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Title: **Ultima Replicated Optics Research**

1.0 Background

The need exists within NASA for the development of both designs and processes to produce very large integrated space based mirrors which will be deployed to high altitude orbits to avoid known low earth orbit issues. This investigation encompasses replicated optical component processes suitable for fabrication of high precision segments for integration into an ultra-lightweight and very large (20 meter) space telescope. While most certainly the issue of deployment vehicle capacities and size are issues, the underlying methods must be suitable for a system to be expanded from a compact transport format to the actual functional mirrors and telescope assembly. The methods studied do not include the more classical processes for near-term fabrication of large space telescopes. One approach is to produce segments which are of the same contour such as spherical such that many segments can be used interchangeably from a replication process. It is in this light that a large spherical primary mirror is considered.

1.1 Summary

Designs are reviewed incorporating processes suitable for replication of precision spherical segments of very large (>20 meter diameter) telescopes combining ultra-lightweight and high precision. These designs must be amenable to assembly and alignment after deployment . The methods considered lie outside the present scope of fabrication, deployment and alignment considered to date. Design guidlines for reducing the weight and low frequency resonance in low G environment were given by The Serius Group, Dr. Glenn Zeiders, and are considered baseline for this activity. The goal of a rigid design of 10 Kg/M^2 is being persued for the Next Generation Space Telescope (NGST) and is not likely adequate for advanced efforts. Flexures have been considered for maintaining the figure of many lightweight structures by control loop processes. This adds to the complexity and weight to the extent that it becomes difficult to recover the benefits. Two fabrication guidelines lead to a stiffer and concurrently lighter structure. First the use of thin vertical wall triangular structural reinforcements to increase the resistance to bending is preferred over hexagonal or square similar sections. Secondly, the incorporation of a similar back sheet on a cellular structure markedly improves the geometric stiffness. Neither improves the short range stiffness. Also often overlooked is that selected material properties must include high microyield and low hysteresis in addition to high elastic modulus to weight (stiffness). The fabrication steps can easily exceed the strain requirement.

1.2 Objectives in Statement of Work:

1) Research performance for mirror systems potentially made of spherical segments

2) Research and recommend solutions to problems related to the fabrication of similar mirror segments suitable for integration into a large assembly.

3) Provide recommendations on the preparation of replication master substrates.

4) Provide consultation on the potential replication processes.

5) Define methods of producing monolithic or other structural forms for maintaining high specific stiffness, alignment accuracy and lightweight.

6) Compare performance vs fabrication issues related to segmented spherical mirrors for on-axis and off-axis designs.

2.0 Optical Performance:

Many large space optical systems have been studied including aspheric, and non-aspheric systems. An advantage in replicated pieces of an identical form becomes apparent. The replication processes can produce many components of the same form from a single master. For a large segment to be useful as an element of a large mirror the use of identical spherical segments is advantageous.

2.1 General Cases of Segmented Mirror Replication

In the case of an on-axis aspheric mirror such as parabolic or hyperbolic design, the use of a separate master for elements of each radially different section is required. Additionally each circumferential row will have at least two different pieces enabling staggering of elements such as hexagonal or other close packed perimeter configurations. For the case of more complex pieces, it may be required to have even more masters, diminishing the advantages of replication. Likewise if the mirror is aspheric and off-axis even fewer pieces will be identical.

2.2 Spherical On-Axis Mirror

The spherical mirror is unique in that properly designed segments, both radially and axially are similar or identical. For the extreme case it is conceivable to fabricate such segments for the entire mirror from one master. The actual lack of similarity might come from edge mounting features or a central mirror of the largest deployable size. A minimal number of masters is required for fabrication of the elements since the edge features could be added to the final replicated form rather than be copied from a master. The central mirror would be the largest deployable mirror segment and would have a segmented mirror interface perimeter. The outer perimeter of the largest central mirror (may be ommitted in Swartzchild or Cassegrain equivalent designs) would have the required interface for the first row of the smaller hexagonal segments for a hexagonal close packed (HCP) design. In this case conceivably, a very large mirror could be made from segments replicated from only two masters.

