

UltraLITE Glass/Composite Hybrid Mirror

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ABSTRACT

The mass of the primary mirror has dominated the mass of larger aperture (>1 m class) telescopes. Spaceborne telescopes have much to gain from a significant reduction in areal density. Areal density is often limited by the stiffness to weight ratio of the primary mirror. Two key factors drive this criteria: telescope structural characteristics (launch and deployment) and fabrication requirements. A new class of hybrid composite mirrors has been designed, prototyped, and fabricated to demonstrate the advantage of the high stiffness to weight ratio of carbon fiber composite materials and the superior optical fabrication for low expansion glasses. This hybrid mirror utilizes a unique "set and forget" fabrication technique. A thin meniscus of glass is mounted to a stiff composite support structure using composite flexure rods. The meniscus is lightweighted using waterjet pocket milling and is conventionally polished to a precise radius of curvature. This meniscus is then supported on the flexures and actuated to a precise figure. The flexures are fixed and the actuators are removed. The substrate is then ion figured to achieve the final figure. The areal density of this mirror is 10 kg/m². Surface figure on a 0.25m aperture prototype was demonstrated at better than $\lambda/4$ (visible) prior to ion figuring. Two 0.6 m mirrors are under fabrication. The design of the mirror and results of the fabrication and testing will be discussed.

Keywords: Mirror, lightweight mirror, low areal density, hybrid mirror, composite mirror, space optics

1. INTRODUCTION

1. Motivation for Lightweight Optics

Major efforts^{1,2,3} in space optics have inspired research in lightweight optics. A trend in space borne telescopes has been an increase in collection area and in resolution. Both of these demands in performance require larger primary mirror aperture sizes. Larger primary mirrors can be achieved using either monolithic or segmented mirrors. Since the primary often dominates the mass budget of the telescope, either of these options imply larger mass for the overall system. Technologies that enable lighter primary mirrors (<15 kg/m²) will enable lower mass telescopes with larger apertures to be deployed in space reducing the launch costs of these missions.

Table 1.1: Common Materials for Lightweight Mirrors

	ρ Density kg/m ³	E Young's Gpa	α CTE ppm/K	K Thermal Cond. W/m-K	sqrt(E/ ρ) Freq for same Geom	α/K S State
Pyrex	2230	63	3.300	1.13	1.06	21.676
ULE	2210	67	0.030	1.31	1.10	0.170
CFC	1780	93	0.050	35.00	1.44	0.004
Aluminum	2700	68	22.500	167.00	1.00	1.000
MMC	2910	117	12.400	123.00	1.26	0.748
Beryllium	1850	287	11.300	216.00	2.48	0.388
SiC	3210	465	2.400	198.00	2.40	0.090

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2. Materials

Materials for primary mirrors deployed in space must meet several criteria: low density, low thermal expansion, high stiffness, high thermal conductivity. Low density contributes to low mass. Low thermal expansion contributes to minimizing the impact of thermal gradients on the optical prescription. High stiffness results in low mass by virtue of structural efficiency. High thermal conductivity eliminates time dependent thermal gradients that can impact the figure of a primary mirror. The following table (see Table 1.1) is a summary of materials^{4,5} that have been used in telescopes.

Note that carbon fiber composites exhibit many of the desirable properties. However, although these materials are space qualified and are used in many systems ranging from the Chandra X-Ray telescope to microwave RF reflector dishes, they have not been successfully used as the optical surface of visible quality mirror. Given their excellent thermal expansion match to glass, composites can be combined with low expansion glasses to form a structurally efficient glass-composite hybrid mirror.

3. Designs

Lightweight mirrors have been created using a variety of designs.⁴ Popular designs include contoured back, open back pocket milled, sandwich, actuated. The most structurally efficient of these designs is the sandwich mirror. The sandwich structure (closed back and continuous facesheet with a low density core) offers the highest stiffness with the least mass.

4. Fabrication Methods

The fabrication methods for constructing lightweight mirrors can be classified into substrate manufacturing and optical surfacing. Lightweight mirror substrates have been manufactured using casting, bulk machining processes such as milling and grinding, waterjet pocket milling and bonding/fusing of materials. To avoid the quilting effects often observed using traditional polishing, optical surfacing has been accomplished using computer controlled small tool polishing and ion figuring. The selection of materials often dictates the method of fabricating the substrate and the method of polishing. These factors combine to ultimately determine the areal density of the lightweight mirror.

