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Lightweight Mirror Structures for Mechanical Beam Steering

Defense applications of space-borne laser radar require a sensor that can point to a large number of targets — in rapid succession and over a wide field of regard. By using a full-aperture, mechanically steered flat mirror, the requirements for high-acceleration beam steering can be met. Three alternative mirror structures were designed and their performance was evaluated through computer simulation. The mirror structures were (1) a thin glass sandwich coupled to a deep backup structure, (2) a full-depth beryllium sandwich, and (3) a full-depth graphite/epoxy sandwich. Unlike existing large steering mirrors, these mirrors can survive angular accelerations as high as 1000 rad/s^2 during steering, yet still limit residual vibration amplitudes after steering to $\lambda/20$ rms at 10.6 μm. All three designs can use existing fabrication technologies to meet performance goals.

Traditionally, large mirrors are not meant to be mobile; they are heavy and, at best, move slowly. Imagine the need to move a mirror the size of the Hubble Space Telescope primary mirror rapidly through many high-acceleration steps. Further imagine that after each step structural vibrations must be made to dissipate very quickly. Such are the beam agility requirements for some future space-borne laser radar systems involved in optical discrimination efforts of the Strategic Defense Initiative.

Meeting the beam agility requirements associated with addressing large numbers of randomly distributed targets in a rapid sequential fashion has been one of the most challenging aspects of designing a space-borne laser radar system. We are attempting to design and develop a 2-m aperture beam-steering system with a mechanically steered full-aperture flat mirror capable of as much as 3° rotation in less than 20 ms [1]. The steered mirror is mounted in the system shown in Fig. 1.

The features that distinguish this steering flat from previously designed steering mirrors are its size, 2.2 m, and its ability to survive angular accelerations as high as 1,000 rad/s^2. Other steering mirrors that can tolerate such accelerations have been considerably smaller; similar size steering mirrors are incapable of withstanding these accelerations.

During operation, the mirror in Fig. 1 is rotated by three actuators spaced 120° apart. In the worst case simulated, the mirror was rotated through 3° in 16 ms. The rms surface figure of the mirror must settle to $\lambda/20$ rms within the additional 4 ms. The wavelength used in this study is 10.6 μm, so the required surface figure is about 0.5 μm rms.

To minimize residual vibrations, the mirror must be lightweight yet stiff enough to make its natural frequency (fundamental mode) at least 300 Hz. In addition, although the small deformable mirror in the unexpanded beam can correct large spatial-frequency thermal distortions, the overall thermal growth of the mirror should be minimized.

Three structures — a thin glass sandwich coupled to a deep backup structure, a full-depth beryllium sandwich, and a full-depth graphite/epoxy sandwich — promise to meet most, if not all, of these objectives. In this article, we will discuss fabrication issues and the results of structural analyses of these mirror structures.

Thin Glass Sandwich/Deep Backup Structure

The most common family of mirror materials in use, and also proposed for future use, in

