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Testing NGST Segment Technology in a 3.5-m Space Telescope

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Abstract. A 3.5-m space telescope built soon with a thin glass mirror would be valuable both as a facility for scientific observations from the ultraviolet through near infrared, and as a test of technology for ultra-lightweight mirror panels. Before deploying the NGST, which would need six or eight panels at 3.5-m size, a flight test of a single panel would be very desirable. We are currently building a 2-m prototype mirror panel with a 2 mm thick glass faceplate. It meets the lightweighting specs set for NGST and is expected to exceed those for surface quality when tested at cryogenic temperatures. We estimate 93% Strehl ratio at 1 μm wavelength, 69% at 300 nm and 30% at 100 nm. This prototype has a shallow, spherical surface and non-ruggedized actuators unsuitable for spaceflight. The next step will be to build a segment-sized 3.5-m telescope mirror, engineered to survive the launch environment and to demonstrate actuator fault tolerance and figure control from measurements at cryogenic temperatures of simulated starlight. After qualification in 2002, the 140 kg mirror would be available for a space mission. A 4-mirror telescope design is suggested here that takes advantage of the direct active control of the primary mirror to eliminate the need for a deformable mirror. It achieves a diffraction limited field of 5 $\times$ 15 arcminutes, incorporates a fast steering mirror to correct for telescope mispointing, and has a plate scale matched for direct focal plane placement of detector arrays. Such a lightweight and simple telescope could be accommodated in a Midex-class mission, independent of the NGST program, but laying the scientific and technical groundwork for the much more powerful telescope.

1. Principles of Thin Glass Mirror Technology

1.1. Mirror Concept

Single 8-m class mirrors with the asphericity and accuracy needed for NGST are being produced today in glass, for ground-based telescopes (Fig. 1). Our concept for future space telescopes is to build as far as possible on this ground-based heritage, taking advantage of two decades of development of technology for large mirror fabrication and metrology and for active wavefront correction.

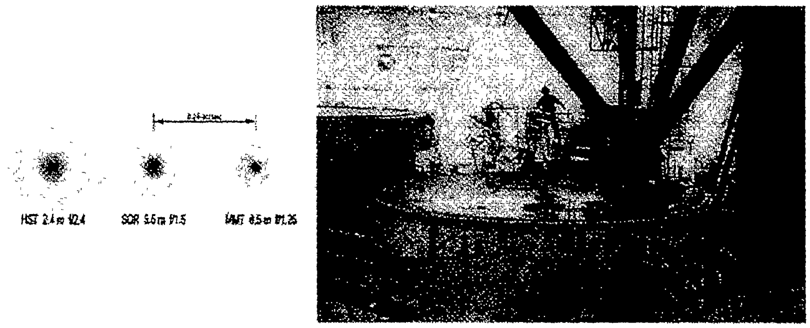

Figure 1. Image quality at 0.5 μm wavelength for the HST and from surface figure measurements of two mirrors completed at the University of Arizona Mirror Lab for ground-based telescopes. The 3.5-m Starfire Optical Range mirror (f/1.5) has 19 nm rms surface error, the 6.5-m Magellan I (f/1.25) has 19 nm (Martin et al. 1992; Martin et al. 1998). Two mirrors with almost the same size and figure as the NGST, 8.4-m at f/1.14, are now being made at the Lab for the Large Binocular Telescope (Hill & Salinari 1998).

The critical evolution needed for space is to make the mirrors much lighter in weight. The density of ground-based 8-m class mirrors, including their actuators and steel cells, is 1000 kg m^{-2} while the NGST target is 15 kg m^{-2} (Stockman 1997). Our solution has been to develop a method by which an 8-m glass membrane 2 mm thick (5 kg m^{-2}) can be finished in one piece by the current process to the specified aspheric figure, while bonded to the face of a heavy mirror (Miller et al. 1998). It is then cut into segments which when unglued are remounted on stiff, lightweight panels, also weighing 5 kg m^{-2}. A trick for manufacturing the glass membrane described below ensures it is free of stress while being figured, so it will not distort when unglued.

The second new requirement for space is to operate the mirror at cryogenic temperatures. Even small inhomogeneities in thermal expansion will cause the support to distort on cooling by 200 K. This is taken care of in our concept by using multiple, adjustable attachment points that allow for lateral differential expansion on cooling. These provide remotely controlled screw adjustment in the axial direction to recover the original glass shape. The principle is illustrated in Fig. 2 (Angel et al. 1997; Burge et al. 1998). To avoid local distortion when attachment is made to the panel, the screw adjustment points must not introduce local bending moments. Ways to avoid this hazard have been developed for the prototypes described below.

This technology relies on internal stiffness to hold mirror shape against vibrations, and active control to hold the shape over long time periods. The backing structure is made from thin sheets of carbon fiber composite laminate. This material is extremely stiff, strong, and light, and can be made into optimized structures with thin sections and very low weight.