2. DESIGN CONCEPT

The design for the UltraLITE telescope includes a segmented primary mirror. Three mirror petals, 0.6 m in diameter, are deployed and phased to act as a single primary mirror. The design criterion for the mirror segments is summarized in the following table (see Table 2.1). A key requirement is an areal density of 10 kg/m².

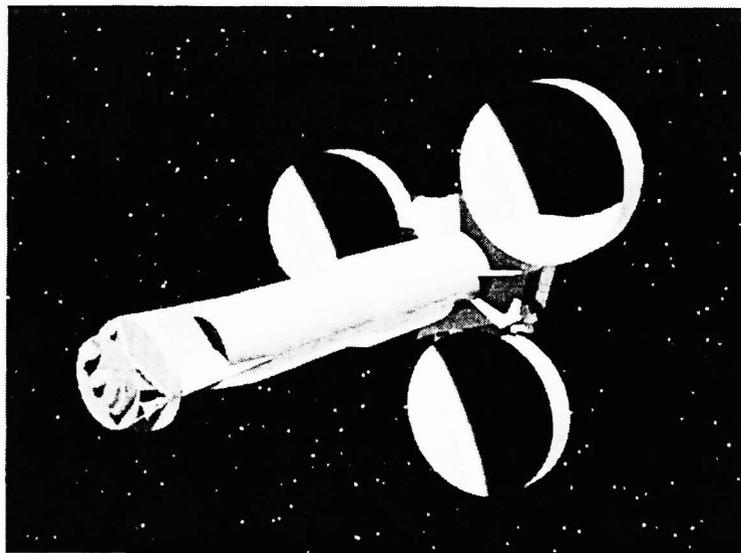


Figure 2.1: Diagram of the UltraLITE Telescope

The primary mirror design was selected in order to optimize the use of glass and composite materials as well as minimize the manufacturing costs. A diagram of the UltraLITE telescope is shown in Figure 2.1. The primary mirror consists of three circular mirror segments. The design for each mirror segment meets all of the requirements in Table 2.1.

Table 2.1: Requirements Matrix for the UltraLITE Mirror

Description	Requirement
Areal Density	< 10 kg/m ²
Clear Aperture	600 mm diameter
Segment Diameter and Thickness	Three mirrors fit within a 1.17 m. diameter fairing
Segment Shape	Circular
RSS (Figure and surface WFE combined)	0.032 wvs @ 650 nm
Concave Spherical Mirror	5 m
Tolerance on Absolute Radius	± 0.2%
Tolerance on Relative Radius (Between Segments)	± 40mm
Bandpass	450 - 850 nm
Reflectance	93% on average over the band pass (91% absolute)
Surface Roughness	10-20 angstroms
Total Fabrication Budget	0.061 wvs RMS WFE @ 650 nm
G-Release	0.015 wvs RMS WFE
Segment-to-Segment Figure Match	0.050 wvs RMS WFE
Thermal/Figure (Thermal Distortion)	0.020 wvs RMS WFE
Temp Range	± 5 °C from RT
Survivable Temp Range	- 5 °C to 90 °C
Modal	Fundamental Frequency of 80 Hz when Supported at 3 Mounting Locations
Random	Positive (+) Margin of Safety
Acoustic	Positive (+) Margin of Safety

1. CFRC Support Structure

The majority of the stiffness of the mirror is provided by a carbon fiber composite (CFRC) support structure. This structure consists of a COI proprietary SNAPSAT⁵ design that utilizes flat laminates, precision machined using a waterjet, and bonded together using self-tooling features. The structure is a sandwich that maximizes the stiffness of the substrate and minimizes the mass. The sandwich structure interfaces with a series of pultruded rods that serve as flexures that accommodate any strain difference between the glass facesheet and the composite support structure.

Carbon fiber composites incorporate organic resins that absorb moisture from relative humidity in the ambient environment. COI has developed a barrier to the moisture absorption consisting of a series of metallic layers. The design of the composite structure and pultruded rods includes features that allow the application of this moisture barrier to the composites.

2. Actuated Glass Third Surface

Low expansion ULE glass was selected for the optical surface in order to minimize the risk in polishing the visible quality figure. In order to minimize costs and areal density, a third surface mirror approach was taken. A thin glass membrane served as the optical surface. This membrane is supported on a series of flexure rods. During fabrication, these rods are actuated to attain coarse figure. Once coarse figure is achieved, the rods are bonded in place and the actuators are removed. After curing the adhesive bonds to the rods, the mirror surface is ion figured to achieve the final figure.