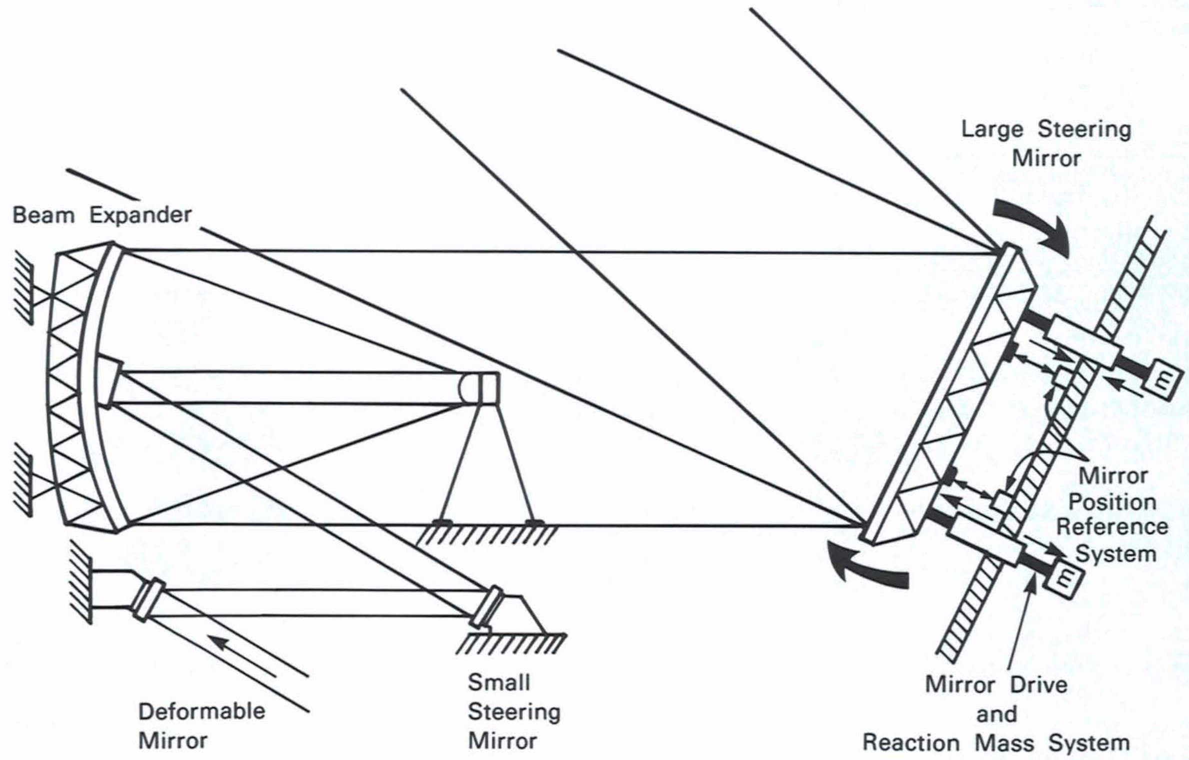

Fig. 1 — Mechanical beam-steering system components.

either space or terrestrial telescopes are glasses and glass ceramics, such as fused silica, fused quartz, Pyrex, borosilicate, Zerodur, and Cervit. These materials can be lightweighted, have low coefficients of thermal expansion, and are dimensionally and temporally stable. But their disadvantages include both brittleness and low dynamic tensile strength (10.3–13.8 MPa or 1,500–2,000 psi). A mirror made from one of these materials could meet the minimum natural frequency specification of 300 Hz. However, the mirror would be so heavy that actuator forces of more than 90,000 N (20,000 lb) would be required to produce the required 3° of rotation in 16 ms.

Such high actuator forces would be likely to overstress the mirror faces at peak acceleration times. Furthermore, it would be difficult to attach actuators directly to the material without creating stress concentrations that would pose an even greater threat to the mirror's integrity.

These stress problems can be circumvented by coupling a thin glass mirror to a backup structure, which reduces the weight of the structure and the forces required to rotate it. In Fig. 2, for example, a lightweight, 5-cm deep, ultralow expansion (ULE) fused silica mirror is coupled to a backup structure. The mass of the mirror and backup structure is only 65% of the mass of an all-glass mirror with the same aperture, and the estimated peak stress in the glass surface is roughly 29% less than the peak stress of an all-glass structure. This hybrid design is basically a large sandwich — the top face is a thin glass mirror, the bottom face is a planar grid of tubular equilateral triangles, and the core consists of partial or full tubular tripods.

The mirror itself is also a sandwich. The dimensions of the mirror are based on a design recently used by Corning and Kodak [2], which is the lightest mirror of this size. The front and back face sheets of the mirror in Fig. 2 have thickness of 0.25 cm; the core depth is 4.6 cm. The 3.8-cm square core cells are formed of 0.13-cm thick walls. The core elements are fusion-welded together, and the face sheets are subse-

