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SECTION IV (Cont'd) WORKSHOP PANEL REPORT:

2. FABRICATION

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INTRODUCTION

What aspects of optical fabrication technology need to be developed so as to facilitate existing planned missions, or enable new ones? Throughout the submillimeter to UV wavelengths, the common goal is to push technology to the limits to make the largest possible apertures that are diffraction limited. At any one wavelength, the accuracy of the surface must be better than $\lambda/30$ (rms error). The wavelength range is huge, covering four orders of magnitude from 1 mm to 100 nm.

At the longer wavelengths, diffraction limited surfaces can be shaped with relatively crude techniques. The challenge in their fabrication is to make as large as possible a reflector, given the weight and volume constraints of the launch vehicle. The limited cargo diameter of the shuttle has led in the past to emphasis on deployable or erectable concepts such as the Large Deployable Reflector (LDR), which has been studied by NASA for a submillimeter astrophysics mission. Replication techniques that can be used to produce light, low-cost reflecting panels are of great interest for this class of mission.

At shorter wavelengths, in the optical and ultraviolet, optical fabrication will tax to the limit the most refined polishing methods. Methods of mechanical and thermal stabilization of the substrate will be severely stressed. In the thermal infrared, the need for large aperture is tempered by the even stronger need to control the telescope's thermal emission by cooled or cryogenic operation. Thus, the SIRTF mirror at 1 meter is not large and does not require unusually high accuracy, but the fabrication process must produce a mirror that is the right shape at a temperature of 4 K. Future large cooled mirrors will present more severe problems, especially if they must also be accurate enough to work at optical wavelengths.

At the very shortest wavelengths accessible to reflecting optics, in the x-ray domain, the very low count fluxes of high energy photons place a premium on the collecting area. It is not necessary to reach or even approach the diffraction limit, which would demand subnanometer fabrication and figure control. Replication techniques that produce large very lightweight surfaces are of interest for x-ray optics just as they are for the submillimeter region.

Weight and surface accuracy are not the only dominant factors that affect optical fabrication. Surface shape is equally important, affecting the difficulty of both polishing and testing surfaces. Thus, because spherical or near spherical surfaces are by far the easiest to both polish and test, telescopes needing high accuracy surfaces have favored them, even at the expense of long focal length mirrors and correspondingly less manageable and longer spacecraft. A definite challenge for future optical fabrication is to remove this limitation. At wavelengths shorter than a few tens of nanometers, reflection takes place only at grazing incidence, forcing the use of deeply parabolic or hyperbolic surfaces whose curvature is more nearly cylindrical rather than spherical. While not requiring overall diffraction limited accuracy of angstroms or less, these surfaces must have extreme smoothness on small spatial scales, if they are to reflect efficiently.

An issue that will be of increasing importance in future space optics is the degree to which active deployment or control and adjustment are required. The Hubble Space Telescope was designed to be basically passive, the optical system as finished on the ground was supposed to be accurate and stable enough that once the alignment is set in space, it should not depend on frequent adjustments. Future systems, with larger sizes or higher accuracy or both, may make more or less use of active or adaptive systems to relieve requirements for thermal, dimensional, or vibrational stability. Errors from gravity release, thermal release (new figure on cooling), and figuring errors may be correctable in space. The trade-offs between inherent stability and correctability will require much study, particularly with regard to different temporal and spatial scales.

As challenging as these requirements are, we are fortunate to be able to build upon many important developments that have taken place in the last decade in mirror fabrication. The HST mirror used what were at that time innovative fabrication techniques; however, work done that has been largely sponsored through the U.S. Department of Defense during the last decade makes much lighter mirrors possible today. Examples of these lightweight mirrors are illustrated in Figures 14, 15, and 16. Recently there have been important developments in the technology of figuring and testing of mirrors. Active control of mirror surfaces is being actively pursued in this country and abroad in both defense and astronomical applications.