Because of the changing thermal environment and instability of the structure on-orbit, the mirror will require periodic adjustment of the screw attach-

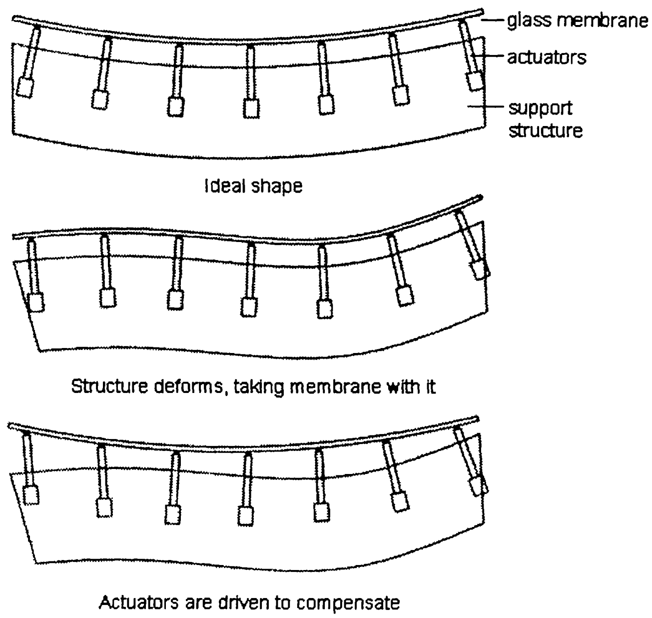

Figure 2. Principle of ultralightweight mirror with position actuators to compensate distortion of the support structure.

ments. The information to make these corrections will be derived from wavefront measurements of stars, using techniques for closed loop servo control already developed for adaptive optics. Correction to the optical diffraction limit of a ground-based 3.5-m telescope has been accomplished, as shown by images taken with the SOR 3.5-m telescope shown in Fig. 3. The spacing of control actuators here is 12 cm relative to the entrance pupil, similar to the density anticipated for the space mirrors. The fact that adaptive control works on the ground is very encouraging for active space optics, because the fast control speed to compensate atmospheric turbulence makes the job much more difficult than the periodic adjustment to correct for creep of the NGST support structure.

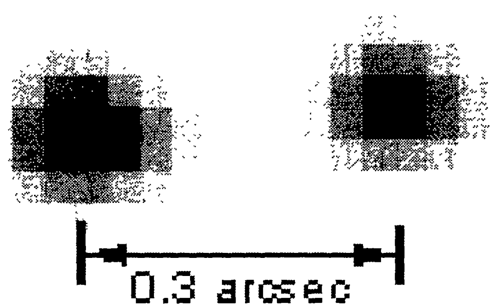

Figure 3. Images obtained at 0.85 μm wavelength with the USAF Starfire Optical Range (SOR) 3.5-m telescope of the binary star κ Peg. The correction was based on wavefront errors sampled at 1500 Hz. The FWHM of these images is 0.059 arcsec, close to the diffraction limited width of 0.050 arcsec (courtesy R. Fugate).

For correction in closed loop of the slow thermal distortion of a mirror in space, long exposures with the wavefront sensor are permitted. Furthermore, because the error is localized at the primary, reference stars over a wide field show the same error. The density of faint field stars is high enough, even at the galactic poles where they are sparsest, that one can always be found for which a few minutes integration will be sufficient to derive corrections for actuators spaced by 10 cm. Also, in contrast to the situation for adaptive atmospheric correction, active control in space over the primary will yield a large field of many arc minutes corrected to the diffraction limit (Angel & Woolf 1998).

The wavefront sensor could be a dedicated instrument, optimized for efficiency and accuracy, or could be derived from in-focus and out-of-focus images from a simple focal plane array, via phase retrieval algorithms (Redding et al. 1993). Calculating the required actuator adjustments is straight forward. Since position actuators are used to control the flexible membrane, each actuator simply moves in proportion to the phase error local to that actuator.

There is general acceptance that closed loop operation will be required inevitably to hold the figure of the ultralightweight NGST mirror, but there remains an understandable desire to avoid excessive complexity. All methods, though, invoke the use of active correction with many actuators. In our implementation, the actuators are located behind the primary, where there is enough room to engineer redundancy. Because they apply zero force (their purpose is to allow the backing structure to move without distorting the glass), bad actuators can be disconnected without seriously impacting system performance.

If an actuator fails for any reason, it will be disengaged from the glass. Control of the glass surface will use the neighboring actuators. The alternative to correcting the primary mirror directly is to compensate for its figure or boundary phase errors with equal but opposite errors made in a deformable mirror at a pupil conjugate to the primary — the standard method of adaptive optics. However, this greatly impacts reliability. It adds another small but complex mirror whose tiny actuators, if they fail, will likely have to remain stuck. Since their job is now to contort the deformable mirror by applying force, even if they could be disconnected their correction function would be compromised.

1.2. The 0.53-m Diameter Prototype

A first test of the manufacture and position support of a thin glass membrane was made in 1996 (Miller et al. 1997). The membrane started out as a thick blank of Zerodur with very low internal stress. Its back side was polished as a convex spherical surface and then attached to a support blank with matching concave surface. Pitch was used as the bonding agent, because it yields over time to relieve internal stresses. (The blank was made initially thick, so as to resist strain on the initial attachment). Thinning, figuring, and testing were completed by conventional means, after which the shell was removed by melting the pitch. It was mounted via 36 piezo-driven screw actuators to a carbon fiber support. After adjustment, tests at room temperature showed a surface profile dominated by sagging between the support points. The distortion from residual internal stress was barely detectable, no more than 33 nm rms after removal of the calculated gravitational bending (Fig. 4). The mirror would thus yield diffraction limited imaging at 1 μm wavelength, meeting or exceeding the NGST baseline for imaging performance. As we show below, higher accuracy with good performance into the visible and ultraviolet is expected in larger mirrors with the same membrane thickness and improved actuators.