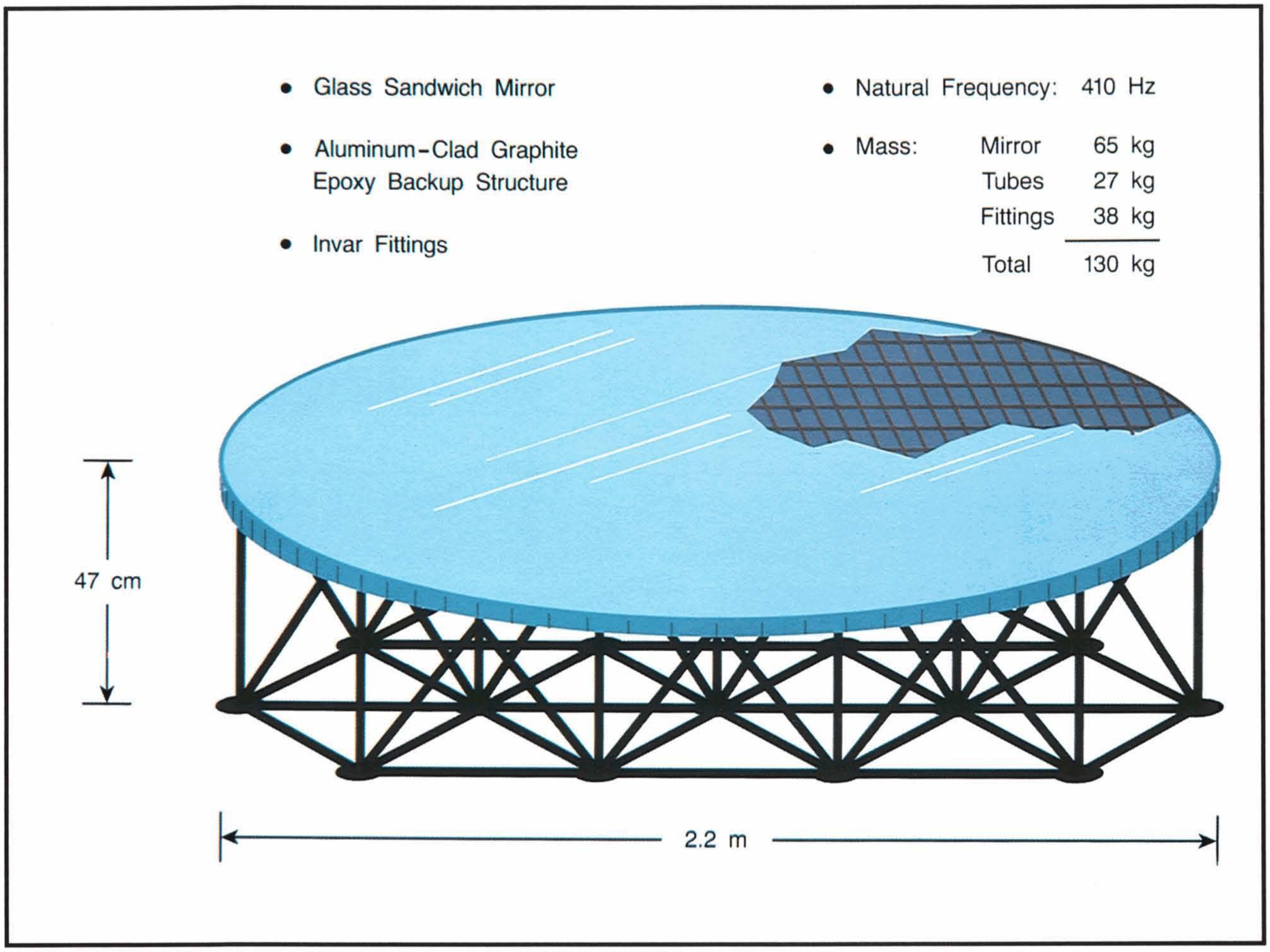

Fig. 2— This hybrid design significantly reduces the mass of the steering mirror. Stresses associated with pointing the mirror are also reduced.

quently frit-bonded in place.

The 42-cm deep backup structure consists of a tetrahedral array of aluminum-clad (inside and outside) graphite/epoxy tubes and Invar fittings. By itself the backup structure has no stiffness, but once the 19 apexes of the tetrahedra are joined to the ULE sandwich, the entire structure becomes rigid. The mass of the mirror structure in Fig. 2 is 130 kg; the natural frequency is 410 Hz.

By coupling the three actuators directly to the backup structure, the applied loads are distributed over several of the 19 attachment points of the backup structure to the glass mirror. This load distribution alleviates the high stress concentrations that create a problem for the all-glass mirror. The most appropriate position for attachment of the three actuators is at the radius of percussion, where dynamic reaction

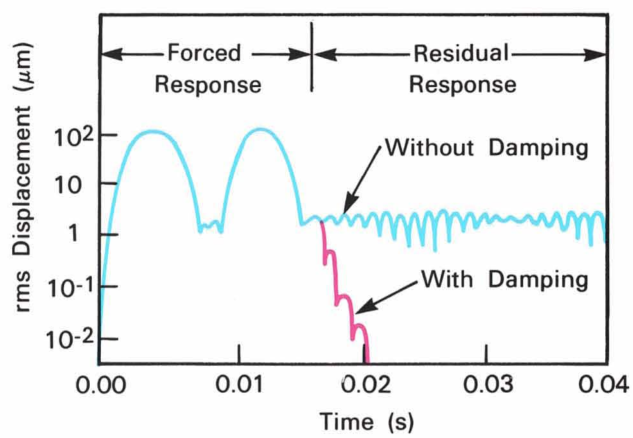

Fig. 3 — Response of a hybrid mirror to a 3° rotation executed in 16 ms.

loads are at a minimum.

A simulation of the rms mirror surface deflection is plotted against time in Fig. 3. In this calculation, the mirror was rotated 3° in 0.016 s. A sine-cubed forcing waveform was used to rotate the mirror. The sine-cubed waveform was selected to suppress vibration in modes at frequencies higher than the lowest natural frequency [1]. The peak actuator force required for this rotation is 71,170 N or 16,000 lb, a force 28% less than that required for the all-glass structure.

The first mode of vibration (Fig. 4) is dominant during both the forced and the residual response of the mirror. During the forced response segment, the mirror is in motion and so surface distortions are not a concern, even though the maximum surface stresses are experienced during this period. For the example shown, the peak dynamic tensile stress in the mirror surface is predicted to be about 7.7 MPa (1125 psi). This stress should not pose a problem for short-term dynamic loading, because the mirror should be capable of withstanding at least 10.3 MPa (1500 psi).