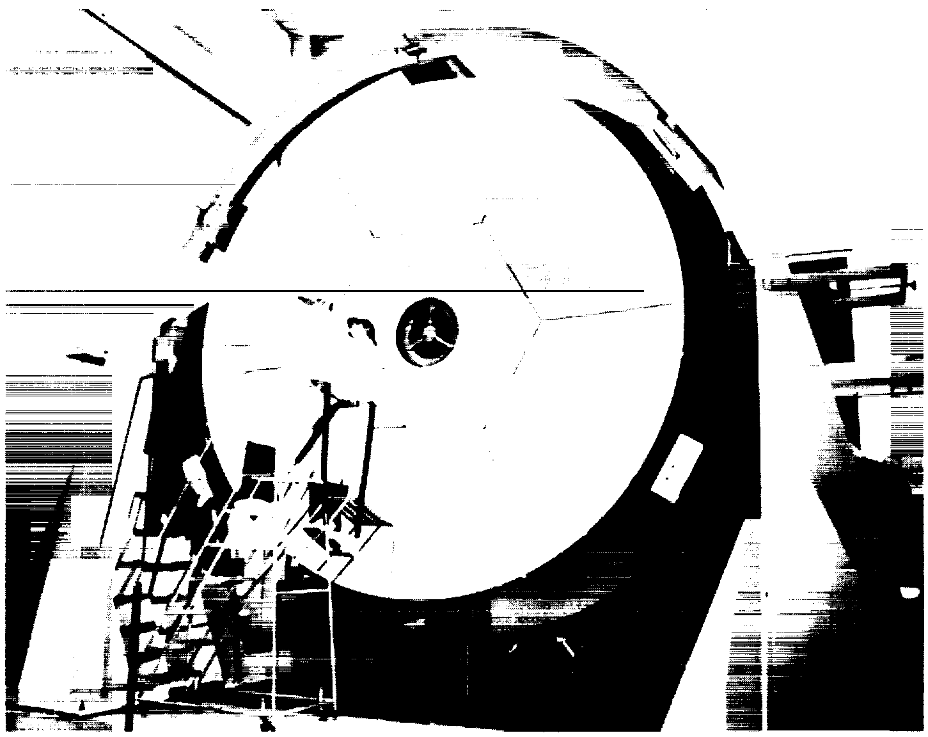

Figure 14. Large Adaptive Mirror Program (LAMP) – ITEK active segmented primary mirror (LAMP) representing a factor-of-10 reduction in weight over passive mirror technology. The active mirror can compensate for on-orbit environments to maintain optimum performance.

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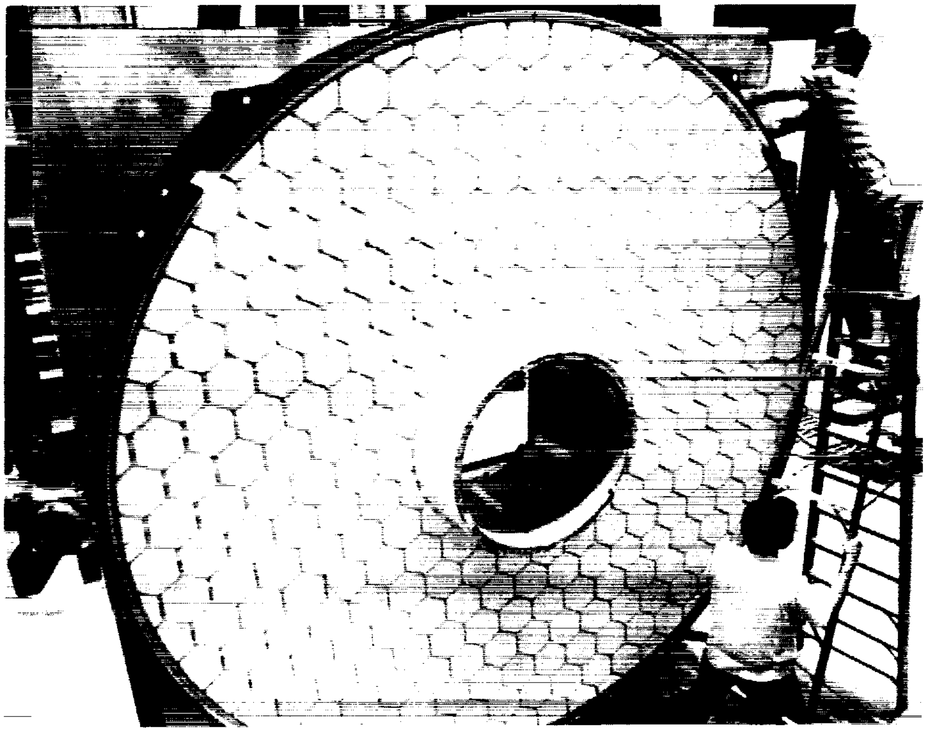


Figure 15. ARC 3.5 m Mirror – One of three 3.5-m honeycomb mirrors cast by Steward Observatory Mirror Laboratory. The fastest of these, f/1.5, is being figured at the laboratory with a stressed lap, and currently stands at 28-nm rms surface error. (Courtesy of Steward Observatory Mirror Laboratory.)