3. MATERIAL SELECTION

1. Carbon Fiber Reinforced Composite

Material selection in the composite was driven by matching the thermal expansion of the composite to the thermal expansion of the glass. The thermal expansion of the composite is determined by four factors: fiber properties, resin properties, percentage of resin and fiber, and the orientation of the fibers in the laminate. In order to achieve a match, precise control over these variables must be achieved. Limited selection in fibers is available. Since stiffness and thermal expansion were both critical, K1352U was chosen. The choice of low moisture absorbing, stable, platable resins is extremely limited. Therefore, 954-3 was chosen as a resin system. The percentage of resin/fiber (fiber volume fraction) was selected to balance the negative thermal expansion of the fiber with the positive thermal expansion of the resin to yield a zero thermal expansion laminate. Finally, the fiber orientation was chosen to achieve a pseudo-isotropic laminate; a laminate that has equal thermal expansion in the plane of the laminate.

In order to match the thermal expansion of the flexure rods with the glass facesheet and composite support structure, similar materials were used for the flexures as were chosen for the composite laminates.

2. ULE Glass

ULE expansion glass was chosen for the glass facesheet. This material is in a class of low expansion glasses commonly used for stable lightweight mirrors. In addition to its thermal properties, it also has the unique ability to be formed using a slumping process. In this process, a plano sheet of ULE may be formed into a meniscus merely by elevating the temperature above the glass transition temperature and below the melting point of the glass.

4. STRUCTURAL ANALYSIS

Key evaluation criteria for lightweight mirror design is the performance of the mirror during loads that will be encountered during deployment and operation. For the design of the UltraLITE telescope, the highest structural loads occur during the launch into space of the telescope. Although the telescope design includes thermal control via heaters, the relevant thermal loads are the variations in temperature that are expected during operation.

1. Structural Loads

The predicted performance of the mirror under spacecraft launch loads met all of the UltraLITE telescope requirements. The maximum stress was evaluated and compared against the allowables for the materials. The design meets all performance requirements for the UltraLITE lightweight mirrors.

The mirror will be tested in a 1-G environment, i.e., on Earth. However, deployment will occur in a 0-G environment. As such, it is important to consider the effects of gravity on the mirror figure. Were this mirror to be used in a ground experiment, this prediction would be moot. However, in order to demonstrate that the design and manufacturing process are traceable to a spaceflight telescope, the mirror should deflect less than the amount that can be corrected during the actuation and ion figuring processes. Figure 4.1 diagrams the predicted 1-G effects on the mirror design. Note that the RMS is less than 0.5 waves, well within the capabilities of actuation and ion figuring.

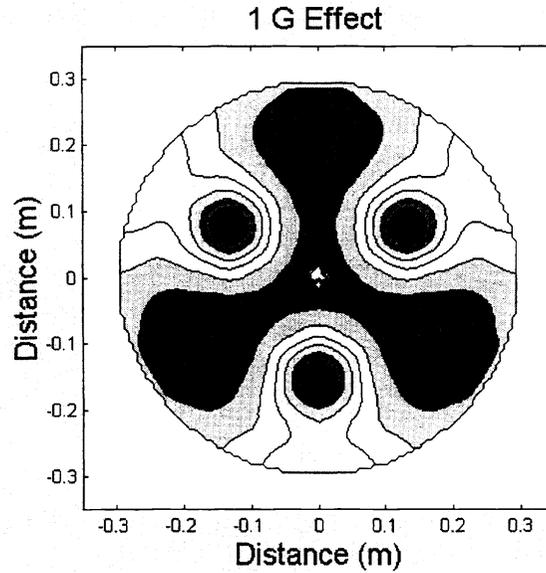


Figure 4.1: 1-G Effect on FEA of the Mirror (RMS = 0.46λ). 1-G Effects will be removed during fabrication.

2. Thermal Loads

The thermal loads during operation are fairly small. However, in order to maintain figure, the thermal expansion of the mirror must also be small. Figure 4.2 shows the predicted distortion through the range of temperature during operation.