Within the 4-ms residual response time, surface distortions must be attenuated to the $\lambda/20$ rms surface figure. A modal damping ratio of 3.1 at the actuator attachment points creates the damped results shown in Fig. 3. (No internal

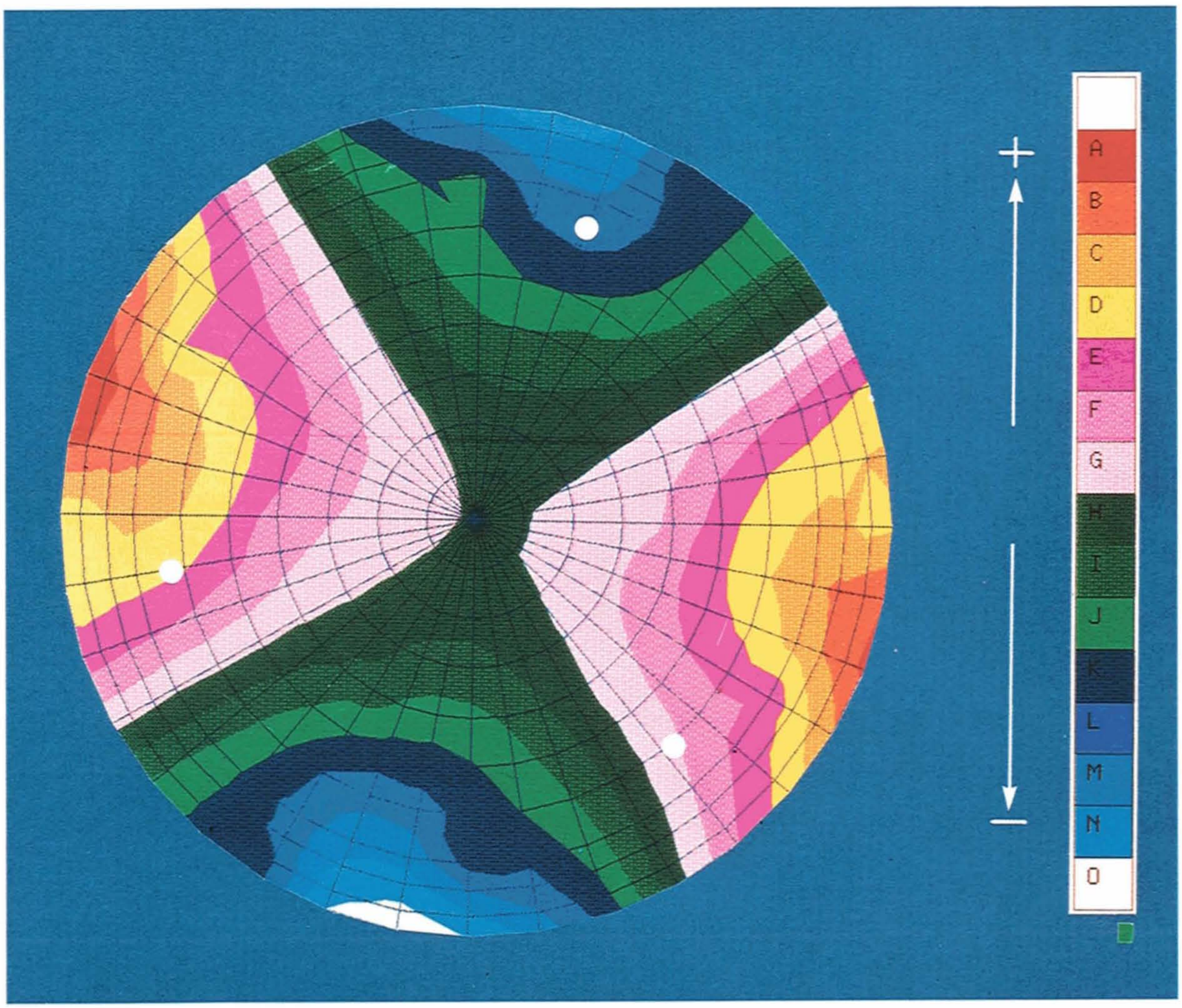

Fig. 4 — First mode vibration shape of the hybrid mirror.

structural damping is assumed.) The response is attenuated to about 0.02 μm within the total allowed retarget time of 20 ms. By increasing the retarget time or by reducing the rotation angle, the stresses and residual vibration amplitudes can be reduced further.

The low coefficients of thermal expansion (CTE) of the system minimize distortions due to thermal inputs. ULE has an inherently low CTE and the clad tubes are designed for a near-zero CTE. Moreover, the Invar fittings provide a good thermal match between components in the structure.

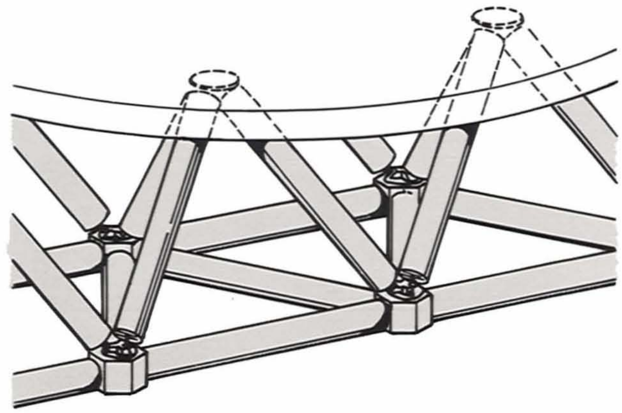

Fig. 5 — This close-up view of the hybrid mirror's backup structure reveals the tetrahedra and triangles that comprise the core.

Fabrication and Assembly

Exploratory discussions were initiated with lightweight mirror fabrication experts at Corning Glass Works regarding fabrication of a ULE sandwich [3]. The discussions led to the conclusion that a ULE mirror with the required dimensions could be fabricated by using state-of-the-art frit-bonded mirror technology [2]. Because of concerns about handling the mirror, they recommended that the thicknesses of the face sheets and of the core walls be increased slightly.