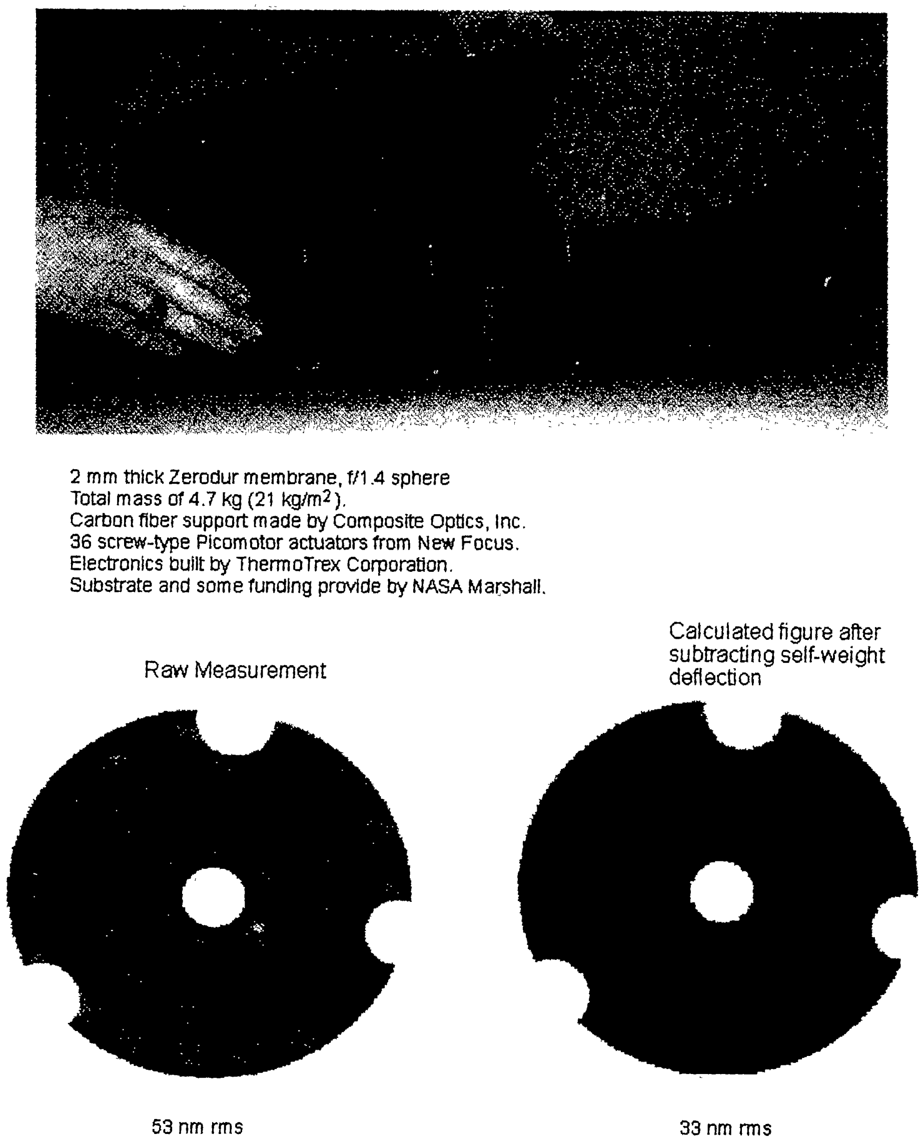

Figure 4. The 53-cm NGST prototype, with optical measurements after manually adjusting actuators to optimize the figure.

2. Current 2-m Cryogenic Prototype and Details of Expected Performance in the Optical and Ultraviolet

2.1. The 2-m Prototype

Our team is currently building a 2-m prototype mirror aimed at 20 nm rms surface accuracy with mass density 13 kg m^{-2}, including cabling and electronics

(Burge et al. 1998). Development of this NGST Mirror System Demonstrator (NMSD), funded by NASA Marshall Space Flight Center, provides a critical step towards flight optics. The 2-m mirror, shown in Fig. 5, is a scaled up version of the concept proven with the 0.5-m mirror. It will be tested at 35 K (Jacobs et al. 1998) under interferometric control in an advanced cryogenic facility being built at Marshall. The mirror will use cryogenic screw actuators with 6 nm rms resolution at cryogenic temperatures. The glass membrane is being made at the University of Arizona from borosilicate glass (Borofloat from Schott) because this material has zero CTE at 35 K and could be made as a 2-m, homogeneous meniscus blank.

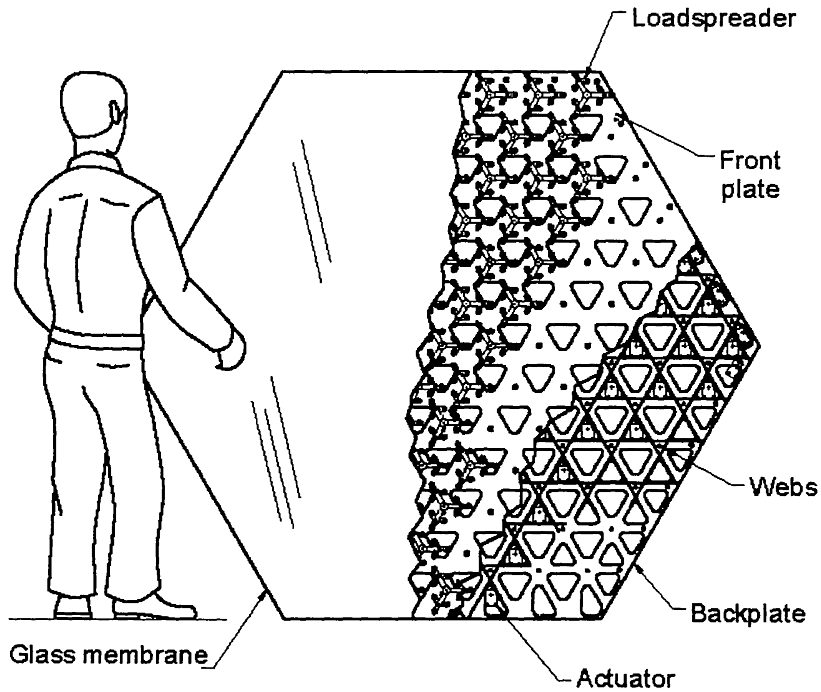

Figure 5. 2-m prototype under construction at the University of Arizona.