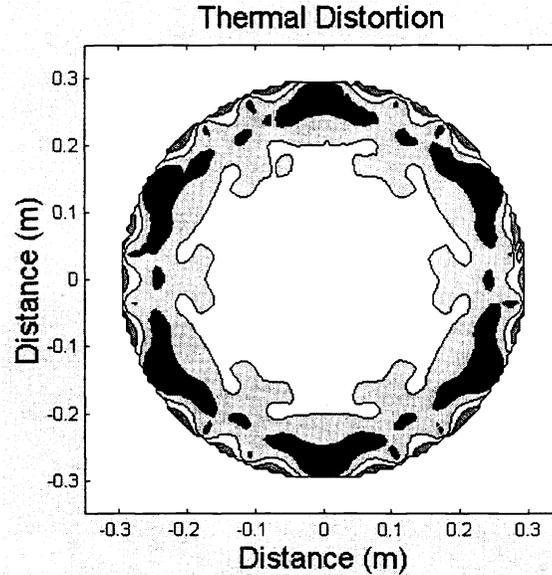


Figure 4.2: Thermal Effects on the FEA of the Mirror (RMS = 0.029λ)

5. PROTOTYPE MIRROR (0.25 M)

1. Mirror Fabrication

In order to verify the design and fabrication method of the 0.6 m mirror, a sub-scale prototype was fabricated. This prototype used a 0.25 m glass facesheet, composite flexures, and a composite support structure. The goal of this prototype was to demonstrate the construction principles and the actuation methodology. Ion figuring was not performed on this mirror.

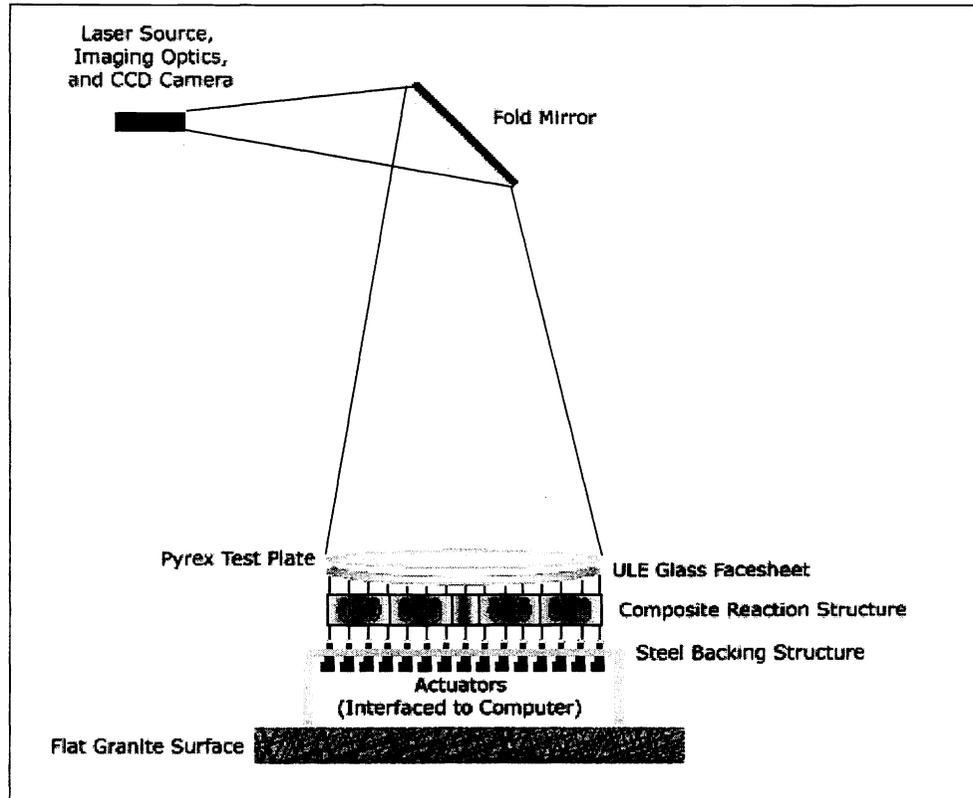


Figure 5.1: Actuation and Metrology Test Setup at the University of Arizona

For this prototype, the glass was not slumped, it was machined out of a solid substrate of ULE. The glass was ground to the appropriate radius of curvature and then lightweight pocketmilled using a waterjet process. The composite structure was manufactured using pultruded rods for flexures and laminates assembled using the SNAPSAT process. The composite structure was then coated with a metallic barrier to prevent moisture from permeating the resin matrix.