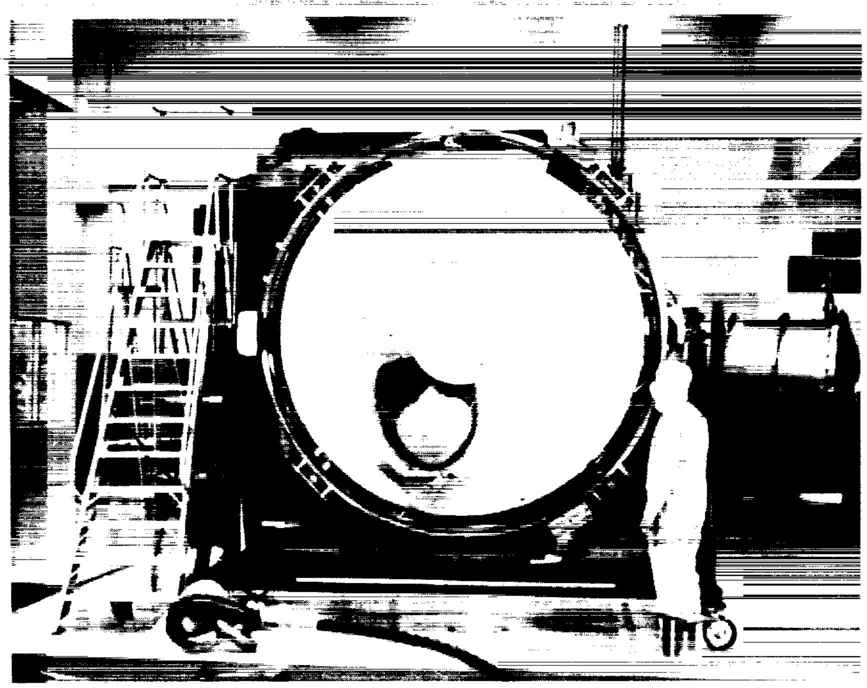


Figure 16. Hubble Primary Mirror

We now examine optical fabrication requirements in somewhat more detail for missions in each of the three spectral regions of interest to astrophysics that were identified in the introductory presentation on the Astrotech 21 mission set (see Section II). These requirements are summarized in Table 14. The key parameters are the area of each mirror or panel, the total number of panels that is needed, the rms error (which is primarily driven by the minimum wavelength), and the panel areal density.

UV Optical – The pertinent missions here are the Far UV Spectroscopic Explorer (FUSE), Astrometric Interferometry Mission (AIM), the Lunar Transit Telescope (LTT), Next Generation Space Telescope (NGST), and the Imaging Interferometer (II). The natural limiting UV wavelength is 91.2 nm below which the hydrogen opacity of the intergalactic gas impedes observations. It also happens that the throughput of conventional normal incidence telescopes falls off rapidly below this wavelength as a result of the rapidly declining normal incidence reflectivity of mirror coatings.

The conventional criterion for the diffraction limit leads to a surface accuracy of $\lambda/30$, which is 3 nm rms at 91.2 nm. However, if scattered light must be reduced to lower levels, the scattering criteria are more exacting. For example at 633 nm, 3 nm rms will yield scatter of 10^{-3} and 1 nm of 10^{-4}. Thus a fabrication goal of 1 to 3 nm that provides low scatter in the visible and diffraction limited performance in the vacuum UV is a natural goal for future large optics. This compares with the present state of the art for large optics of 10–30 nm. To achieve this order of magnitude, improvement will require progress in materials, structures, fabrication, and testing technologies.

Additional demands will be placed on mirror technology by cooling the mirrors. With the prospect that adaptive optics can significantly enhance the resolution of ground based telescopes in the visible and near infrared, it is expected that a future large space telescope (NGST) will provide larger benefits in the infrared (1 to 20 μm) because of the low space backgrounds. This will require radiative cooling of the mirror to 100 K or lower. Simultaneously satisfying a requirement for low background cooled operation while maintaining 1 to 3 nm figure stability is extremely difficult.

At the Astrotech 21 Workshop on Large Filled Aperture Telescopes, requirements for a Next Generation Space Telescope were developed. A key issue is whether all the requirements can be met in a single telescope or whether it is more cost effective to develop telescopes separately optimized for the ultraviolet and the infrared. The requirements and possible design approaches for large filled aperture telescopes are indicated in Table 15.