The design of the 2-m mirror anticipates the requirement to withstand launch. Each actuator acts through load spreaders to transmit launch forces equally through 9 points on the glass. The load spreaders pivot freely to ensure that they do not induce moments that would distort the membrane. The 2-m mirror will be tested dynamically with low level exciting forces, but financial and schedule constraints have not allowed it to be worked through to the point of withstanding rigorous launch testing. We have already put a 1-m membrane on a fixed point mount through the acoustic loads of launch without damage, and we plan to subject a 0.5-m mirror to complete proto-flight testing.

The 2-m NMSD has a 20-m radius of curvature, chosen to match that of the flight mirror so it has the same shell stiffness. Since the influence of the actuators is dominated by local effects, the performance of the 2-m demonstrator should be representative of the surface quality obtainable with a large mirror.

2.2. Expected Performance in the Optical and Ultraviolet

A detailed simulation of the 2-m mirror was performed using finite element modeling. The effects of material inhomogeneity on cooling to the 35 K operating temperature are the largest. These were evaluated using a power spectrum for the membrane CTE variations estimated from sample measurements, and were simulated at discrete frequencies with random phase. Other effects taken into account were residual strains from annealing, blocking strains, and miscellaneous effects from the membrane support. Control of the surface using all actuators was simulated, and a surface map generated by adding the effects of all 17 different models that approximate surface distortions. As corrected by the actuators, the overall surface figure was 27 nm rms, which includes the entire 2-m hexagonal optic, with no guard band around the edge. Plots of the simulated surface are shown in Fig. 6.

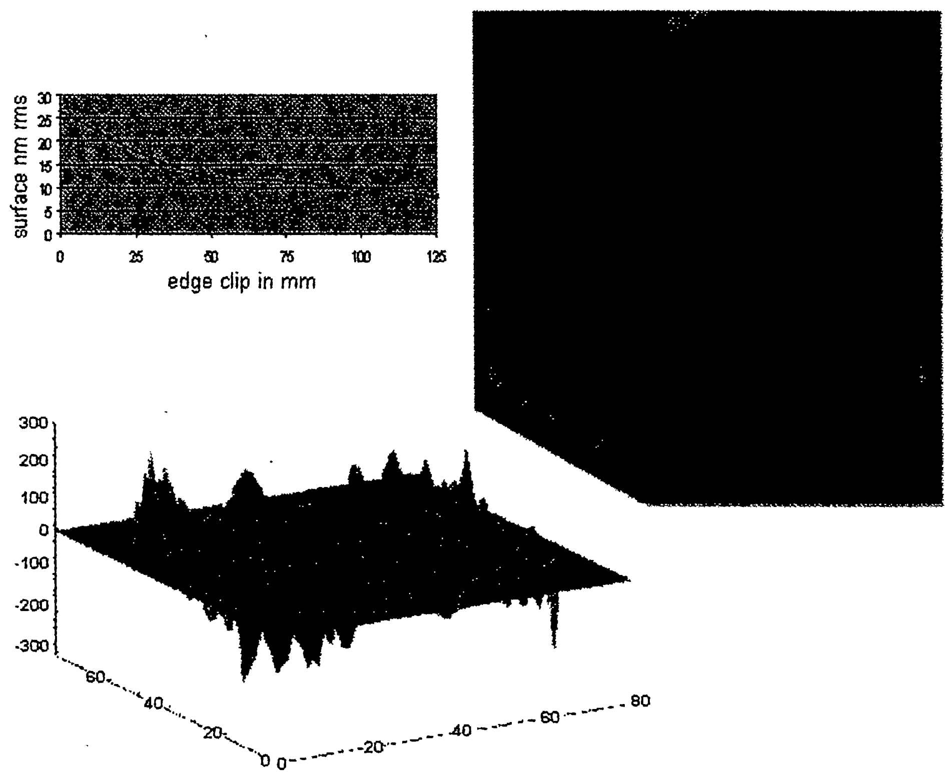

Figure 6. Surface maps showing simulated figure errors of 27 nm rms over the 2-m hexagonal mirror. The insert graph shows the effect of clipping data at the edge.

The point spread functions for star images reflected at different wavelengths from the surface were calculated using FFT analysis. The finite element data were sampled at 80×80 pixels across the 2-m part, with 25 mm square pixels. These surface data were converted to phase re-sampled, and were placed in the center of a 1024×1024 array and the point spread function was calculated at several wavelengths by taking the modulus-squared of the Fourier transform.

Only the central 512 × 512 region was used to determine the PSFs shown in Fig. 7, to avoid aliasing effects.

A strong, diffraction-limited central spike is dominant in the PSF at all wavelengths. For 100 nm light and a 3.5-m version of our mirror, this central spike has 25% of the energy in a 6 milli-arcsecond (mas) FWHM lobe. The mirror surface errors diffract 75% of the energy into a diffuse halo 0.57 arcsec wide. At 300 nm, the telescope focuses 60% of the energy into a central core 20 mas wide and diffracts 40% of the light in a 1.7 arcsecond halo. The mirror is fully diffraction limited (*Strehl* > 80%) for wavelengths > 500 nm.