The backup structure, which supports the glass mirror, is illustrated in Fig. 5. The structure consists of an array of tetrahedra joined together with fittings. Before the mirror is bonded to the backup structure, the height of each tetrahedron can be adjusted to a predetermined value by using the differential adjustment screws that are inside each tube. After the mirror is bonded in place, the screws can be used to make the mirror as close to flat as possible.

Fabrication and assembly of the mirror to the backup structure require addressing a number of design issues:

- sizing and fabrication of core and face tubes,
- material selection and design of the fittings,
- pre-mirror-attachment height adjustments,
- post-mirror-attachment figure adjustment.

The components of the backup structure were chosen to conform as closely as possible to the low CTE of the ULE sandwich. The tube dimensions were selected to maximize the natural frequency of the completely assembled structure (mirror and backup structure), thereby minimizing the amplitudes of the residual vibrations.

Because of graphite/epoxy's low weight, high stiffness, and low CTE, it is an ideal material for the tubes. Graphite/epoxy's material properties have, in fact, prompted the development of new tube manufacturing technologies for the NASA Space Station Program. One of the most notable of these manufacturing technologies was developed by Lockheed [4]. In the Lockheed process, aluminum cladding is added to the interior and exterior surfaces of the tubes, a process that minimizes dimensional changes caused by the hygroscopic nature of graphite/epoxy. This process also prevents atomic oxygen erosion, which is a concern in the Low Earth Orbit environment where the mirror will be deployed. And by carefully controlling the thickness of the aluminum cladding, the CTE of the tube can be tailored to be nearly zero without adding significant weight.

The tubes for the backup structure can also be produced by using a fabrication process developed at Lincoln Laboratory. Like the Lockheed process, it adds aluminum cladding to graphite/epoxy tubes. However, in the Lockheed process, dry graphite is drawn through a cylinder formed by the outside and inside aluminum cladding, after which epoxy is injected into the graphite matrix and then cured.

The Lincoln Laboratory technique consists of roll-wrapping graphite/epoxy (P75/SG12

Fig. 6 — This apparatus is used to fabricate the aluminum-clad tubes in the glass sandwich/deep backup structure.

prepreg) around an aluminum tube, compression-mold curing the graphite/epoxy, and then bonding an outer aluminum tube to the graphite/epoxy by room-temperature-cure adhesive injection. Figure 6 shows a photograph of the apparatus developed for this process.

The tubes for the backup structure must be joined to one another and to the mirror with fittings that have a low CTE. Figure 7 shows the dependence of CTE on temperature for five materials [5]. Near 0°C, Invar and Super Invar both exhibit acceptably low CTEs. The CTE of Invar and of fused silica are a good match, as are the CTEs of Super Invar, ULE, and Zerodur. In addition to having a low CTE, Invar is widely available and easy to machine, so it is an excellent material for the tube fittings.

Full-Depth Beryllium Sandwich

The second of our three designs for a beam-steering mirror is a full-depth sandwich mirror. The excessive weight and brittle nature of glass made it a poor material for this design, but beryllium, with a lower density (1.85 g/cm^3, compared with 2.21 g/cm^3 for ULE) and significantly higher Young's modulus (287 GPa, compared to 67 GPa for glass), is an ideal candidate. Beryllium is also considerably easier to attach to the actuators, because it is not as brittle as

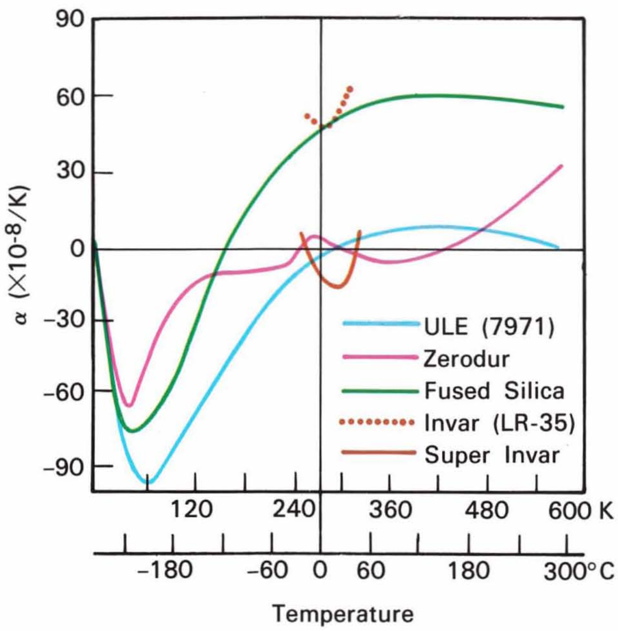

Fig. 7 — The coefficients of thermal expansion of Invar and Super Invar are near zero at 0°C. The values of the CTEs of Invar and fused silica are closely matched. The CTEs of Super Invar, ULE, and Zerodur are similarly close. (Redrawn from Ref. 5.)

glass. Furthermore, beryllium has a much higher yield stress at both the macro- and micro-stress levels, 276 MPa and 27.6 MPa respectively. (Macro yield stress is the stress value at a strain of 0.2 percent on a material's stress strain diagram. Micro yield stress is the stress at 1 micro strain on the same diagram.)