2.3 Design Activity

The ultimate in versatility is a large mirror made of very small flat segments which can be used to approximate any shape. The small size required to achieve decent performance dictates that consequently the number of segments becomes very large. This in turn becomes unmanageable in terms of edge sensors and actuators to maintain figure in any dynamic design. The approach for ULTIMA is to produce the largest deployable elements to be assembled into an array comprising the mirror with the fewest segments permitting proper performance. Reflective systems with spherical elements for the largest surface and perhaps correcting reflective or refractive optics for the smaller surfaces may be most appropriate. Additionally so long as the spherical mirror is high quality the corrections for aberrations can be computationally corrected to some extent.

2.4 Comparison of Designs

The use of larger spherical sections has been compared to similar designs using aspheric configurations. The number of different replicated parts to be fabricated is easily determined. Performance estimates have been compared for two designs considered. The desire to make a large number of identical primary segments in order to maximize the benefits of replication leads to the use of a primary with a purely spherical curvature. Thus, one of the tasks of this effort was to review, investigate, and evaluate large aperture telescope designs utilizing spherical primaries to see if any would be feasible for a 20 m class space telescope.

2.5 Optical Design Requirements for Feasibility Study

Based on various input (from the first ULTIMA study, the current NGST study, other team members in the current ULTIMA study, and the literature), a set of baseline optical design requirements were developed (see Table 1 below). An aperture diameter of at least 20 m is required to get the desired resolution and light gathering ability. The critical waveband for high-Z observations is 4-11 μm. Projected detector technology limits the practical field-of-view (FOV) to around 2 arc minutes. Diffraction-limited resolution is required at the shortest wavelength of 4 μm. This leads to an angular resolution requirement of 50 milli-arc seconds (mas). In order to get 2 detector pixels per resolution element (Nyquist limit) and assuming 8 μm pixels, a system f-number of 4 is required. Lastly, an image of the primary coincident with a downstream mirror is highly desired in order to assist in the correction of any residual misalignments of the primary segments resulting from deployment and/or environmental disturbances. These requirements are not meant to be the last word - cases can be made for a larger aperture, a wider waveband, a larger FOV, and finer resolution. However, this set of requirements is suitable for determining the feasibility of various optical design concepts.

Design Parameter	Requirement
Primary aperture diameter	20 m
Primary shape	Spherical
Field-of-view	2 arc min
Waveband	4-11 μm
Resolution	Diffraction-limited at 4 μm = 50 mas
F/#	4
Primary reimaging	Yes

Table 1. Optical design requirements.

2.6 Results of Optical Design Feasibility Study.

A literature search revealed considerable research into large aperture telescopes with spherical primaries.[1-5] While none of the design concepts found in these references meet all of the requirements above, some are quite close and together they give a strong indication that such a design is possible. Based on these works, two designs were developed to demonstrate feasibility for an ULTIMA-type mission. The first design is based on the classical concept of a rigid structure holding all of the optical elements together. This requires a fast primary to minimize the distance between the primary and secondary. The second design is based on the newer approach of free-flying optical elements, such as envisioned for space-based interferometers. This allows for a much slower primary and a smaller amount of spherical aberration to correct for in the downstream optics. Of course, the downside of such a concept is the requirement to dynamically maintain and/or correct the alignment between the primary and the downstream optics. This will be discussed further in a following section.

2.6.1 Fast Design

The fast design, shown in Fig. 1, is a variation on the 4-mirror design in reference 4. Three downstream mirrors are required to correct for the spherical aberration in the fast primary as well as to put the final image plane behind the primary. The primary is an F/1.25 sphere. The secondary is an F/3, 4 m diameter asphere that is located 19.5 m from the primary. This separation, less than the diameter of the system, should be manageable for rigid structural members. The tertiary is an F/2, 4 m diameter asphere located in the same plane as the primary for easier mounting. The quaternary is an F/9, 2.5 m diameter spherical mirror located at an image of the primary (9 m from the primary). The final F/4 image is located 1 m behind the primary. The magnification factor between the primary and quaternary is only 8, minimizing the potential errors for off-axis fields when correcting primary misalignments with the quaternary. A 2 m diameter primary segment (100 would be required) would map onto a 25 cm circle on the corrector.

Several actuators or active segments could be placed within this circle, allowing for sub-primary segment correction. The design is diffraction-limited over a 2 arc minute FOV at 4 μm.