2. Mirror Test Results

This glass was mounted to the flexure rods and the system was mounted to an actuator bed designed and developed at the University of Arizona. The actuators were Picomotors that use a threaded screw that is rotated by a piezo material. Although the actuators are not calibrated, the figure is monitored using an interferometer. Feedback is provided to the actuation system and the mirror was adjusted. Figure 5.1 shows the metrology and actuation test setup at the University of Arizona.

The mirror was actuated manually until a figure of 0.155λ RMS was achieved. The flexures were then bonded to the support structuring, permanently establishing the figure of the mirror. The figure was monitored over a period of 24 hours while the adhesive cured and remained stable. After this period the actuators were removed from the mirror. Some change in the figure was recorded at this time. The majority of the figure change was in optical power. This was attributed to a support structure that did not meet all of the stiffness requirements. The support structure was modified prior to finalizing the design of the 0.6 m mirror.

6. MIRROR (0.6 M) STATUS

Currently, the 0.6 m mirror is in the process of being fabricated. The composite structure has been completed along with the moisture barrier and the glass has been slumped, polished, and lightweighted. The remaining steps are: integration of the glass and composite, actuation of the glass, bonding of the flexures, and ion figuring.

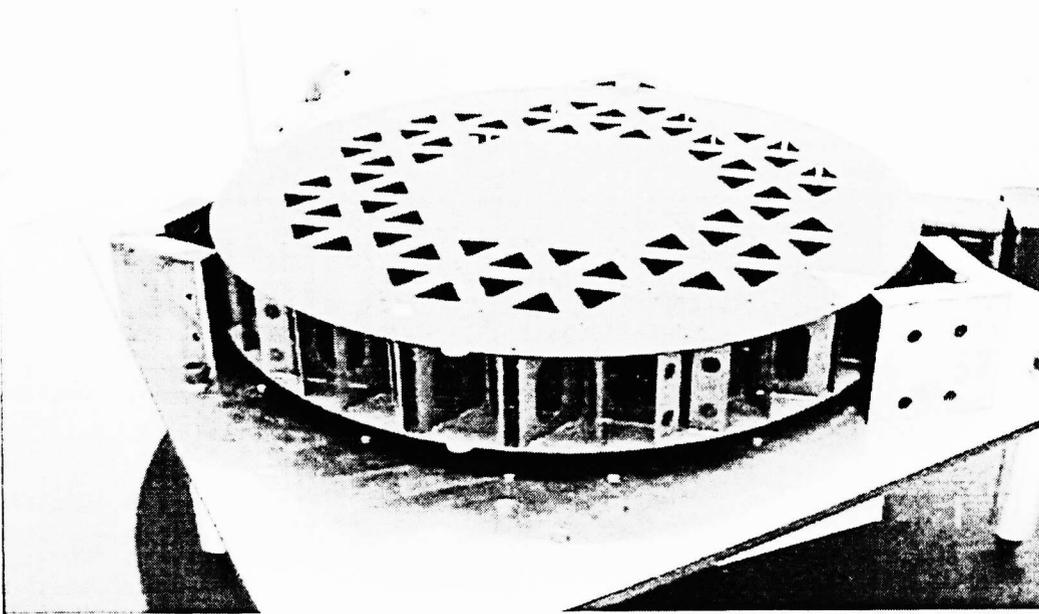


Figure 6.1: Support Structure During Assembly

1. Composite Fabrication

The composite support structure was manufactured to the design specifications. The photograph (see Figure 6.1) show the laminates after waterjet machining and during the assembly process. The support structure has been assembled along with invar fittings for mounting. A moisture barrier has been applied to the entire structure. Figure 6.2 shows representative data of the moisture barrier, indicating that the barrier is effective at preventing noticeable weight gain due to moisture absorption.