Table 14. Optical Fabrication Requirements

MISSION	Primary Element Area (m^2)	Number of Elements	RMS Error (nm)	Panel Areal Density (kg/m^2)
HST	4.5	1	10	200
KECK	2	36	50	200
FUSE	1	1	1 – 5	
LTT	8	1		50
AIM	.07	6	3	5 – 10
NGST	50	1	1	100
II/FFT	1	60	2 – 3	10 – 20
COLUMBUS	50	2	30	300
GP-B				
LAGOS				
SOFIA	6	1	150	50 – 100
SIRTF	1	1	50	
SMIM	1	4 – 7	5000	< 15
LDR	4	90	1000	< 15
SMMI	19	4	3000	< 10
SVLBI	4	100	5000	
AXAF	5 (1600 cm^2) [a]	20	3 AR	63 (P1 Mirror)
XST			1 AR	
HXIF				
VHTF	30		1 AR	
Integral/NAE				
GRSO				

[a] AXAF effective collecting area at 1 keV

Table 15. Next Generation Space Telescope Issues

Optical Design	-2,3,4 Mirror Configurations -Primary Focal Ratio -Pupil Stops -Beam Steering -Pupil Correction -Dilute Apertures
Primary Design	-8-m Monolith -Segmented
Active Control	-Sheet -Segments
Mirror/Lens Materials	-Alpha = 0 at 100 K (ULE) -Homogeneity of Alpha -Alternates to Silica -UV Transmission
Fabrication Methods	-Ion Beam -Stressed Lap -Membrane -Chemically Controlled Polish (CCP)
Figure/Surface Coatings	-Surface Roughness (Scatter<Airy Diffraction) -Emissivity
Testing	-To 8 m at 1–3 nm Accuracy on Scales of 3 cm. -Cryogenic testing at 80 K
Spectral Range	-Panchromatic UV to IR -Separation of UV and IR
Environmental Issues	-Lunar Impacts -Cosmic Ray Environment (Burial in Regolith) -Contamination at vacuum UV (Especially of Cooled Surfaces)

X-ray Telescopes – The resolution of x-ray telescopes is completely determined by x-ray optics and fabrication errors. The diffraction limit is not an issue (as there is no intent of achieving diffraction limited optics in terms of figure quality). Both metrology and tool fit are critical in x-ray optics fabrication. Missions considered here include the Advanced X-ray Astrophysical Facility (AXAF), the Very High Throughput Facility (VHTF), the Hard X-ray Imaging Facility (HXIF), and the X-ray Schmidt Telescope (XST).

AXAF represents a major step forward in x-ray imaging technology with a substantial performance improvement over its predecessor, the Einstein Telescope (see Table 16). The AXAF telescope consists of two sets of nested mirrors, one paraboloidal and the other hyperboloidal in a Wolter Type-I configuration (see Figure 17). The mirrors are fabricated in Zerodur and the system is designed for 0.5 arcsec resolution.

Table 16. Comparison of Einstein, ROSAT, and AXAF Performances

	Einstein	ROSAT	AXAF
Angular Resolution	4 arcsec	2 arcsec (4 arcsec)	0.5 arcsec
Half Power Radius at 4 keV	9 arcsec	3 arcsec at 1.5 keV	0.5 arcsec
Effective Area at 1 keV	400 cm^2	(430 cm^2)	1600 cm^2
Effective Area at 0.25 keV	–	1000 cm^2	4500 cm^2
Spectral Resolution	50	–	1000
Spectral Range	0.2 to 3.5 keV	–	0.1 to 10 keV
Sensitivity in 10^5 sec	5×10^{-14}	–	5×10^{-16}