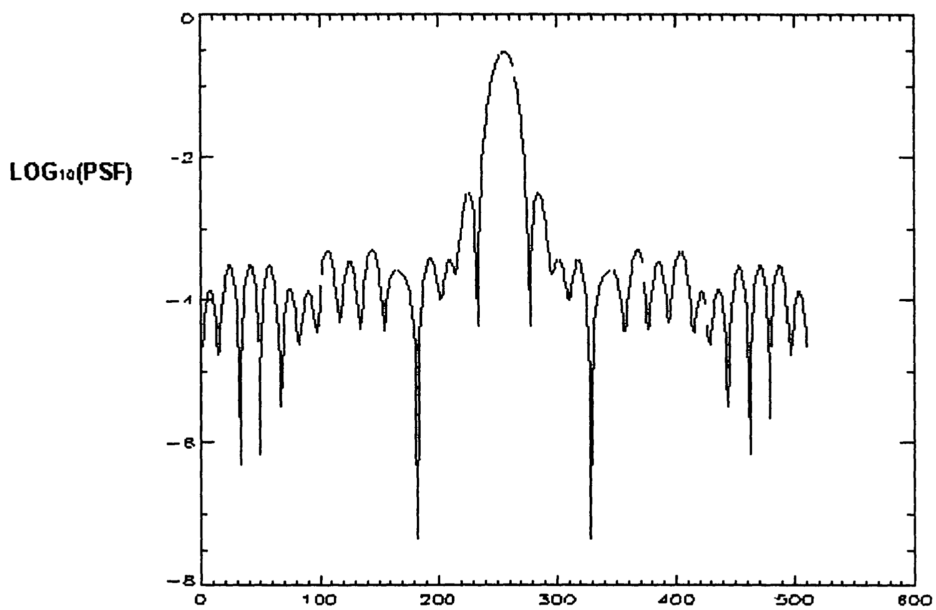

Figure 7. Point spread function calculated for 100 nm light from simulated mirror data, plotted on a logarithmic scale.

The form of the images is somewhat unique to our type of mirror. The PSF core has orders of magnitude more energy density than the sidelobes, an effect that arises because the mirror is always corrected over scales > 15 cm by the actuators. The remaining errors consist of high frequency ripple and prominent edge effects. As a result, the light that is diffracted out of the central core of the PSF goes mostly out to angles > $\lambda/30$ cm or 0.07 arc sec at 0.1 μm. The largest surface errors are localized at the edge, because material strain gradients tend to curl the edges, and the position actuators cannot apply correcting moments at the edge. As a result, the normal calculation of Strehl ratio (defined to be the fraction of energy in the central core of the PSF, normalized by the core for an ideal system) to be much higher than one would predict using the usual Marechal expression for Strehl, $\exp(-\sigma^2)$. The correctly calculated Strehl ratio, a good figure of merit for astronomical images, is plotted as a function of wavelength for our simulated mirror surface in Fig. 8, along with the approximate calculation. The images remain diffraction limited into ultraviolet wavelengths despite figure errors of 27 nm rms, because the edge effects degrade the rms much more severely than they do the Strehl ratio.

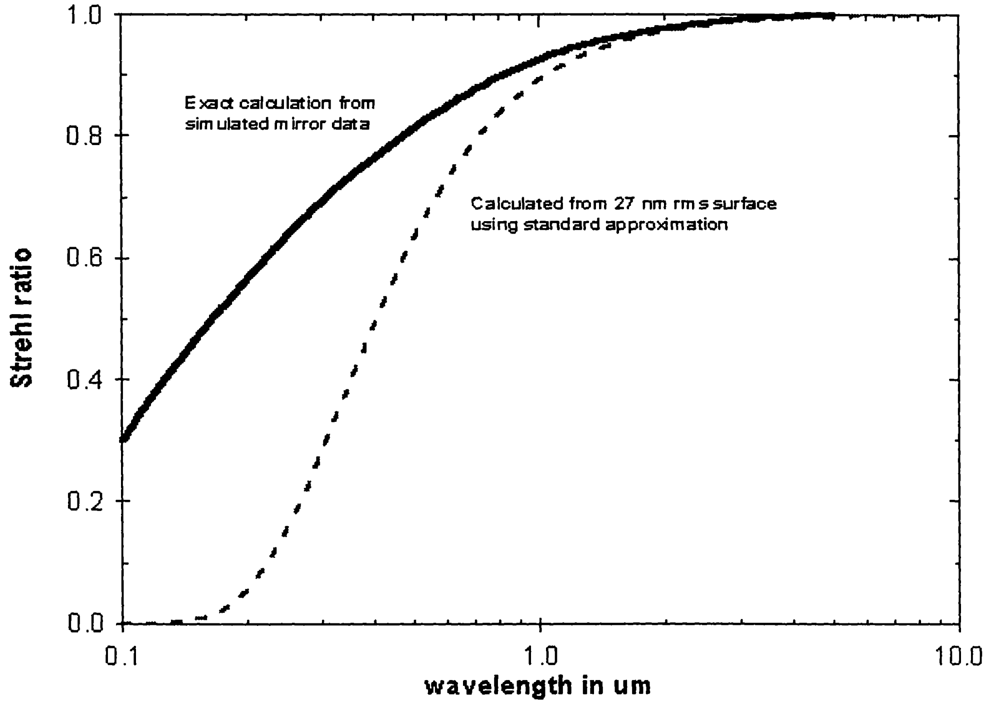

Figure 8. Strehl ratio as function of wavelength, based on PSF analysis and the simplified (and inaccurate) Marechal approximation $\exp(-\sigma^2)$.

