, which could be developed for Proton, H-2 or Ariane V vehicles. We see the development of large diameter launch capability as being of general value to astronomy, making affordable other lightweight, large aperture telescopes to cover other parts of the electromagnetic spectrum.

1. Introduction

The scientific potential of a successor to the Hubble telescope is enormous. In their report "The HST and Beyond", Dressler *et al* (1996) identify the formation of galaxies at early epochs as the key research area. Because they are faint and strongly redshifted, a larger telescope in space is needed, optimized for the 1 - 5 micron spectral region.

Studies are now being undertaken by NASA for such a telescope, called the Next Generation Space Telescope (NGST), which would provide a large increase in collecting area over the 4 m^2 collecting area of the Hubble. The larger aperture would not only give stronger signals, but at infrared wavelengths where it is diffraction limited, it would form sharper images, increasing sensitivity to faint objects. The goal for image sharpness is to be diffraction limited at wavelengths as short as 1 micron. A further major improvement in sensitivity is envisaged through the elimination of thermal background from the telescope optics, which in the Hubble are at room temperature. This requires operation at cryogenic temperatures, ideally as cold as 40 K. Passive cooling can achieve this goal, given higher orbits and shielding against heat radiated by the Earth as well as the sun. The ultimate sensitivity would be obtained by orbiting the telescope as far as 3 AU from the sun, thereby avoiding the sky background of thermal emission and reflected sunlight from zodiacal dust.

The challenge to the telescope designer is to build to both meet the performance goals and minimize costs. Launch costs could easily dominate if the telescope were heavy, so the main requirement is to make a telescope at low cost that weighs relatively little. If rockets with launch cost of around $100 million are to be used, such as Atlas, Proton or Ariane V, and distant orbits are desired, then the target mass for the telescope and spacecraft should be no more than 2 tons. Any practical design to reach this goal must use advanced new technology. Yet in making this reduction, there can be very little relaxation of mechanical tolerances compared to the Hubble; in fact, pointing accuracy would have to be improved to accommodate the sharper images.

Leading in difficulty will be the primary mirror. The Hubble mirror is 2.4 m in diameter, and is made of rigid, honeycombed glass. Larger honeycombed glass monoliths for ground based telescopes are being made at the University of Arizona Mirror Lab. Figure 1a shows the 6.5 m diameter, 0.7 m thick mirror already completed for the MMT conversion, with a very fast paraboloidal surface (f/1.25). Images are shown in fig 1b, calculated from the actual surface contours recorded by interferometry. Diffraction limited down to optical wavelengths (24 milliarcsec FWHM at 700 nm), this existing mirror would make an excellent NGST, but for its weight. Even though 80% lightweighted, with 1 cm ribs and 3 cm facesheets similar to Hubble's, it weighs 10 tons. This is at least an order of magnitude higher than is needed for an affordable launch.

In sections 2 and 3 below, we show how the fabrication method already proven with the above mirror can be adapted to make a mirror assembly that is far lighter, yet has comparable accuracy.

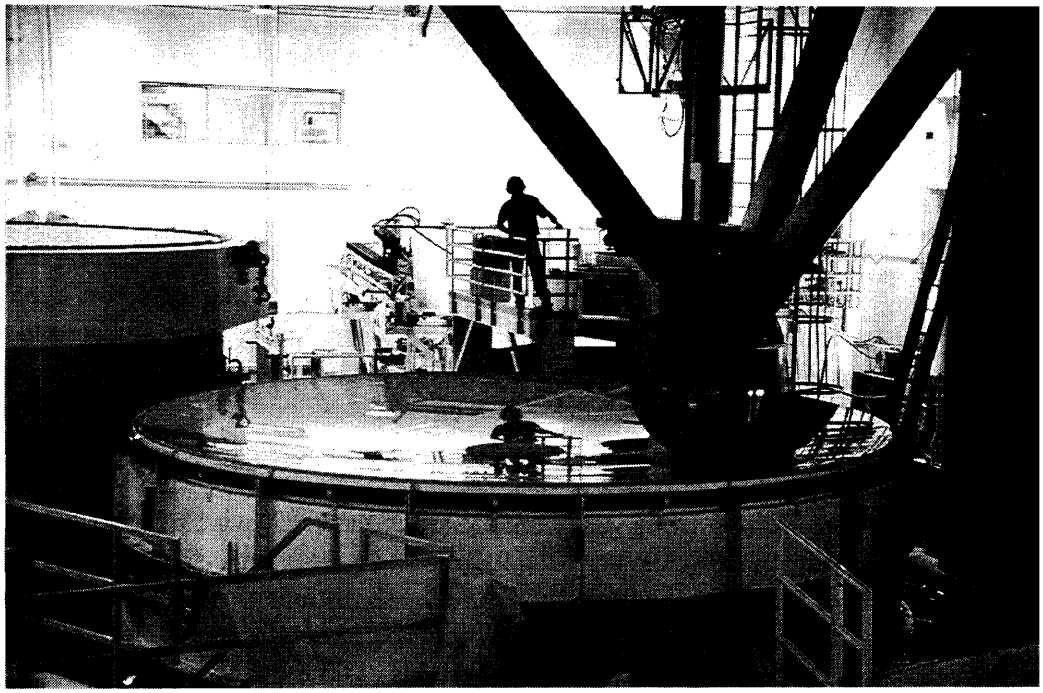


Figure 1a. Completed 6.5 m mirror in the Steward Observatory Mirror Lab. The stressed lap method, designed for figuring very fast aspheres, was used to finish this f/1.25 paraboloid. It is diffraction limited to below 1 micron wavelength, as shown by the images of figure 1b.