2.6.2 Slow Design

The slow design, shown in Fig. 2, is a variation on a 3-mirror design done by UAH during the first ULTIMA study. With the slower primary, only two downstream mirrors are required for good image correction. The original design had a 20 m, F/4.5 parabolic primary and an overall F-number of 15. The primary was first changed to an F/4 sphere. Now, the second and third mirrors were required to perform a one-to-one relay of the primary image while correcting for the primary's spherical aberration. Thus, the relay was made with two identical F/4, 2 m diameter aspheres that are separated by 8 m and are located 80 m from the primary. The final F/4 image is located at the vertex of the tertiary. The primary is reimaged onto the tertiary mirror with a magnification factor of 10, close to that of the fast design. This design meets all of the requirements in Table 1 above and achieves even better resolution than the fast, 4-mirror design above over a 2 arc minute FOV.

2.6 Additional Analysis Requirements

In the future, a full tolerance analysis of each design should be performed to further examine the feasibility of the approaches. The second design, in which the primary would fly free of the other optics, especially needs further development. Currently, two spacecraft can be maintained to within about ±1 mm and ±2 mrad of each other. While these are impressive accuracies for spacecraft control, they are not of the order of optical tolerances. Thus, a set of scanning mirrors to coalign the primary and auxiliary optics axes in real time may be required.

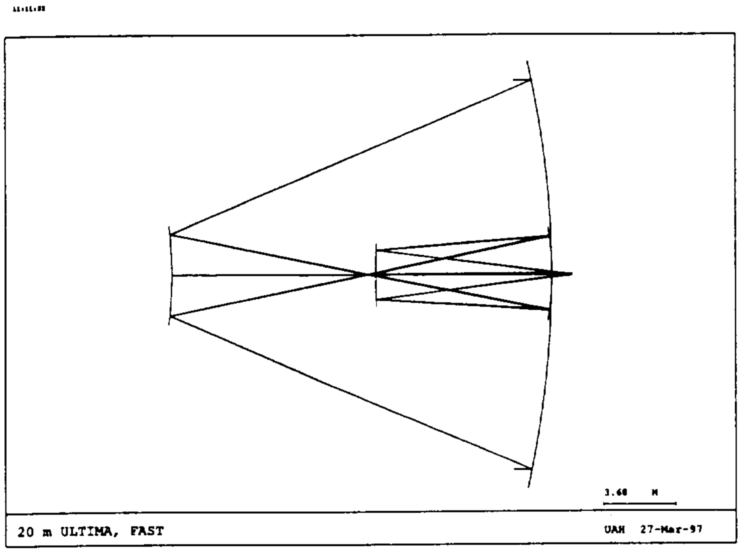


Fig. 1. The fast, fixed design.

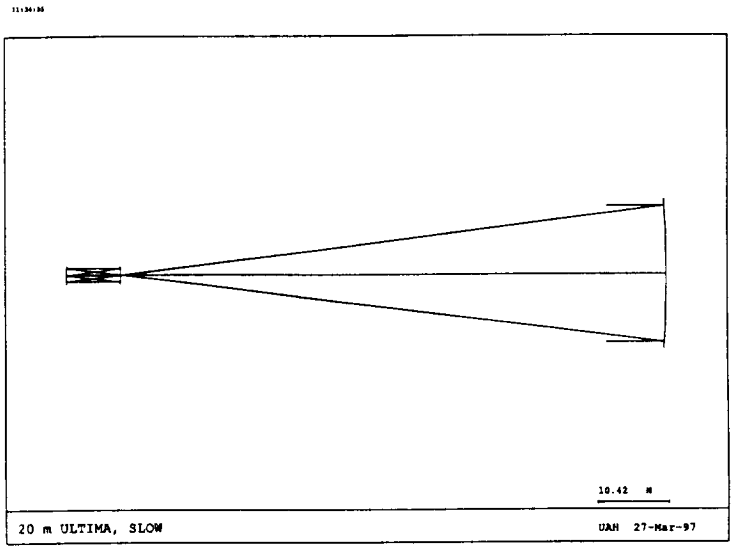


Fig. 2. The slow, free-flyer design.