3. A 3.5-m Mirror as an Advanced Demonstrator of the NGST Mirror System

3.1. Requirements for the Next Mirror Prototype

The successful demonstration of the 2-m prototype should prove the essential requirements of low weight, surface accuracy, and cryogenic operation, but a number of practical engineering issues will remain. A system with actuators that are fault-tolerant needs to be specifically demonstrated at the size of a full-scale segment. Because several hundred actuators will be used in larger segments, provision must be made so that failures do not leave uncontrolled bumps or dips in the mirror. The method to disconnect failed actuators mechanically is being developed and needs to be verified, and the quality of surface measured when neighbors take over. The same mechanisms must protect against the acoustic and mechanical vibration environment of launch. A second set of developments relates to fabrication of the membrane segments at the size needed for the NGST, and with the variable thickness characteristic of an aspherized mirror. Handling a full-scale fragile membrane, especially the step of ungluing, presents challenges that need to be tested. The large number of actuators, cables, and attachments require a significant assembly and test effort.

In deciding what size and shape to make a prototype segment, we must take into account how it will be made and tested. Our fabrication method for the 8-m primary, in which the segments are figured together as a single axisymmetric surface, allows for any segmentation geometry, but it does not lend itself to the manufacture of a single off-axis piece. Furthermore, the shape of the segments making the 8-m surface is not yet known. Figure 6 shows the eight-petal concept studied by NASA (Stockman 1997), but other concepts call for division into hexagons (Lillie et al. 1998), or into three large segments like a gate-leg table (Woodruff et al. 1998). For these reasons, we recommend that the new demonstrator be built as a circular, on-axis paraboloid of 3.5-m diameter, as shown in Fig. 9. It is representative of the full size needed for keystone or hexagonal segments.

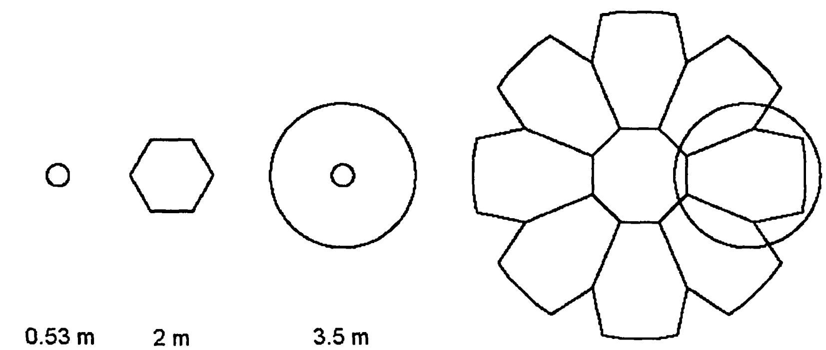

Figure 9. Relationship of the 3.5-m mirror to earlier prototypes and to the 8-m NGST with clipped petals.

The optical quality of the mirror system would be verified in a complete simulation of the NGST control system. The mirror would be configured with a secondary mirror as a complete telescope, and tested with an artificial star in the cryogenic vacuum chamber. To verify closed loop control with wavefront sensing by phase retrieval, the collimated test beam must be achromatic, extending into the infrared. The collimator would be built with a rigid parabolic mirror, with figure similar to the primary. Since we need high confidence in the quality of the test beam, the figure of the paraboloid itself must be verified at cryogenic temperature. The test chamber would include the collimator and telescope facing each other.

An advantage of the 3.5-m on-axis system is that this test configuration could be fitted into the existing facility at Marshall Space Flight Center, the same one being used to test the 2-m prototype (Fig. 10).

These ground tests should provide valuable lessons about how the 8-m NGST itself might be tested prior to launch. A full aperture test in a large cryogenic chamber under an achromatic collimator would be equally desirable, to verify segment phasing and alignment procedures. Alternatively, it might be proven that sub-aperture tests with the 3.5-m collimator would suffice. In either case, the 3.5-m test is likely to result in cost savings in what is potentially a very expensive item in the NGST budget.

3.2. Value of Testing the Mirror Technology in Space

Many additional advantages would result from engineering tests in space. Subscale flight tests are already planned for deployment of the sunshade and mirror

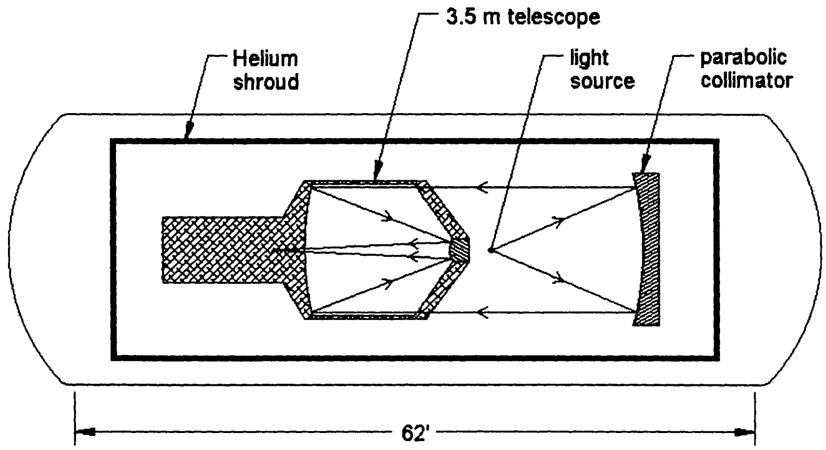

Figure 10. 3.5-m cryogenic test configuration, shown to scale in the existing MSFC vacuum test chamber. A new 19' diameter helium shroud is shown. The parabolic collimator would be imprinted with a computer generated hologram, for verification of figure at the cryogenic operating temperature by interferometry from its center of curvature.

segment (ISIS and NEXUS; Coulter 1998). The same philosophy of "build a little, test a little" applies with equal validity to the mirror segments themselves. We identify below three specific key test areas, but the greatest engineering value will likely be the unanticipated features that become apparent only when the mirror system is operated in space as a telescope.