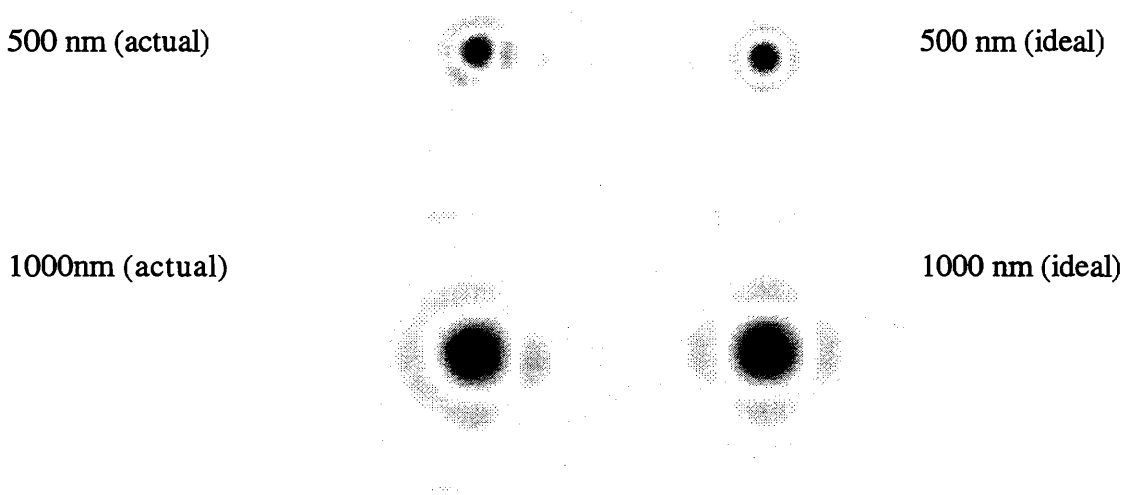


Figure 1b. These are computed for different wavelengths from the wavefront as measured in the shop (labeled actual), and from a perfect wavefront over the same aperture (labeled ideal) for comparison. They are very similar to star images that would be obtained with a 6 m NGST. The scale is given by the separation between images, which is 0.3 arcsecond.

2. The MARS mirror concept

In the new concept, glass honeycomb is replaced with a far lighter rigid structure of low expansion carbon fiber composite. But because carbon fiber composite will not take a high polish, the figured surface that supports the reflecting layer will still be made of glass. A direct deposition of glass is not desirable, since over long periods a large carbon fiber composite structure will not hold its shape to optical precision, given thermal changes and drying out. In our concept, the glass takes the form of a membrane that is linked rigidly to the structure by a large number of screw-type actuators, uniformly distributed. When there is perceptible distortion, the screws will be adjusted to restore the correct figure to the membrane. Since very small distortion can readily be detected in the reflected starlight, this correction procedure ensures that the figure is always nearly perfect. This new concept we call MARS, Membrane with Active Rigid Support.

The membrane must be formed from very homogeneous material, with a "relaxed" shape that is accurate. We cannot rely on using the screw actuators to bend an imperfect membrane into shape, because if any significant force is applied, it will cause local distortion. Similarly, high homogeneity is needed to ensure that the membrane does not distort by "bimetallic strip" effects when cooled to cryogenic temperature. This is in part why we choose glass as the membrane material; it is the most homogeneous material available in sizes up to 8 m diameter. The best glasses are likely to be either fused silica, which has low coefficient over the full range below room temperature, or a high silica glass such as a borosilicate, chosen to have zero coefficient at cryogenic temperature.

The new MARS technology will allow the construction of single mirrors that are not only much lighter, but much bigger than previously possible. This substantially broadens the possibilities for a large space telescope. As long as ultra-lightweight mirrors were restricted in size, our only option was to build large mirrors from smaller elements. Now there is the possibility of building an ultralightweight telescope of 6 m or larger aperture with a single mirror.

A telescope with such a mirror would be fully assembled and tested in a large thermal vacuum chamber before launch. With full aperture illumination, the test of the complete optical system would be made at its cryogenic operating temperature. In this way, the possibility of failure from deployment, thermal distortion, misalignment or imperfect optics is completely eliminated.

3. 0.5 m Prototype

Analysis shows that large diameter but extremely lightweight MARS configurations with a glass membrane only 2 mm thick should be capable of the desired image quality. To test the practical issues of manufacturing and tolerance issues with this thickness of membrane, we have built a prototype. It was made with 0.5 m diameter, but by methods directly scalable up to 8 m diameter.. The number of actuators (36) was large enough that distortion effects on the scale of the actuator spacing were properly explored. Construction of the prototype was part of a NASA funded study made by Lockheed Martin of ways to build the NGST.