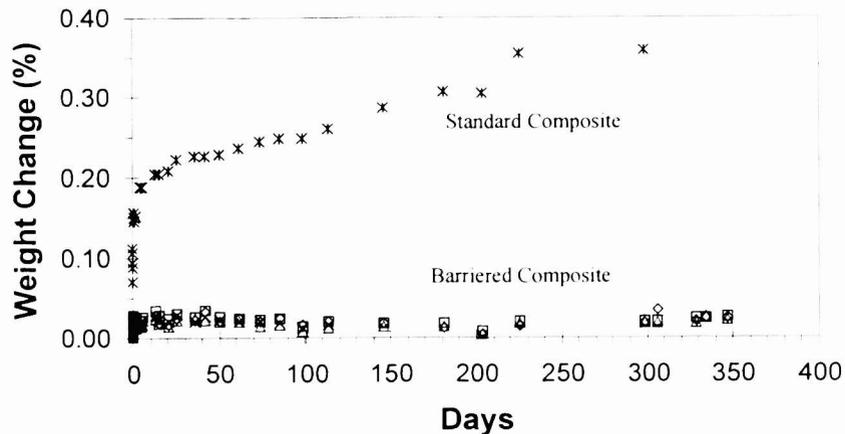


Figure 6.2: Representative Data Indicating Zero Moisture Uptake for Composite Coupons with the Moisture Barrier.

2. Glass Fabrication

The glass fabrication process has also proceeded in accordance with the design. The ULE was slumped using a ceramic mold. The ceramic mold was cast, using an inexpensive resin master. After casting and firing, the mold was post machined to achieve the necessary tolerances. The mold was measured using a coordinate measurement machine (CMM). The surface figure deviation was $27\ \mu\text{m}$ RMS from a perfect sphere. After slumping, the glass facesheet was $66\ \mu\text{m}$ RMS from a perfect sphere. Figure 6.3 shows the glass facesheet after slumping, initial polishing, and waterjet lightweighting.



Figure 6.3: Lightweighted, Slumped ULE Facesheet

3. Assembly and Actuation of the Mirror

The facesheet, flexure rods, actuators, and reaction structure have all been prepared for actuation. Figure 6.4 shows the mirror configured in the metrology system diagrammed in Figure 5.1. The mirror is currently being actuated at the University of Arizona facility. The actuators will be driven by Picomotors similar to the 0.25 m prototype. However, due to the increase in actuators (19 vs 73) the system will be under complete computer control for figure optimization.

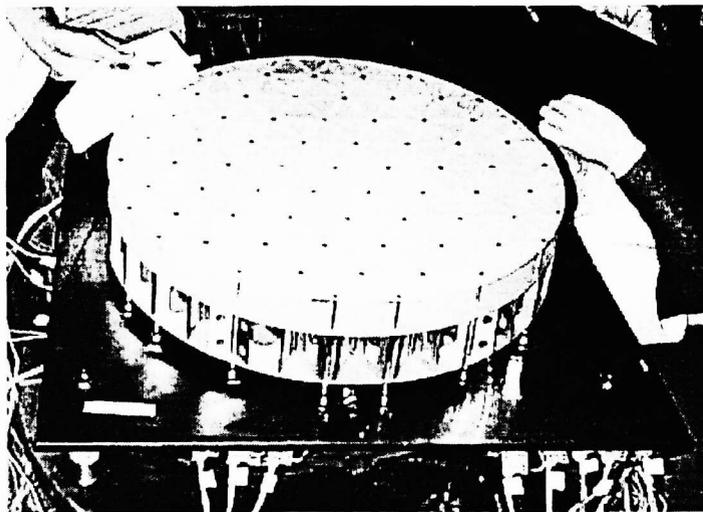


Figure 6.4: Photograph of Lightweighted Zerodur Facesheet Prior to Actuation

4. Remaining Tasks

The remaining task for fabrication includes: actuation of the glass facesheet, bonding of the flexures, and ion figuring. After the mirror figure has been optimized using the actuation, the flexures will be bonded and the actuators will be removed. A map of the surface will be generated using the metrology system (see Figure 5.1) and this map will be used to provide the removal surface for ion figuring. Kodak will provide the ion figuring. Convergence to the final figure is anticipated in two iterations of ion figuring and measurement.

7. CONCLUSIONS

Lightweight mirrors play an important role in the viability of large aperture space telescopes. After surveying available materials for lightweight mirrors, a unique combination of glass and composite materials was selected to create a new type of lightweight visible quality mirror. The design concept for this mirror allows for the optimal use of each material: glass for the optical surface and composite for the structural support. The fabrication method for mirror consists of actuation, permanent bonding, and then ion figuring. Major steps in this process were demonstrated successfully on a sub-scale (0.25 m) mirror. Currently, a 0.6 m mirror is under fabrication to demonstrate this technology. The authors wish to thank the AFRL (contract F29601-98-C-0046) for their support in this effort.

8. REFERENCES

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