One specific performance test that is not possible on Earth is the effect of gravity release. Other space telescope mirrors, e.g., in HST, SIRTF, and AXAF, are solid enough that gravity release is not large and can be modeled and simulated to high accuracy. The ultralightweight construction of NGST segments is inherently more flexible, and thus explicit measurement of the surface precision achieved in zero g will be especially valuable. Only by this measurement can we determine reliably the shortest wavelength for diffraction limited operation by NGST, and thus the wavelength limit to set for its instruments.

Another critical test, paralleling that of NEXUS for segment alignment, will be the on-orbit active control of the surface figure from measurements of the stellar wavefront. Direct, high-resolution wavefront phase measurements (Angel 1994) would be made in addition to those by the infrared phase retrieval methods likely to be used by NGST. The higher resolution would be used to map residual local distortions about the actuators, for a critical performance evaluation. Autonomous active control of mirror figure in space from phase retrieval methods is a further critical technology advance desirable for NGST, and this too would be tested.

A third area is the on-orbit test of passive cooling to cryogenic temperature. There is scarcely any flight experience in this area to draw on, none with large optics. The 3.5-m mirror weighing only 140 kg would be light enough to be orbited to the same distant, cold orbits needed for NGST, where operation at liquid nitrogen temperature or colder could be tested.

4. An Astronomical Mission Using the 3.5-m Prototype

4.1. Potential at Infrared, Optical, and Ultraviolet Wavelengths

We have previously made the case that an astronomical telescope using the 3.5-m prototype mirror passively cooled to 100 K would make a valuable scientific as well as technical bridge to the NGST (Angel & Burge 1998). Its most unique capability would be to explore the very dark sky window between 2 and 5 μm, for example to obtain very deep images of the HDF to redshifts twice those recently reached at 1.8 μm with HST's NICMOS. The 2 - 5 μm region of minimum zodiacal sky background, midway between the peaks from reflected sunlight (0.5 μm) and thermal emission (10 μm), is currently inaccessible for deep imaging by the HST and ground based telescopes, because of thermal background from their warm optics. The shortest wavelength photometric bands of SIRTF, at 3.5 and 4.5 μm will provide initial capability, but will be of limited use for cosmological studies because diffraction by its small (0.85-m) aperture leads to background source confusion. The cooled 3.5-m telescope has 4 times sharper images and 16 times the light gathering power. The infrared sensitivity when operated at 100 K lies intermediate between the HST and NGST, as shown by the limiting point source flux given as a function of wavelength in Fig. 11. The greatest gain over both HST and SIRTF, by a factor of 50 or more, is in the 2 - 6 μm region.

The 3.5-m telescope will have great value for observations in the optical and ultraviolet as well as the infrared. The projected Strehl ratio we calculate for the 2-m segment is a good estimate of the value to expect from a 3.5-m segment with the same mirror technology. If anything, the Strehl should be better if the outer 25 mm in radius which tends to be curled can be masked out. The speckles, including the central core, will get nearly 2 times smaller than we show for the 2-m. The general shape of the halo will not change in magnitude or width, only in the sharpness of the speckles. The larger aperture coupled with sharper, diffraction limited images will result in better imaging performance than for the HST, with sensitivity to point sources nearly a magnitude fainter. The new telescope can also be configured for a much larger field of view, as we discuss below. Its larger light grasp will allow for ultraviolet spectroscopy with better signal-to-noise ratios or higher dispersion than with the HST.

4.2. Optical design and instrumentation

As part of a study for the Integrated Science Instrument Module (ISIM) for NGST, we have looked at the telescope optical design itself with a fresh perspective. A new concept has emerged which is well-suited also to the needs of a 3.5-m space telescope (Fig. 12). In common with other NGST designs under consideration, the cassegrain focus is reimaged with a tertiary, but the design differs in that a fast steering mirror rather than a deformable mirror is located at the intermediate pupil, and this pupil is on-axis. By taking advantage in this way of the primary whose aberrations are corrected directly to eliminate the deformable mirror, the design achieves an annular field 0.5 degrees in diameter with diffraction limited images, and fast guiding with the 20 mm steering mirror that can steer the telescope line of sight by a fraction of a degree on the sky without loss of image quality or field. The requirement for telescope pointing is thus very relaxed. The field for guide stars is large, so a number relatively