3.1 Fabrication of the membrane

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 which will become the membrane and the other the stiff blocking body to which it is attached during fabrication. A spherical convex surface that will become the back of the membrane is first ground on one disc. The second thick disc is prepared as the rigid substrate, 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 short-term stiffness for rigid support during polishing, but also long-term relaxation, which prevents stress in the bonding layer. 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 the 6.5 m mirror at f/1.25 are directly applicable.

For the prototype we chose Zerodur, whose lack of expansion at room temperature is a convenience for fabrication. Jim Bilbro of Marshall Space Flight Center made available discs of high quality Zerodur 53 cm in diameter, from a core of one of the AXAF mirrors. The blocking body was 8 cm thick, and the membrane was made from a piece whose initial thickness was 7 cm. For ease of testing, the front surface was made spherical, with a radius of 1.5 m and sagittal depth of 2.5 cm. Starting from the raw blanks, all the steps of optical fabrication used standard methods, and were completed in 6 weeks. Polishing the front surface is shown in fig 2a, and in 2b an interferogram of the polished membrane surface before removal from the blocking body. The membrane surface at this stage is extremely smooth. Removal was accomplished by warming the blocking body with membrane attached, slightly tilted. When the pitch melted at about 130 F, the membrane slid forward under its own weight, and could then be easily slipped right off. The final thickness of the membrane was measured to be 2.1 mm, its diameter 53 cm, and mass 1.25 kg.

3.2 Actuator implementation

Manufacture of the prototype was greatly simplified by the availability of commercially produced actuators with the required properties. These are "picomotors", made by New Focus for precision adjustments of optics. Weighing only 40 g each, they consist of fine pitch screws driven by piezo actuators in a split nut. Fig 3 shows the actuator assembly, incorporating a model 8301 motor. 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 30 nm, with no hysteresis. Travel of many mm 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 should break away if the force gets too large, to prevent damage to the glass. It must also constrain only the axial motion, allowing the glass freedom to move parallel to its surface, and applying no significant bending moment. All this was accomplished through magnetic attraction, as shown in figure 3. Permanent magnets of neodynium-iron-boron, 0.25" diameter, 0.25" long, 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.

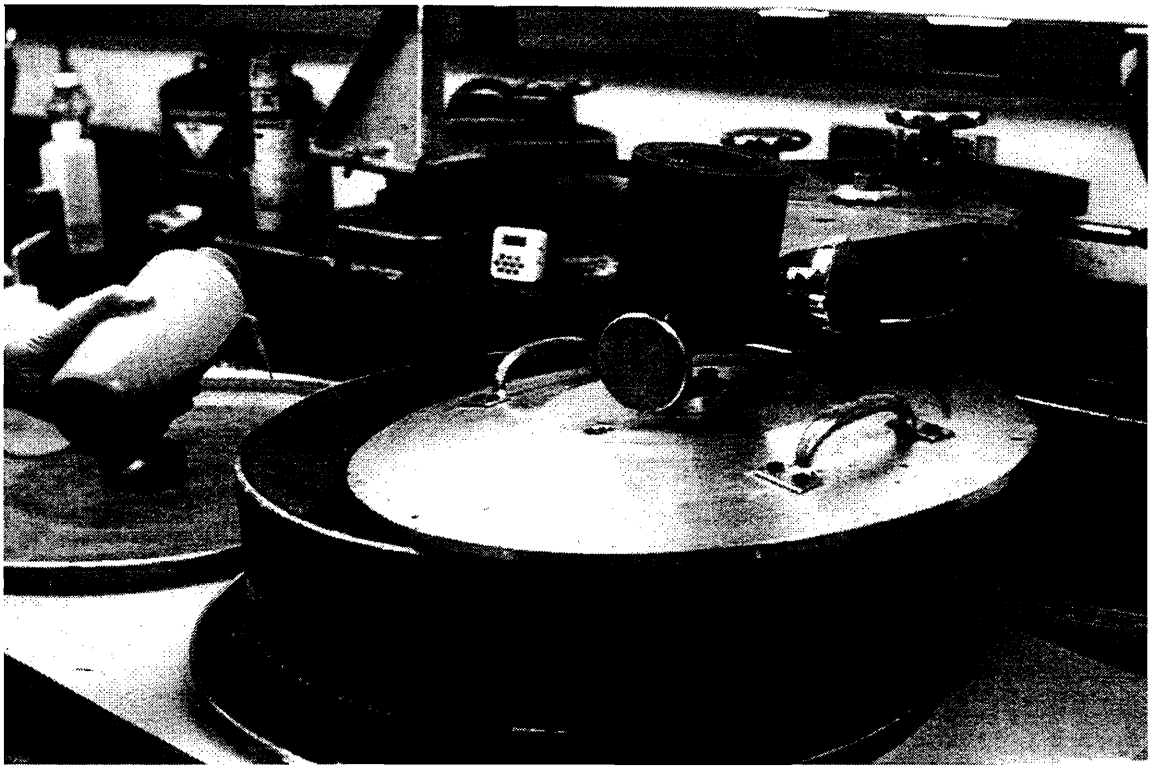


Figure 2a. Polishing with a full size lap. At this stage, the 2 mm thick membrane is rigidly attached to the blocking body several inches thick, allowing the use of standard polishing methods.