2.7 Some Optical Design Issues.

One issue with respect to correction of primary segment misalignments with a downstream optic was discussed extensively during this study. It has been shown by several researchers that when correcting for a piston error of z in a primary segment through an opposite displacement of a corrector mirror segment, that an error of $\delta = 2z(1/\cos\theta - 1/\cos M\theta)$ will be seen for rays at a field angle of θ, where M is the magnification factor between the primary and corrector. There was some doubt by some members of the study team as to whether or not this equation was valid. In order to check it, a 3-mirror design similar to the one above but with a magnification factor of 50 was set up with a small segment at the center of the primary and a corresponding segment on the tertiary. On and off-axis rays were traced with both segments aligned to their parent mirrors and no optical path difference (OPD) was found. The primary segment was then displaced 33 μm. An OPD of 66 μm was seen for rays hitting the segment, as expected. Next, the tertiary segment was displaced 33 μm opposite to the primary segment. The OPD for the on-axis ray was found to be back to zero. However, a ray at a field angle of 0.2° was found to have an OPD of 1 μm, which exactly matches the value predicted by the equation above. Thus, the equation appears to be quite accurate. For this reason, the magnification factor was kept at 10 or below in the above designs. With the specifications listed in Table 1, this would allow for adequate correction across the full FOV of piston errors as large as several mm on the primary.

Another critical issue with regard to the concept of a primary free-flying from the other optics is maintenance/correction of their alignment. As noted above, more work is required to insure the feasibility of this approach. At this point it would seem that, while this is certainly an advanced concept, it is not out of the realm of possibility. It would lead to a whole new class of space optical systems.

Lastly, another idea of actually having the segments of the primary mirror free-flying separately from each other has been discussed. This would obviously eliminate the concerns of assembling and/or deploying a large, rigid structure to hold all of the segments in place. However, the issues of alignment become even harder to deal with than the previous free-flying concept. Furthermore, pointing of the telescope presents an enormous obstacle. It would seem that, at this time, even advanced technology is incapable of making this concept viable.

3.0 Summary of Optical Design Task.

Two designs have been developed which would seem to confirm the feasibility of using a spherical primary, favorable to replication, for a very large aperture space telescope. Excellent image quality was obtained in the 4-11 μm range in reasonable layouts.

4.0 Structural and Material Requirements

4.1 Ultra-lightweight Concept Requirements:

1 - 3 kG/M^2
Deployable Segments
Replication Procedures
High Specific Stiffness
Atomic Nitrogen and Oxygen Stable or Protection
Low Hysteresis
High Microyield Material
Low Internal Stored Energy
Thermal Stability
No Deployment Damage
One - G Assembly, Alignment & Testing
Uniform Cryogenic Cooling Contraction

4.2 Manufacturing Processes Considered

4.2.1 Faceplate / Core Concepts

Lightweight mirrors can be fabricated using replicated faceplates such as gold or nickel with selected core materials bonded to the back side of a deposited material. The face plate is coated onto a precision mandrel and may be either a very thin (0.2 - 10 microns) coating or a thicker self supporting coating such as an electroformed shape. When the thinner coating is used the backing material must be of optical quality at the interface in order to avoid significant print through when the thin coating is separated to become the optical surface. This requires nearly as much effort as producing the optical component and coating it with gold or other suitable materials so there is not a significant cost savings but the weight advantage can be significant. When the much thicker electroformed coating is used on the mandrel then more latitude in the quality of the interface is permitted at the sacrifice of weight. Interestingly though the interface must still be of very good fabrication quality even though the requirements are not as stringent as for the thin surface. Typically the bonding material is a very thin epoxy film of 2 - 4 microns. The following materials are suggested for the sake of saving weight and providing stiffness and preserving the requirement of high microyield strength.

SiC Fibers
Silicon Carbide Continuous Fiber Structure (Thermo-Electron, ERG)
Graphite Fibers (May include CVD Diamond Filaments)
Graphite Continuous Fiber Structure (ERG)
Alternate Ceramic Filaments (Al_2O_3)
Open Cell Structural Pieces (ERG)
Co-Continuous Composite Materials (Hypereutectic Structural Material) VANASIL

Analytical procedures are available for the determination of physical and mechanical behavior of cellular structural materials. Notably M.F. Ashby and L.J. Gibson have reviewed the mechanical behavior of random cell structures of nearly the same size cell and ligaments of a material. They have reviewed both isotropic and anisotropic cells in detail. Others have reviewed composites of metal - fibers and actual performance of composite space mirrors. See references [6-9].