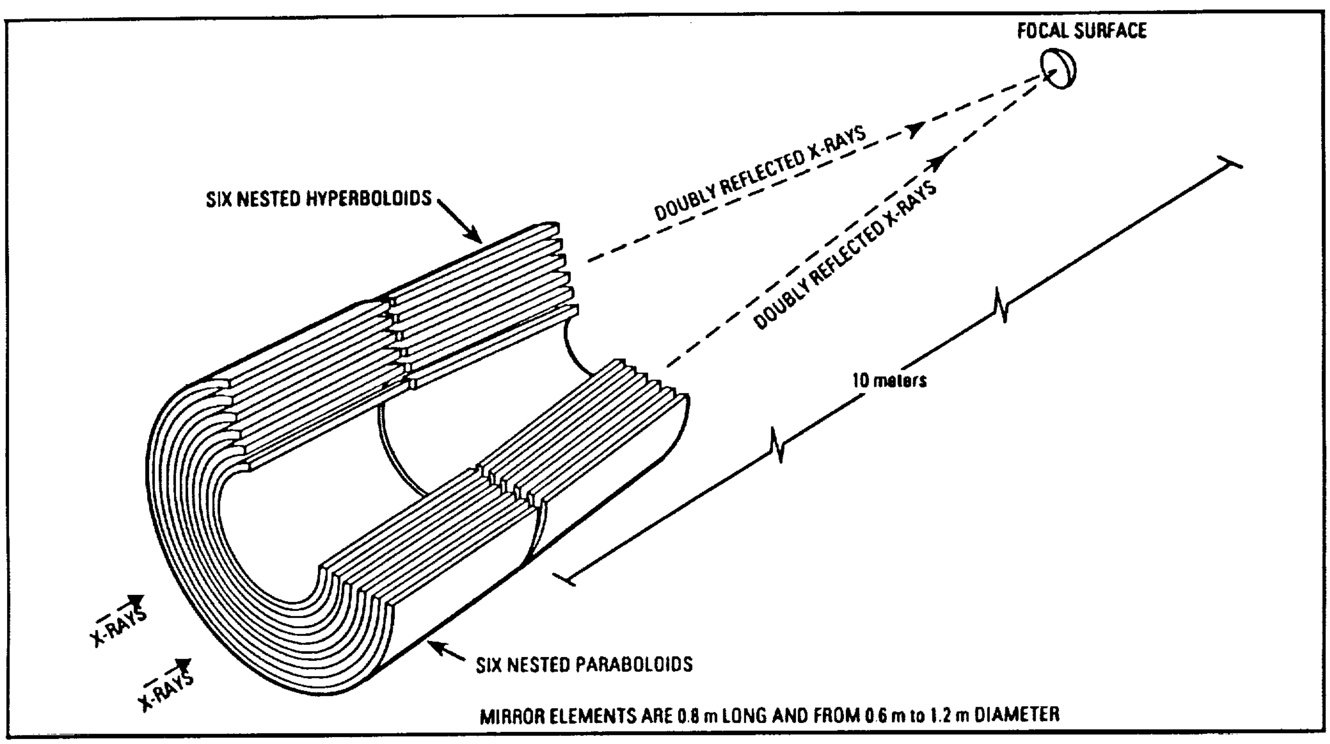


Figure 17. AXAF High Resolution Mirror Assembly (HRMA) – The HRMA consists of six nested paraboloids and six nested hyperboloids. The doubly reflected x-rays focus on a surface 10 m from the paraboloid-hyperboloid interface. Each of the mirror elements are 0.8 m long and range from 0.6 m to 1.2 m in diameter.

The VHTF demands very high light grasp but high angular resolution is not as important as it is for AXAF (because the background is faint). Grazing incidence surfaces larger than 1000 m^2 are required. This leads logically to replication technology as used for the European XMM telescope. The challenges are efficiency and economy in fabrication.

In a grazing incidence telescope, the effective collecting area is increased by nesting as many grazing incidence telescopes as possible. Structural rigidity considerations limit the number of nested telescopes that can be packed into a given envelope and the effective collecting area is highly dependent upon structural efficiency. Therefore, innovative opto-structural designs, test, and fabrication methods that will improve structural efficiency are needed.

Several other kinds of fabrication approaches to x-ray telescopes were considered at the Astrotech 21 Workshop on High Energy Astrophysics held in Taos, New Mexico, including multilayer coated mirrors (Ref. 1) and potentially low cost approaches using flat plate reflecting elements (Ref. 2).

Far Infrared/Submillimeter – For this spectral range the diffraction limit does set the fundamental performance and fabrication requirement.

Two broad classes of telescopes are planned: those with primary mirrors cooled with superfluid helium (such as SIRTF) and those with much larger, passively cooled primaries (such as Submillimeter Intermediate Mission (SMIM), Large Deployable Reflector (LDR), and the Lunar Submillimeter Interferometer (LSI)) (Ref. 3). NASA's Precision Segmented Reflector (PSR) program is developing a lightweighted replicated mirror technology to support these missions. Potentially, this technology may also be applicable to next generation Space VLBI missions (Ref. 4).