The 2.2-m-diameter mirror, shown in Fig. 8, is a 30-cm deep sandwich comprised of 0.25-cm thick face sheets and an eggcrate core (3.8-cm square cells, 0.05-cm wall thickness). The total mass of this mirror is 90 kg and its first mode natural frequency is over 900 Hz. The peak residual rms deflection due to a 3° rotation in 16 ms is about 0.1 μm, even without damping (Fig. 9). The maximum dynamic tensile stress associated with such a rotation is about 5.2 MPa, well below the specified maximum.

The full-depth beryllium sandwich design has two principal drawbacks. Beryllium's CTE is high, 11.4×10^{-6}/K at 300K. (ULE has a CTE of only 0.015×10^{-6}/K.) Moreover, anisotropy and inhomogeneity in beryllium combine to create unacceptable thermal distortions.

If beryllium is to be used at greater than cryogenic temperatures (where its CTE is small), distortions caused by nonuniform solar heating will require correction. Deformable optics offers one way of correcting the thermal distortions. By placing an array of temperature sensors on the backs of both surfaces of the mirror, temperature data can be used, in conjunction with a

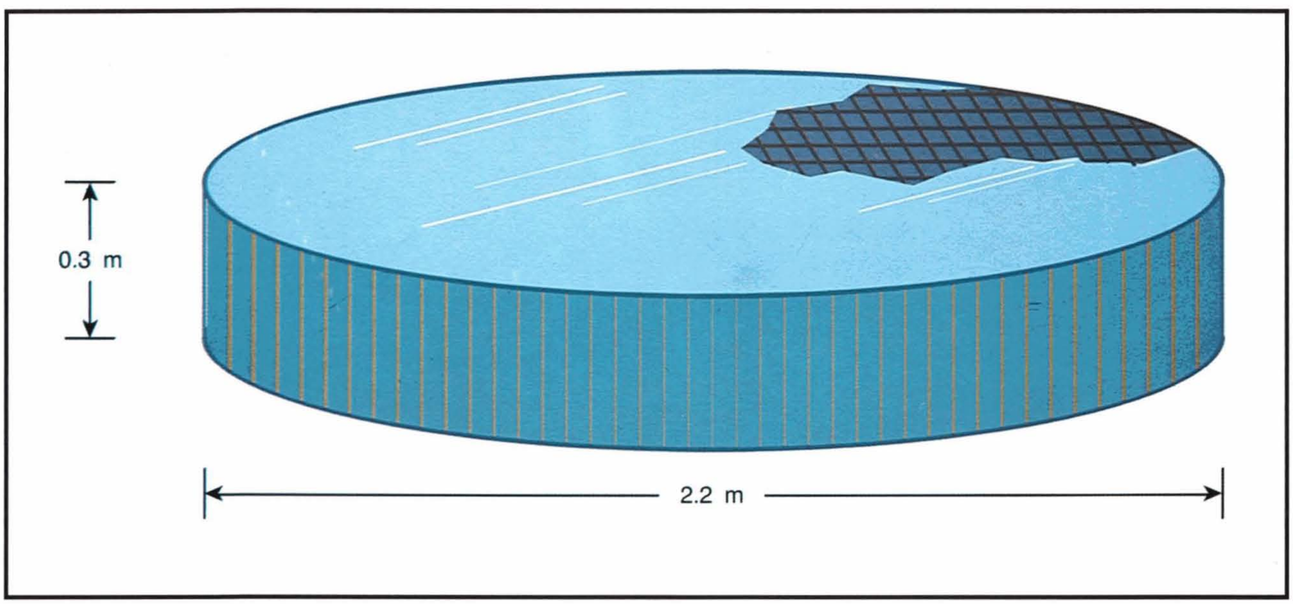

Fig. 8 — This full-depth beryllium sandwich mirror has a natural frequency of 900 Hz. Its mass is only 90 kg.

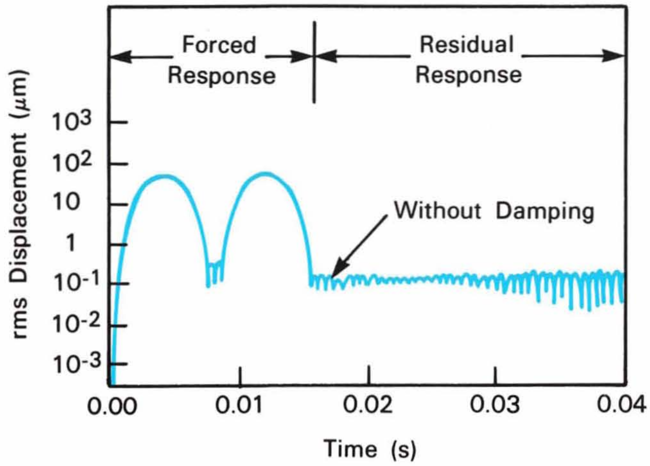

Fig. 9 — The response of a beryllium mirror to a 3° rotation in 16 ms is so small that damping is not needed to meet the residual vibration specification.

finite-element model of the mirror, to determine mirror surface distortions which can be used as error signals for deformable optics. As illustrated in Fig. 10, the deformable mirror could operate in the unexpanded beam of the beam-steering system. The deformable mirror operates open-loop; it receives no information about the effects of compensation attempts.