4.2.2 Advanced Replication Process Materials

In conflict with the extraordinary properties of the fibers or cellular materials available is the noted lack of bonding or filler materials with low expansion or other redeeming matching properties. Particularly difficult is the bonding of thin face sheets to a backing without print through due the issue of high hysteresis and shrinkage of the epoxy materials commonly used. Also the cellular materials have short order spacing usful to reduce the bending moments, but poor matching to the replicated face sheet. Also many cellular materials have relatively poor microyield and creep properties.

5.0 Determine Fabrication Processes

In order to fabricate structured mirror segments for ULTIMA, using replication processes, several requirements are to be established. The material selected has to have the properties listed and must also permit fabrication of a structure unlike the Optics Community is accustomed. The perception is that a faceplate will be deposited from a master substrate (mandrel) and then subsequently backed with a very stiff material in a manner consistent with an open cell or co-continuous fashion to form a very light structure with extremely high microyield and specific stiffness properties. Ideally this material is then sandwiched between the mirror replicated faceplate and a similar thickness backplate to provide a very stable optical segment.

Open cell material and also filaments are available with these properties but are not known to be available in the structured final product described. It is possible to build light components with high stiffness using the fibers (especially graphite) in a matrix of epoxy or other resin. This is not as likely to be acceptable for this concept with epoxy having vastly different properties as described earlier. The intent is that the structure will be "cemented" as a single structure by secondary deposition or by a casting or molding process followed by a dissolution process which permits the fibers or cell structures to become attached not only to the faceplate but also as a monolithic structure with high fiber to fiber attachment integrity and as nearly as possible, the same physical properties.

Processes may include casting hypereutectic silicon aluminum with silicon carbide fibers mixed in. By casting and hot pressing this material, shapes could be formed. Folowing the fabrication of the shape, a dissolution process could conceivably remove all aluminum and eutectic aluminum alloy, leaving the silicon co-continuous stucture with the SiC fibers intact and sound.

Combinations of the processes could be used to produce shapes and structures from the commercial open cell materials available. By proper design the structure would have a specific (apparent) density less than 1 gm/cc. A one meter square section would have a thickness of perhaps 0.3 cm with an aerial density less than 3.0 kg / Sq. Meter.

5.1 Replication Processes Considered

In order to maintain lightweight systems with relatively large elements such as possible in the spherical mirror designs it will be required to provide innovative monolithic replication processes. The use of graphite with certain resin systems in conjunction with deposited mirror faceplates from a master mandrel will be considered. Two major issues persist in the combination of resin/graphite and replicated metal such as electroformed nickel. First the epoxy or other resin systems must be carefully formulated to avoid moisture desorption from causing deformations. The second is the fact that the thermal expansion coefficients generally do not match between the graphite epoxy and the metal faceplate. The first can be mitigated in space since the material can be vacuum dried before final deployment. This will require careful consideration to avoid changes during initial manufacturing and measurement stages of fabrication. The second issue has not been addressed for the case of low expansion composites and the medium expansion electrodeposited metals such as nickel or copper. A novel approach might be to deposit the replicated faceplate from iron (64%) nickel (36%) which is Invar (or invariant metal). Research over more than ten years has lead to suitable deposition processes to plate low stress Invar. This work has been the responsibility of several entities and researchers including D. Engelhaupt now with UAH. The reflective surface would probably be gold for infrared and visible systems. This layer would be extremely thin and of much less consequence on bimetallic distortions. The behavior of the deposited Invar at cryogenic temperatures is not known but since most materials expand at a much lower rate at low temperature it is expected that a composite of low expansion graphite/resin can be matched to provide low distortion as the components cool to space temperatures.

5.2 Silicon Carbide Replicates

Silicon carbide is certainly one of the favored choices if processes and weight can be controlled to yield affordable segments. A novel material combination has been produced by Thermo-Electron Corp. in Boston, MA. This firm has developed a chemical vapor deposition (CVD) process to fabricate silicon carbide components with a two phase silicon carbide comprised of a solid layer deposited on a mandrel followed by a porous layer of fibers injected into the process gas stream allowing a very stiff low density material to be fabricated with extremely high specific stiffness and uniaxial low thermal expansion. The material can also be produced as a three layer composite with pure silicon as the starting surface. The porosity can be tailored to produce an optimum material for different applications. Morton International also located in the Boston area, has produced replicated silicon carbide mirrors of up to 1.5 meters diameter. These mirrors are quite heavy by the requirements set forth although substatially lighter than equivalent quartz or Zerodur (TM).