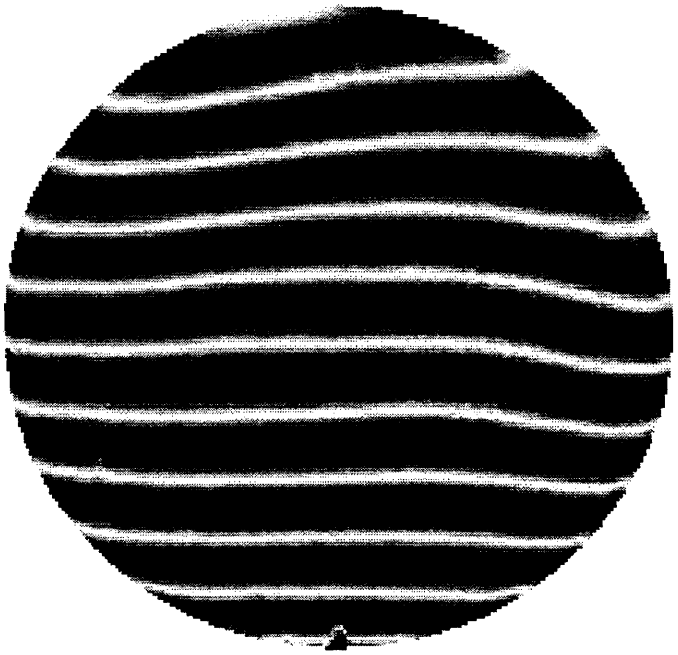


Figure 2b. Synthetic interferogram at 633 nm wavelength of the finished membrane surface, before removal from the blocking body. The smooth fringes indicate an extremely smooth surface on small scales, while the large-scale irregularity represents structure that is completely correctable with the actuators. Care was taken at this stage to polish out completely any surface damage left from the grinding, to avoid surface stress.

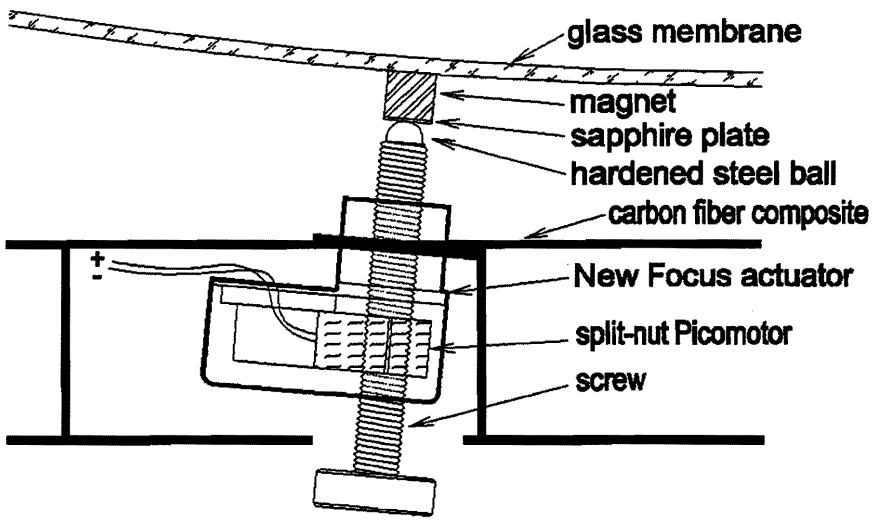


Figure 3 Diagram of picomotor driven actuator and magnet coupling.

The commercial Picomotors operate with a two wire connection supplying nominal 100 volt signals to the piezoelectric elements. The voltages appear as a sawtooth step, the direction of the ramp determining the direction of lead screw rotation. A single driver was used to operate the set of 36 actuators, using a box of simple mechanical switches as a demultiplexer.

3.3 Support geometry and construction

We chose a configuration of 36 supports, arranged in three rings of 6,12 and 18 actuators, as shown in figure 4. This yields an average density of supports of $160/m^2$, somewhat more than the projected optimum for a larger membrane, which would have actuators located on a regular triangular grid except at the edges. This increase is desirable to compensate for the poorer efficiency when small numbers of supports are used, and edge effects dominate. We used a geometry for minimum gravity deflection, with the 3 rings of supports at radii close to the optimum values of 0.26, 0.58 and 0.88. Following Nelson *et al* (1984) and taking the mechanical parameters and dimensions of the Zerodur membrane, we calculate an rms quilting of 50.0 nm

The carbon fiber composite support structure shown in figure 4 was built by Composite Optics, Inc. of San Diego. Its diameter is 53 cm, the same as the glass membrane, and thickness 40 mm. One mm thick face sheets were made from flat stock to simplify construction, and the internal ribs are radial and tangential. The 20 mm sag of the membrane from the inner to outer actuator rings was made up by using the longer stroke actuators in the outer ring. The actuators were mounted inside the structure on secondary plates tilted to match the glass curvature, to act normal to the glass surface. The mass of the support structure alone is 2.0 kg, and the total mirror assembly with membrane and actuators 4.73 kg.