Fabrication of the Beryllium Mirror

The beryllium sandwich mirror can be fabricated in either of two ways. The first fabrication method uses rolled vacuum-hot-pressed (VHP) sheet and aluminum brazing in the same way as the Thematic Mapper scan mirror used on Landsat D satellites [6]. The second method uses a hot isostatic pressing (HIP) process [7,8].

VHP beryllium can produce the required mirror in one of two ways. The earliest versions of the Thematic Mapper were fabricated by brazing rolled faces to "eggcrated" core elements, which were photo-etched from rolled sheets [9]. This method had two drawbacks. The first drawback

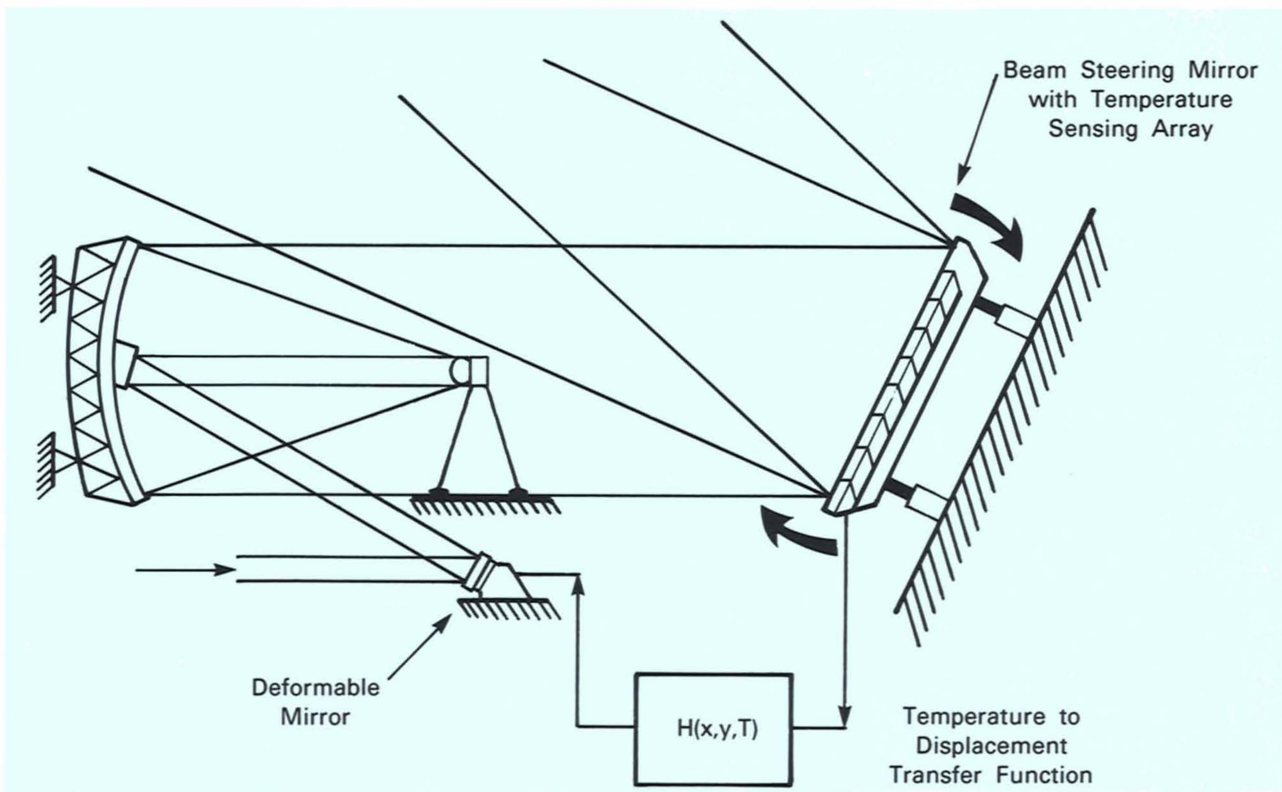

Fig. 10 — A temperature-sensing array on the backs of the surfaces of the large steering mirror, combined with a detailed finite-element model of the mirror, provides adjustment signals to the deformable mirror. Using the adjustment signals, the deformable mirror can compensate for thermal distortion in the steering mirror.

was that the in-plane and transverse values of CTE varied by as much as 3 to 4%. The second drawback was that the thermal mismatch at the core/face-sheet joint caused quilting of the mirror surface during excursions from room temperature.