6.0 Fabrication Tests

Materials ordered or available for testing include:

1) Reticulated Silicon Carbide
2) Reticulated Carbon
3) Aluminum Foam Metal
4) SiC Fiber Filled CVD SiC
5) Nickel Coated Graphite Fibers
6) Nickel Electroform Process
7) VANASIL Foam Metal (Al-Si Hypereutectic)

6.1 Electrocomposite Plating

The first approach tested was plating the nickel with nickel coated graphite fibers using small cylindrical pieces of aluminum as substrate. One sample has been submitted to materials (4612) for cross section analysis. Two others are intact for inspection. With moderate effort it is possible to electroplate significant percentiles of the fibers into the deposit. The material appears to be sound and even withstood machining cuts (at the expense of the tool). Electrodeposition of a metal with the nickel coated fibers in the solution was explored for this brief effort as a candidate process amenable to the electroforming processes performed at MSFC. A structure could be formed with excess fibers such that the plating attaches the fibers but is not used to fill the void spaces. This structure would be on the back of a sound faceplate replicated on a substrate. By filling the porous material with a removable material such as wax, it then becomes possible to form a continuous backplate. The filler material is then removed by melting or dissolution and a monolithic sandwich structure is achieved without adhesives.
The immediate goal is to achieve 50 vol% of the fibers in the deposit. While this seemed heuristic, it was possible. The nickel coated fibers are 10 - 20 wt% nickel as delivered but this could be reduced. The fibers are PAN graphite such as is used in composites. The nickel coating on the fibers is reported as 0.09 microns thick and the fibers are 7 microns diameter nominally. The density of the fiber material is about 1.8 grams per cubic centimeter. A deposit of 50% each nickel and fiber was achieved with a density of about 5.3 grams/cc. See figure 3.

Figure 4 is a sketch of the desired results for an extended effort and Table 2 is a list of anticipated properties. This would include a reinforced material from nickel - iron plating for lower CTE and much higher strength and hardness than conventional nickel, along with included fibers for additional pinning, increased modulus, and strength along with lower density. This would demonstrate that commonly mutually exclusive parameters such as CTE, elastic modulus, micro and macro yield and density can be specifically tailored in favorable directions for fabrication of optics concurrently. Many cellular materials have relatively poor microyield and creep properties. The first available cellular material for this study was 6101 - C aluminum which was very ductile. Tests were made to determine if the material could be stiffened without severe weight penalties. Electroless nickel was plated on samples to form a 12 micron thick coating surrounding the aluminum ligaments. The load - unload curves show a dramatic improvement in the otherwise poor hysteresis. See figure 5.