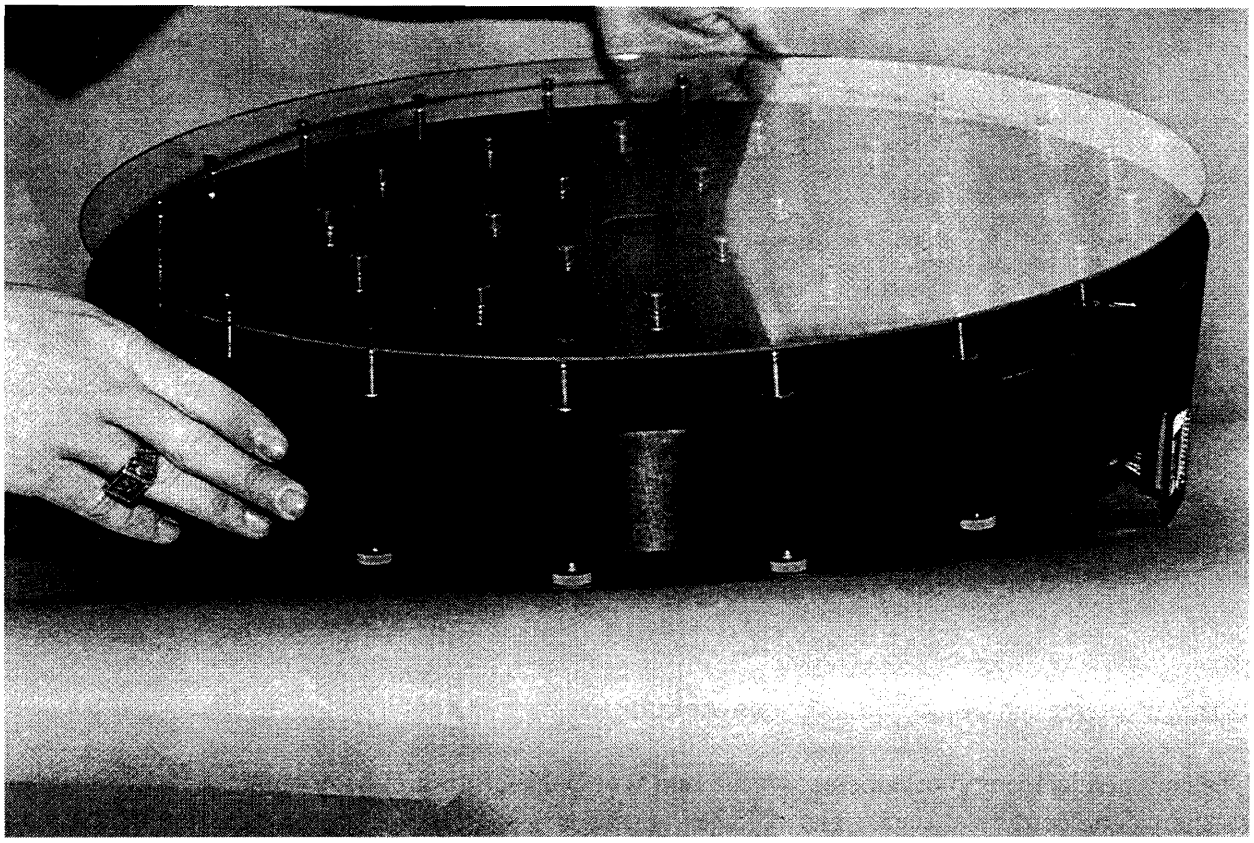
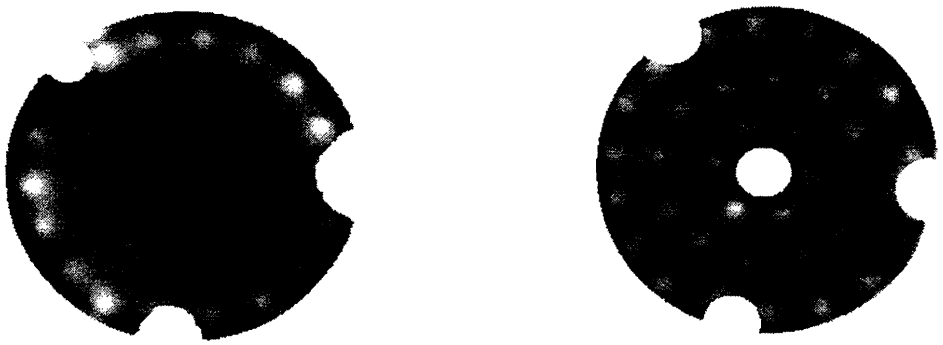


Figure 4. Completed MARS prototype with unsilvered glass membrane.