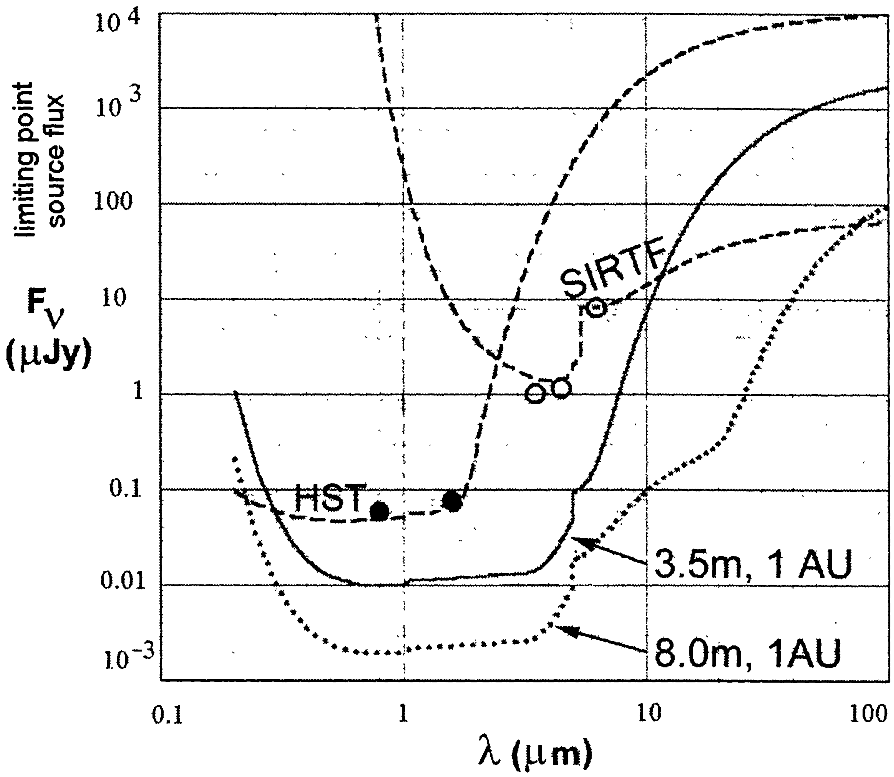

Figure 11. Sensitivities to unresolved point sources for different telescopes, computed on a consistent basis as a function of wavelength for 10 σ detection in 10,000 seconds in a broad pass band, $\lambda/\Delta\lambda = 0.25$. The NGST at 40 K and 3.5-m telescope, taken to be at 100 K, are assumed to be diffraction limited to 1 μm wavelength (33 nm surface error), and SIRTF to 5 μm. The sensitivity measured for HST plotted as filled circles and the projections for the SIRTF IRAC camera plotted as open circles are consistent with the model. (The new optical camera for HST will give improved sensitivity below 1 μm, bringing it in line with the D^2 scaling with aperture expected in otherwise similar telescopes limited by the optical zodiacal background.)

bright stars will always be accessible, even in fields with heavy obscuration. The re-imaging scale suitable is chosen for direct placement of imaging arrays, with no further relay optics so the entire optical train to the detectors has only four reflective surfaces. The off-axis annular field shown in Fig. 12 has a plate scale of 1 mm arcsec^{-1}, chosen for Nyquist sampling of diffraction limited images at 300 nm with 10 micron pixels and at 600 nm with 20 μm pixels The inner and outer field radii about the telescope axis are 2.4 and 7.2 arcminutes (140 and 400 mm), allowing for the placement of many 4096$\times$4096 CCDs.

Ultraviolet spectroscopy at high spectral resolution is potentially an important scientific application for the telescope. For unresolved sources such as stars and quasars, an instrument matched to diffraction limited images is remarkably simple and could be made inexpensively. An example is the prism cross-dispersed spectrograph reported by Ge et al. (1996), optimized for diffraction

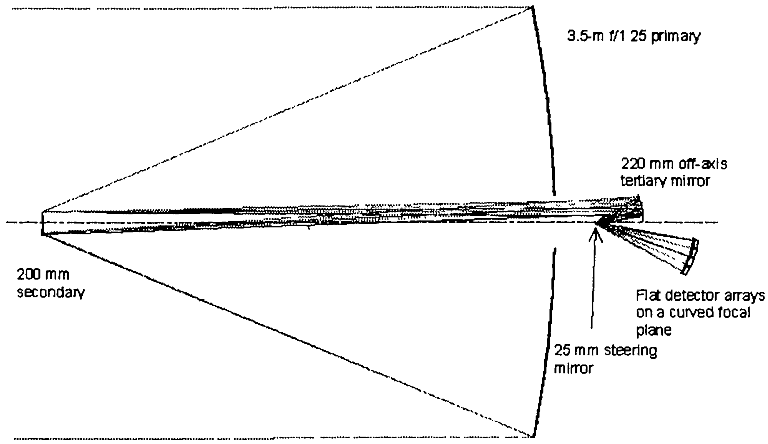

Figure 12. Optical layout of a 3.5-m space telescope that steers its line of sight over 0.5° with a 20 mm flat mirror.

limited images from adaptively corrected ground-based telescopes. Resolution of 200,000 over an octave of spectral coverage is recorded on a single 2048×4096 CCD detector.

At infrared wavelengths, smaller plate scales are needed to obtain Nyquist sampling of diffraction limited images. For example, the 0.2 arcsec images at 3.5 μm wavelength would be sampled by an infrared array at a plate scale of 200 μm arcsec^{-1} for two 20 micron pixels per diffraction width. This scale would be achieved by relaying a separate keystone shaped, 3-arcminute field by a similar tertiary/steering mirror system configured for smaller magnification.

5. Schedule

The past and current mirror prototypes have been built quite quickly. The 0.53-m prototype was built in about 4 months, from the start of funding and acquisition of the Zerodur blanks to the interferometric tests shown in Fig. 4. The 2-m prototype is scheduled for room temperature tests 16 months after funding, with cryo testing 4 months later. This interval includes melting and annealing of the blocking body and membrane blanks, and installing a helium shroud at the Marshall test facility.

We believe the 3.5-m mirror could be manufactured in about 2 years. Three 3.5-m mirrors at f/1.5 and f/1.75 were cast and figured at the Mirror Lab by the same method to be used for the 3.5-m membrane (Fig. 9). The optical figuring of the last of these (the WIYN mirror) took 2 months. The 3.5-m prototype would be made from standard Zerodur. This glass has a low expansion coefficient of 2×10^{-7} K^{-1} over the operating range 70 - 90 K, as well as being conveniently low for fabrication at room temperature. 3.5-m blanks are available from stock, and if ordered soon for delivery by mid-1999, the first 3.5-m, 2 mm thick aspheric meniscus could be completed before the end of 2000. The cryogenic test facility started in 1999 could be ready for tests in 2001. Such an aggressive schedule would allow for a very complete evaluation on the time scale needed for NGST to make an informed choice of proven mirror technology and still make a 2007 launch.

6. Acknowledgments

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