The fabrication panel considered the state of technology for fabricating mirrors, lenses, and other optical elements. A mirror is typically a carefully shaped structure with a few hundred atoms thickness of metal on its surface. Transmitting elements such as lenses typically consist of a structure in a homogeneous transmitting material with two or more carefully shaped surfaces typically with coatings in refractive material. Key material/structural properties are the rigidity and weight of the material, thermal and long term stability and radiation resistance. Traditionally, surfaces have been figured in an iterative process involving machining, grinding, polishing, and testing. Thus the fabrication/figuring process considered by this panel is tightly interwoven with the materials/structure and testing disciplines covered by two other panels. Table 17 summarizes the recommended technologies identified by the panel.

Five topical areas are covered:

- Replicated Optics
- Figuring at the 1 nm Level
- Making a Lightweight, Cold 4 m Mirror
- Systems Issues in Optical Fabrication
- Innovative Enabling New Missions

In addition, three other issues were considered by the panel because of their importance to building an effective infrastructure for implementing future missions.

- Facility Needs
- Educational Issues
- Developmental Methodology

Table 17. Fabrication Technologies Recommended for Astrophysics Missions : 1992-2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Replicated Optics	Develop Enabling Replication Techniques Necessary for X-ray and Submillimeter Astrophysics Missions	Automated Polishing Rapid Replication Mandrel Material Composite Facesheet Thermal Stability Areal Density	VHTF XST LDR SMIM SMMI	'03 '95 '01 '95 '05
Figuring Large Optics to 1 nm (Non Cryogenic)	Develop Techniques and Processes for Figuring to 1 nm rms, at Large Scales (8 m)	Lightweight Blank Fabrication Surface Polishing Metrology Control of Subsurface Damage Deterministic Finishing	LTT FUSE AIM NGST II SOFIA	'95 '92 '97 '02 '04 '91
Lightweight, Cryogenic, Aspheric Mirrors	Demonstrate Fabrication of 4-m Aspheric, Cryogenic Mirror at 2 – 3 nm rms	Cryogenic Test Facility Lightweight Blank Fabrication Figuring At Nanometer Scale Fabrication Testing	LTT NGST Lunar SIRTF	'95 '02
Systems Issues	Identify and Develop Key Systems Areas That Have the Greatest Impact on the Fabrication Process	Smart Structures On-Orbit Techniques Rigidity Segment Fabrication Mounting	All	'93 - '04
Innovative Techniques	Provide Support to Basic Research and Development Activities That Have Potential for Improved Fabrication, or Offer Solutions to Innovative Optical Designs	Monitoring/Measuring Material Removal Continuously Adaptive Thin Film/Membrane Systems High Throughput, High Resolution Optics for High Energy High Energy Optical Designs Advanced Refractive Elements Advanced Processing Techniques	All	1996

REPLICATED OPTICS

A. Technology Assessment

Increasing the throughput of optical systems requires the development of mirrors that are both lightweight and low cost. The fabrication of a precisely figured optical surface is likely to continue to be an expensive process requiring the commitment of expensive machinery and manpower. The development of replication technology to reproduce high fidelity copies of optically figured surfaces is of great interest. This technology appears to be particularly pertinent to submillimeter telescopes and x-ray grazing-incidence telescopes (see Figures 18 and 19).

Replication technology is being developed in NASA's Precision Segmented Reflector program for submillimeter astrophysics mission such as SMIM, LDR, and SMMI. It is also being pursued by European Space Laboratory (ESA) for the nested grazing-incidence x-ray telescopes to be used in the x-ray spectroscopic mission (XMM). In Figure 19, the processes used in replication fabrication of submillimeter and x-ray mirrors are illustrated.

Although the figure requirements for submillimeter and x-ray missions are roughly similar, x-ray applications make more severe demands on surface smoothness. We recommend that NASA also begin the development of replication technology for its future x-ray missions beyond AXAF to complement its current programs in submillimeter telescope fabrication.