3.4 Wavefront sensing and adjustment

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 ruling was used to make measurements while the screws were brought into rough alignment, then a phase shifting interferometer for precision surface metrology to a few nm accuracy. Surface adjustments were made manually from contour maps obtained in this way. The surface height at each actuator was measured, and a correction entered by sequentially stepping each picomotor-driven actuator. This cycle of measurement and correction was then iterated to obtain the most accurate surface. The radius of curvature is not determined by the interferometer, and initially the reference wavefront in the interferometer against which the mirror wavefront is nulled was set with too steep a curve. This resulted in the surface of fig 5a, in which the weight is clearly being taken disproportionately by the outer ring to force increased curvature, as shown by the bigger bumps above the actuators. Subsequently, the actuator screws were repositioned with the natural curvature of the membrane so the weight is taken evenly, as shown in 5b. The rms amplitude obtained from this map is 53 nm.



(a) (b)

Fig 5. a) Interferometric map of departure from a spherical reference, coded in gray scale with white= high. The rms departure from a perfectly spherical surface is 88 nm. The curve is being forced to be deeper than the natural shape, with the weight being taken largely by the edge ring, as shown by the ring of strong bumps over the actuators. b) actuators correctly set to the natural meniscus shape. The rms error is now 53 nm. The three bites removed from the edge data are regions where the surface was distorted during manufacture (see text).

3.5 Results from the prototype

1) The bumps in the surface in fig 5b are the result of the membrane sagging between the support points under its own weight. The measured 53 nm rms distortion is in good agreement with the 50 nm expected from the mechanical properties of the membrane. In a gravity free environment, these bumps would largely disappear, and the residual errors would be consistent with 33 nm surface accuracy needed for the desired 1 micron diffraction limited imaging with the NGST.

2) The actuator spacing chosen for the prototype is adequate to deal with residual errors in the natural shape of the membrane without causing excessive local distortion. The corrective forces are clearly less than the weight carried by each actuator, which is about 35 grams or 0.35 N.

3) The good natural shape verifies that zerodur has adequately low internal stress and that residual surface stresses left by the manufacturing process are in general adequately low. The only trouble we encountered during manufacturing arose from the shims used to set the 100 micron thickness of the pitch bond to the blocking body. These were not removed soon enough in the subsequent grinding and polishing of the membrane, and left edge features which are masked out in the interferograms. Subsequent small scale tests have shown the problem is easily corrected by removing the shims directly after the pitch has hardened.

4) The simple magnetic coupling used for the actuators works well, with little evidence for parasitic forces from bending moments or lateral friction. The picomotor-driven actuators also work well, with enough resolution and lack of hysteresis to set an accurate surface.

5) The prototype mirror has reached the level of lightweighting needed for the NGST. 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.

4. A 6 m cryogenic MARS mirror

4.1 Mirror system design

We adopt 6 m as the target size for a new space telescope using a single, monolithic MARS mirror. As we discuss below, fairings large enough for a completely assembled telescope of this size could be developed for existing launch vehicles. With an area of 28 m^2, 6 m aperture also comes close to an order of magnitude gain over Hubble (4 m^2). The resolution (FWHM) set by diffraction, λ/D, will be 34 milliarcsec at 1 micron wavelength.

We choose f/1.25 as the nominal focal ratio, the same as the completed 6.5 m MMT mirror. This is fast enough to make a compact telescope, but is also limits the asphericity to yield a membrane of reasonably uniform thickness. With a spherical back surface and a paraboloidal front surface, the peak-to-valley thickness variation will be 750 microns, from 1.6 mm at the edges and center to 2.35 in the mid zone. The mass of such a membrane of fused silica or borosilicate glass is 123 kg.

The optimum membrane thickness and number and mass of actuators depends on several factors now being studied in detail. The fundamental requirement is that the reflecting surface be held to within 30 nm (rms deviation) of the true figure. This is needed to ensure high Strehl ratio (80%) at 1 micron wavelength. Various factors may contribute significantly to this error, and must be budgeted. We have determined from the prototype that static errors from manufacturing should be acceptably low, given supports spaced about 10 cm. Inhomogeneity in the expansion coefficient, which will cause "bimetallic strip" bending when the membrane is cooled to cryogenic temperature, needs to be explored by analysis and experiment, as we discuss below. An important result of analysis is that the distortion due to material property variations in the original blank is independent of membrane thickness. Dynamic errors can also arise during operation if resonant frequencies are too low and spacecraft vibrations strong enough. For 10 cm support spacing, resonant frequencies of the membrane are > 100 Hz, so significant amplitudes seem unlikely. A third kind of error is the change in shape when the 1 g load experienced during lab testing is released. The gravity bending amplitudes must not be so large that their release cannot be predicted to better than 30 nm. Again, 10 cm spacing for the 2 mm membranes is seen to be adequate from the prototype.

The actuator mass should not dominate over the membrane mass it supports, thus if there are 100 actuators per square meter, they should weigh no more than 43 grams each. This is close to the mass of the picomotor actuators used in the prototype, which were not optimized for low mass. Note that the total mass of the glass and actuators is then still only 250 kg, an extremely low value for 6 m aperture.