Graphite/Nickel Electrocomposite

Fig. 3

ULTIMA

LOW DENSITY - LOW EXPANSION

ULTRA -HIGH STRENGTH - HIGH MODULUS

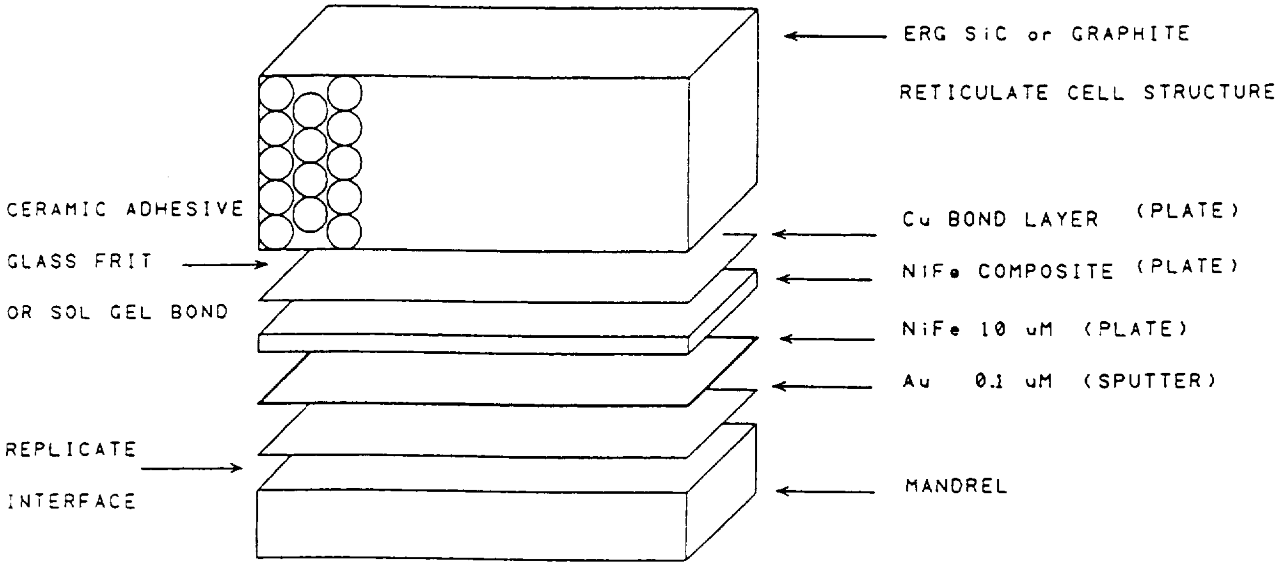
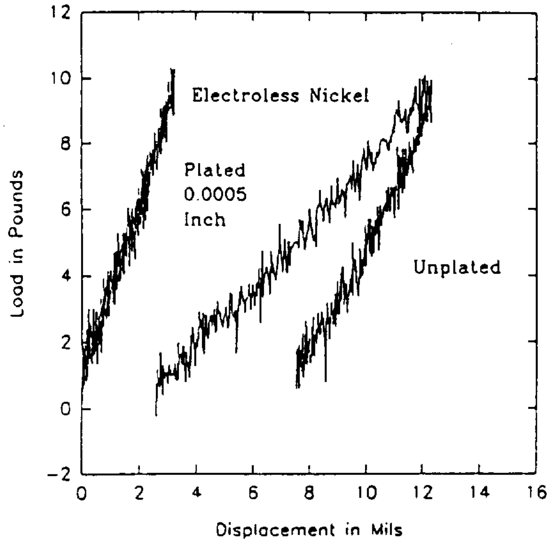
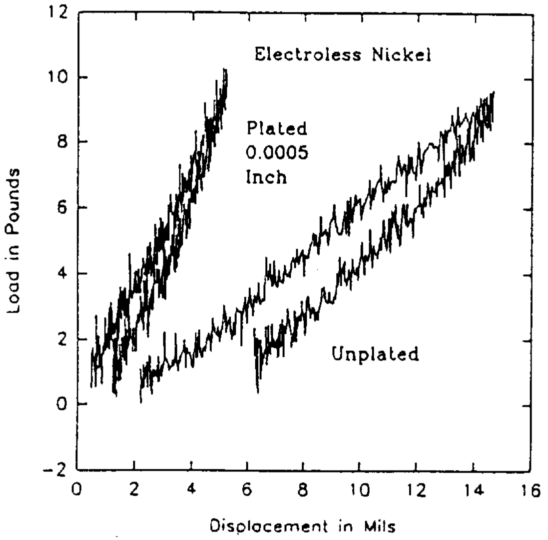