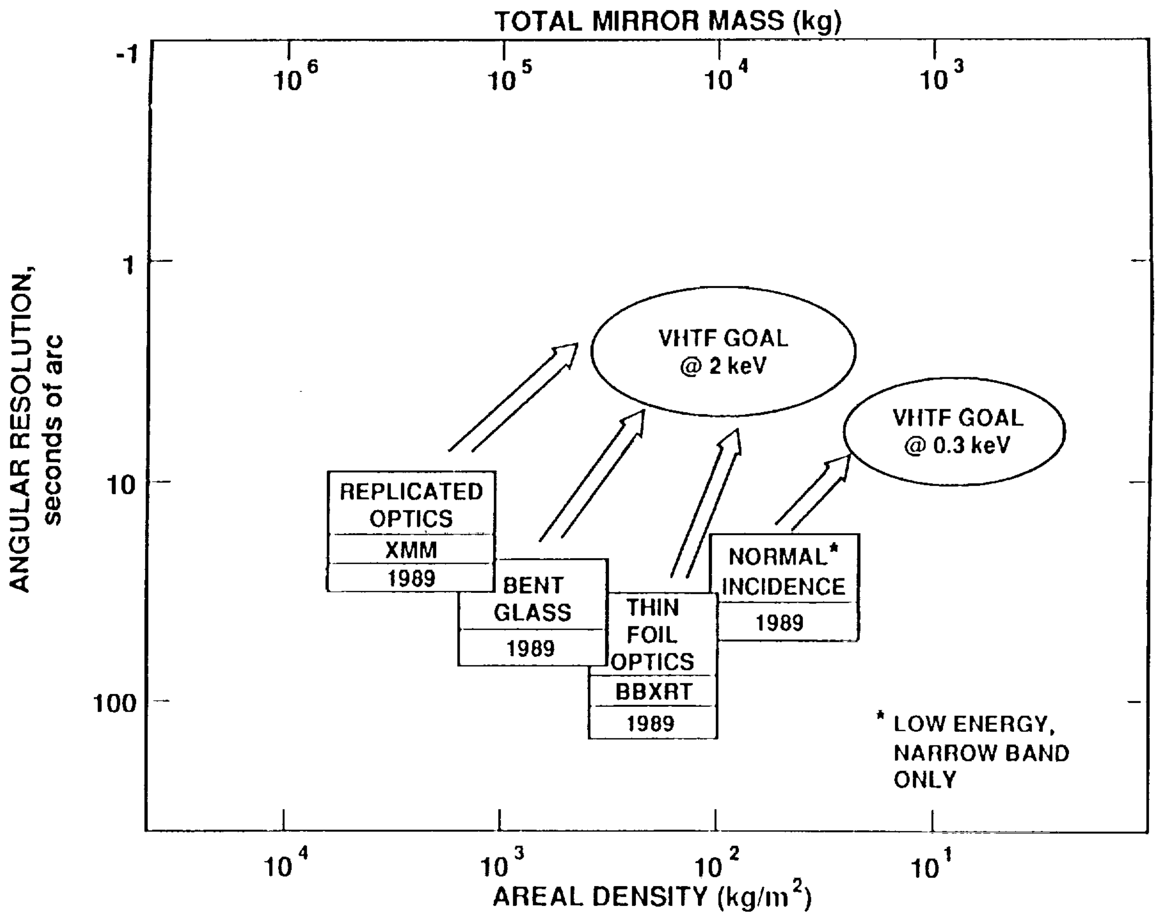


Figure 18. High Energy Requirements for Lightweight Mirror Technologies

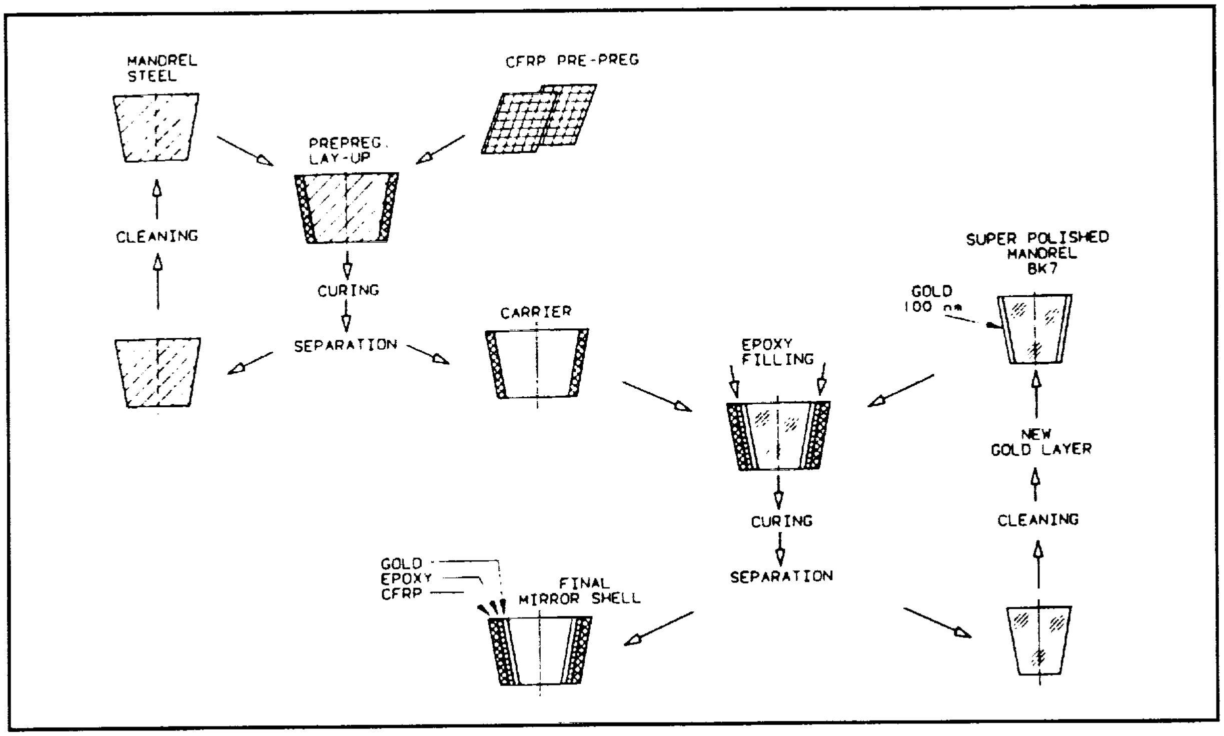


Figure 19. XMM Mirror Shell Process Diagram

B. Development Plan

A total of six critical technologies needed, three for x-ray and three for submillimeter replicated optics (Table 18(a) and (b)). Essential to the submillimeter missions are large, smooth, accurate composite face sheets that are supported on a lightweight sandwich construction. The need is for 1-µm figure and roughness of 2-m panels. The current state of the art is 1.0-µm figure and roughness, and 1-m aperture. Present panels also have large variations in radius of curvature.

Once the surface quality can be met at ambient temperature, the technology will need to be pushed to the temperature regions required for the submillimeter telescopes. The 2-m panels will need to maintain their qualities to a temperature of 80 K. To support the very large missions (LDR for example), areal densities of less than 5 kg/m^2 will be needed.

The development of automated polishing of cylinders for x-ray mirrors (Figure 20) is necessary. The current state of the art in x-ray replication is achieved with the Zeiss Mandrels being used for the XMM. This technology does not have the accuracy required for next generation x-ray telescopes, and can only work on cylinders with about 10% of the area required for future astrophysics missions.