The total mass of the mirror assembly must include that of the carbon fiber composite support. Preliminary work by Composite Optics ands Lockheed indicates that an integrated dish and secondary support tripod could be built up from 1 mm thick flat sections to yield comfortably high resonant frequency and stiffness, with a mass of about 400 kg.

In space, the 28 m^2 membrane will be supported at some 2800 points. Adjustment of each individual actuator requires knowledge of the shape with good spatial resolution. We propose to make the

measurement in a way similar to that used in the optical shop. During fabrication, the surface of the 6.5 m mirror was repeatedly measured to an accuracy of about 10 nm. This was done by interfering the wavefront reflected back to the center of curvature with a reference wavefront. From the resulting interference fringe patterns, recorded for several different settings of phase between the two wavefronts, phase over the surface is computed for each pixel over a 256 square grid. In the shop, this is done with a laser reference source, but the same type of measurement can be made at the telescope focus using light from an unresolved star. This is also spatially coherent over the whole aperture, so white light fringe can be formed, given an unaberrated reference beam obtained by passing some of the starlight through a spatial filter (Zernike, 1934). Such an implementation of the phase shifting method for stellar wavefront sensing has been described by Angel (1994) and demonstrated by Colucci (1993).

In space, autonomous control of the mirror figure would be desirable. After new target acquisition, and at intervals of hours or days, determined by experience, surface measurements would be made by pointing to an adequately bright star near the program field. The correspondence between the phase measurements and correction signals is one-for one, so the control algorithm is simple. Nevertheless, care will be needed to ensure system reliability.

An important design issue will be to allow for actuator failure. Because there are many actuators, there is a finite possibility that one or more will hang up, or drive up or down out of control. We must allow for this with mechanical breakaways, and provide for complete disconnection of a failed actuator, allowing nearest neighbors to take over its role. The actuator spacing must be such that adequate control is maintained, even when some actuators have failed.

4.2 Areas for experiment and technology development

Choice of glass - We used Zerodur for the prototype because discs of low internal stress were immediately available. It has zero expansion coefficient at room temperature, but not when cryogenically cooled. Fused silica is a better choice, because its coefficient is low and reverses at low temperature, so the overall length at 40 K is about the same as at room temperature. By the addition of boron oxide, a glass can be made with coefficient exactly zero at a specified cryogenic temperature, so some form of borosilicate glass may be even better. At 6 m size, a silica blank would have to be fused from several smaller boules. A key issue is thus uniformity of expansion across the boundaries and whether a cooled membrane made from fused boules will show distortion at the joints. To explore this issue, we are undertaking to make a new 53 cm membrane from a blank with such joints, and to test it at low temperature.

Fabrication and handling of larger membranes - While we have successfully made a 0.5 m membrane, it is clearly a big step to 6 m. The whole process of manufacture, including the making of thin pitch bonds, and avoiding any stress during figuring, will be explored at intermediate sizes before 6 m is attempted. This will also allow us to gain experience in handling larger membranes with special fixtures, rather than by hand, as was possible with the 0.5 m prototype.

Actuators - The picomotor-based actuators used in the prototype are clearly a good starting point, and the picomotor principle may well be the basis for flight actuators. For operation in space, a crucial step will be to improve the materials for cryogenic operation - the present piezo material is

not adequate. Also, lubrication to maintain the right slip-stick properties after prolonged vacuum exposure would need to be developed. We have mentioned already the need for mechanical breakaways. A further requirement is the need for the membrane to survive the mechanical and acoustic loads during launch. The actuator coupling for operation in orbit may not be adequate for the launch phase, in which case additional elements may have to be added, or brought into play through the launch phase. Designs must be developed and tested exhaustively.

2.5 m full test - We plan to make a full system test at the 2.5 m size. The meniscus would be of the final material selected for the 6 m. Figuring would be to an f/1.25 paraboloid, to the NGST spec. The actuators would include breakaways, and be cryogenic. The assembled mirror, with lightweight carbon fiber composite support, would be tested both cryogenically and in closed loop operation in a telescope with a starlight wavefront sensor. This complete Hubble-sized mirror will serve as the proof of concept. We note that it would weigh under 100 kg, more than an order of magnitude less than the Hubble mirror assembly. It should also cost more than an order of magnitude less.

4.3 Schedule and budget

Figure 6 shows schedule and budget estimates for a program that, starting now, would lead in 6 years to a 6 m flight mirror suitable for the NGST. These estimates, prepared by the Steward Observatory Mirror Lab and ThermoTrex, are crude at this stage, but we believe that the $58M total and 6 year time scale is not unrealistic. For reference, the price of a 6.5 m mirror figured to better than NGST spec is $8M, including the fabrication of the honeycombed borosilicate glass blank and full aperture interferometric testing. The catalog price for 3000 picomotors (not yet optimized for cryogenic operation) is just over $1 million. ThermoTrex has built adaptive optics systems with 1500 controlled degrees of freedom, with 1 msec response time. The closed loop control needed for a MARS mirror is far simpler, requiring update rates many orders of magnitude slower.