Fig. 4

Load and Unload Curves for 10 PPI Cellular Aluminum



Load and Unload Curves for 20 PPI Cellular Aluminum



Load and Unload Curves for 40 PPI Cellular Aluminum

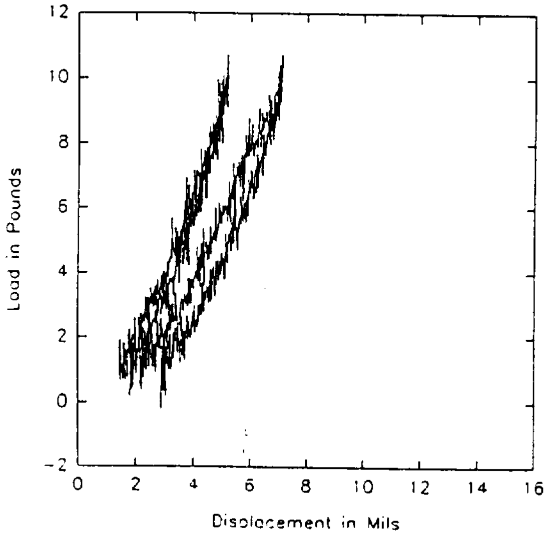


Fig. 5

6.2 Fabrication of Mirrors with Cellular Backing Materials

A flat 19 centimeter mandrel was available from another project and was used to plate face sheets and test several of the purchased cellular materials from ERG Inc. The mandrel was used to deposit from 0.15 to 0.50 millimeters of nickel in eleven tests. Two of the tests resulted in failure due to lack of low stress control. This in turn caused distortion in the optical components. The others were plated using the MSFC computer controlled process in place in EH-24. Four cellular material samples were used for bonding tests and included the 0.25 inch graphite, 0.5 inch graphite, 0.25 inch Vanasil, and 0.5 inch Vanasil. The Vanasil was unique in that ERG had never produced this material prior to this request. Three additional mirrors were made from this mandrel using the nickel plated 6101 - C aluminum material. Also two mirrors were produced without backing to observe the quality of the stress controlled plating and appeared to be very good. The bonded parts appeared to exhibit some print through when the foam metal or graphite was glued on using three types of epoxy. Each part was successively better as less epoxy was applied improving both the weight and print through issues. The first part was bonded with a conventional epoxy filled with graphite spheres and the second was bonded with a graphite filled acetate cure marine epoxy. The CTE was measured for this material from -130 C to 23° C and found to be unacceptably high. See table 3. This epoxy was applied, followed by a thin a layer of fiberglass which was laid onto the uncured epoxy. This was followed by a second layer of epoxy to bond the graphite after the first cured. The first part had an aerial mass of 5.0 Kg/M^2 which was considered to be very good. The second was slightly higher at about 6.0 Kg/M^2. The parts looked very good but showed a faint pattern characteristic of the fiberglass weave in the interferometer. Also the overall point to point contact of the graphite showed, however a distinct improvement was noted for the second part.

Next a blended epoxy with a stated CTE of 13 PPM/° C was purchased and used to bond the 0.5 and 0.25 inch Vanasil to electroformed facesheets while the facesheet remained on the mandrel. These two parts were plated 0.5 mm thick and had an aerial density of about 8.0 Kg/M^2. Although significant improvement was noted the added thickness did not entirely prevent the print through. The second piece was fabricated in two stages yet a small print through was observed. An additional test was made with a thin silicone RTV sheet as a separator. This part showed no short order print through but suffered longer range distortion.

7.0 Summary

Unique combinations of replication capabilities will provide new technologies permitting fabrication of extremely large precision space optics for use beyond the next generation of telescopes. Replication processes will permit affordable fabrication of segments which can be packaged for deployment and assembled into very large optical systems in space. The use of spherical mirrors allows the minimum number of different components to be used. Advantages occur in the edge sensing and control because of similarity of segments in the mirror. The overall optical system must compensate for the aberrations which a large spherical mirror introduces. Processes are described which should allow a monolithic approach to the entire macroscopic mirror segment with engineered properties of ceramics or metals eliminating moisture absorption distortion issues predominantly plaguing the organic filled composites.

Table 2 Properties Anticipated from Composite Deposits of Nickel Alloys

CTE (PPM/°C)	MASS Gm/cc	TENSILE STRENGTH KSI	MODULUS MPSI	MICROYIELD KSI 20 PPM OFFSET
Ni				
13.0	8.913	110	28	30
Ni-Fe				
2.0- 4.0	8.0	270	30	180
Metal Graphite Composite				
2.0	5.3	300	45	200

Table 3 CTE AND Tg DATA BY THE TMA TECHNIQUE ON CURED SAMPLES OF MARINE EPOXY.

Sample Number	TMA Sample Height, mm	Glass Transition Temp, Tg, °C	Coefficient of Thermal Expansion, CTE, µm/m°C, on 2nd TMA temperature scan		
			-130°C	-130°C to 0°C (slope)	23°
1	18.7160	25.90	36.7	52.9	116
2	19.3824	24.65	35.7	53.2	116
3	15.9347	25.40	37.9	53.3	118
4	13.1134	23.28	41.7	53.5	121
		Avg = 24.81 Std Dev = 1.14	Avg = 38.0 Std Dev = 2.63	Avg = 53.2 Std Dev = 0.25	Avg = 117.8 Std Dev = 2.36

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Note: The electroformed nickel - iron data is from comprehensive work done by D. Engelhaupt for Phillips Laboratory, Kirtland AFB, NM while at MMOA - 14 Reports and also unpublished work done at Bendix, KC, MO (1978 - 1987).

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