The second method of using VHP material involves machining pockets into two plates and then brazing the pocketed sides together along the mirror's centroidal axis. Although this method eliminates the quilting, CTE anisotropy and inhomogeneity are still problems. Consequently, to preserve the rms surface figure, the temperature of the mirror must be maintained at a uniform level. Although this approach is feasible for a 30-cm deep mirror, the high cost of beryllium and the amount of material lost during the machining process make it an extremely costly process.

Using the HIP process produces a mirror with a more uniform CTE. The in-plane and transverse directions of the CTE differ by less than 0.5%. The principal drawback to the HIP process is that an autoclave is required to fabricate a monolithic mirror; the largest existing HIP autoclave can fabricate optics only as large as 1.5 m in diameter.

For any of these fabrication techniques, the high CTE of beryllium requires special attention during use. The search for a low-CTE, low-density, high-stiffness alternative has directed us to an examination of composite materials.

Full-Depth Graphite/Epoxy Sandwich

Our third mirror design is a full-depth sandwich of graphite/epoxy that provides four desirable features: high stiffness, high tensile strength, low weight, and low CTE. Compared with the all-beryllium sandwich, a 2.2-m-diameter graphite/epoxy sandwich has a calculated mass of about 75 kg and a calculated first mode natural frequency of about 680 Hz. And, like the beryllium mirror, the graphite/epoxy design would not require damping to reduce residual vibrations.

The calculated results look attractive, but it is not yet clear how to create an adequately flat optical surface with this structure. Furthermore, we have not yet determined how to deal with the anisotropic, inhomogeneous, and hygroscopic nature of the material.

Reflector panels of graphite/epoxy face sheets on an aluminum honeycomb core have been developed at the Jet Propulsion Laboratory in Pasadena, CA [10] and at Steward Observatory in Arizona [11]. Producing the required surface accuracy and maintaining it at varying temperatures has remained a problem.

Other composite materials, including graphite/glass and metal-matrix/graphite, share many of the problems (except for the hygroscopicity of graphite/epoxy) when used as optical substrates. For all these materials, the most significant problem is thermal cycling-induced micro-cracking of the matrix, which causes CTE changes.

Researchers at Lincoln Laboratory are investigating possible ways to make graphite/epoxy materials practical for application as mirror substrates. Initial indications show that the use of aluminum cladding on the face sheets and on the core walls can circumvent the hygroscopic problem.

Dimensional stability remains a problem. A 14-cm square by 2.5-cm deep graphite/epoxy sandwich mirror blank consisting of an eggcrate core and aluminum cladding on all surfaces has been fabricated. The front face of the blank was diamond-turned, which permitted us to make interferometric measurements after performing thermal tests. Initial experiments indicate that, if the mirror has been properly thermally conditioned beforehand, it maintains its surface figure when subjected to temperature cycling within its expected operational temperature range. We are conducting further evaluation of the dimensional stability of clad graphite/epoxy mirrors.

Summary of Steering Mirror Designs

Table 1 lists key characteristics of the three steering mirror structural designs. For comparison, an all-glass design is included with the table.

The lightest mirror is the graphite/epoxy sandwich. Its low mass leads to the lowest

TABLE 1
Comparison of 2.2-m-Diameter Beam-Steering Mirror Concepts

Material	*Units*	*Glass*	*Hybrid*	*Beryllium*	*Graphite/Epoxy*
Mass	kg	200	130	90	75
	lb	441	285	198	165
Frequency	Hz	370	410	910	680
Actuator	N	99,200	71,170	43,800	36,700
(3° in 0.016 s)	lb	22,300	16,000	9,850	8,250
Peak Stress	MPa	11.4	7.7	5.2	4.3
	psi	1,650	1,125	750	630
Allowable Stress	MPa	10.3	10.3	27.6-276	690
	psi	1,500	1,500	4,000-40,000	100,000

actuator force. The highest frequency mirror is the beryllium design, which also features the smallest residual vibrations. The graphite/epoxy sandwich design exhibits a low CTE, but it presents problems with dimensional stability during thermal soak or cycling. The beryllium design has a high CTE and requires thermal-distortion correction. Surface stresses are not a problem for the beryllium or the graphite/epoxy design, and damping is not required to meet the $\lambda/20$ rms surface distortion goal.

The hybrid design has a low CTE, but it does require damping to reduce residual vibrations. Furthermore, the fragile nature of glass introduces some risk of breakage during rapid acceleration. The all-glass design is simply too heavy and too fragile. As already mentioned, it is included here for comparison only.

The technologies needed for fabricating any of the three mirror designs are under investigation. Efforts are particularly directed at fabrication of aluminum-clad composite tubes, and at fabrication and assembly of composite mirrors. Thermal distortion issues are being evaluated to assess their impact on system performance in various space environments. Discussions with representatives from the companies that manufacture the materials and the components are continuing.

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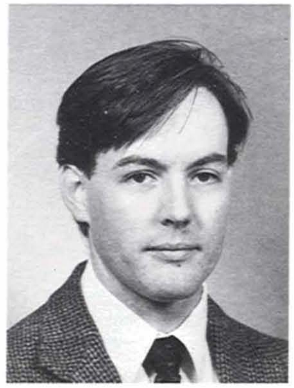

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