Task	*Calendar Year* 1997 1998 1999 2000 2001 2002 2003 2004	Cost ($M)
0.5 meter cryogenic membrane fabrication & test	--□	0.3
Flight-qualified, cryogenic actuator development	----------□	4
2.5 m MARS fabrication and test	----------□	3.5
6 meter blank procurement	----------□	10
6 meter membrane fabrication	----------□	10
Support structure fabrication	----------□	5
MARS mirror assembly (flight-qualified)	----------□	5
Shape control system development (not flight)	----------□	5
Final full-aperture illumination test at Mirror Lab	----------□	5
Project Engineering and Management		5
Contingency		5
		$57.8

Figure 6.

5. Discussion

5.1 A complete telescope and spacecraft with 6 m MARS mirror

Preliminary estimates by Lockheed indicate a total spacecraft weight considerably less than 2 tons should be possible. All the elements of the spacecraft, including optics, science instruments and the spacecraft components, would be supported by a single integrated carbon fiber composite structure.

To test the complete assembly in a thermal vacuum chamber, we have devised an inexpensive method to make a full aperture collimator in the vacuum chamber using the 6 m blocking body already made to fabricate the membrane. This has a spherical surface, but can collimate monochromatic light through the use of a computer generated hologram. The shape error of the sphere at the cryogenic test temperature would be first measured from the center of curvature, then the hologram would be built to take care of any figure distortion as well as spherical aberration.

5.2 Launch possibilities

Present launch vehicles have the capability to place a 2 ton spacecraft into distant orbits, but are not currently provided with fairings of diameter greater than 4 m. Ariane V, H-2 and Proton would have the authority to control aerodynamic loading of a fairing of 7 m diameter, large enough to house a 6 m telescope. The cost of developing the large fairing is estimated at around $100 M, not much more than the cost for modifying a Boeing 747 to accomodate the 2.5 m SOFIA telescope. The performance loss from drag is not large. Suppose the drag for a 7 m diameter shroud is about 5 tons, and lasts for about 30 seconds, and the rocket fuel has a specific impulse of 300 seconds; then an extra 0.5 tons of fuel will be expended, compared to hundreds of tons of fuel in the booster and first stages. A larger impact may come from the increased mass of the larger shroud, which cannot be dropped until the vehicle is well clear of the atmosphere.

5.3 Advantage of a fully assembled telescope with monolithic mirror

Radio or long wave infrared telescopes that could be folded for launch in a small fairing and subsequently deployed have been under consideration for many years. The possibility of using an Atlas to launch an 8 m NGST, similarly deployed to reach the far more demanding near-optical diffraction limit, is also now under consideration. This approach would eliminate the need for new fairing development, and might allow the somewhat larger size, if the larger, more complex structure can be made light and stiff enough. MARS technology would be well suited to making ultra lightweight segments of optical quality.

A scheme that would remove the need for segmenting and deploying the primary mirror itself and still fit in existing shrouds is to use a MARS mirror in the form of a rectangular or elliptical monolith, about 4 x 8 m in size (Angel *et al.* 1996). This would still require some deployment of the full optical assembly.

There are, though, many advantages to launching a monolithic mirror in a fully assembled telescope. The absence of boundaries and discontinuities across the mirror surface will result in less scattered light, especially important in the study of close, faint companions. It will also greatly simplify the metrology and control system. The probability of a successful mission is much higher for a fully

assembled telescope, because of the full operational test made possible prior to launch, and there is no risk of large mirror elements getting stuck or not taking up their exact position during deployment. The only moving parts of the MARS based telescope are the many identical screw actuators, which have small motion, are a single small part that can be tested exhaustively before and after mass production. By using enough of these so some are "spare", we can be made fundamentally tolerant of actuator failure. Such tolerance is not possible for mechanisms to unfold a mirror.

The simplicity of monolithic construction will result in lower total costs, particularly if the cost of large fairing development is shared. In this regard, we note that such a new launch capability would enable a range of other large lightweight missions, of particular value to astronomy. A large diameter launch capability, once developed, will make practical the launch of simply built, rigid lightweight telescopes of different types to cover the electromagnetic spectrum. As an example, it is possible that the first test launch before NGST of the expanded fairing could be used to orbit an inexpensive 6 m dish for far infrared and submillimeter astronomy. This would be an extremely powerful research tool in its own right, and could also be used to test NGST technology. If, by contrast, every new telescope larger than 3 m has to be individually configured and verified for folding and deployment, costs could be prohibitive.

If we could be sure that single reflectors much larger than 6 m would ultimately be needed in space, and that they should be deployed rather than assembled in space, then the technology for automatically unfolding large optical mirrors might be worth developing for its longer term value. But for the largest astronomical space telescopes, arrays of smaller single dishes may be preferred, as they are for most of the largest optical and radio telescopes on the ground, for example the VLA and the VLT and the LBT (Salinari, 1997). Interferometric arrays yield higher resolution than single apertures of the same area, and are clearly preferred for critical applications, like the imaging of Earth-like planets in other solar systems (Angel and Woolf, 1997). A simple but powerful successor to the monolithic NGST could thus be made by orbiting two similar 6 m dishes and a beam combiner, three separate spacecraft that would be operated as a two element interferometer with variable baseline by precise station keeping.

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