Most x-ray telescopes consist of nested arrays of cylindrical surfaces. Improved speed in cylinder production is a necessary development with a production target of 50 cylinders per year (the current capability is a small fraction of this) being reasonable. An important part of achieving this high rate, and achieving the same quality on all replicated surfaces, is the mandrel. Mandrel lifetimes need to be increased and should be developed to withstand at least 50 replications. Part of the development should concentrate on mandrel materials that, while being tough, can be polished and microfigured without major resources in time and manpower being required. Some materials warranting further investigation include sapphire, CVD silicon carbide, crystalline molybdenum, and silicon. Additionally, the questions of how one figures a mandrel and how the mirror release from the mandrel is accomplished must be addressed.

Table 18. Replicated Optics Enabling Technologies Program

(a) X-ray

TECHNOLOGY DEVELOPMENT	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Automated Cylinder Polishing	Zeiss Mandrells for XMM, 0.1 of Required Area, Not as Accurate	Single Cycle Figuring of Cylinders	'98	'93 - '98
Rapid Replication	Finish : 10 Å Over 10 –100 μm for Wolter Type Mirror Typically Takes 1 yr for Mirror With 1 as Resolution, 1–3 Å Finish	Automated Polishing w/ Metrology Feedback Resolution : 1 as Finish : 1 - 3 Å Over 10 – 100 μm 3 - 10 Å Over 100 μm – 1 mm Production : ≈ 50/yr	'99	'93 - '98
Mandrel Materials	Al Substrates With Nickel Coatings, Glass	Materials for Double Mandrells Replications/Mandrell : > 50	'98	'93 - '98

(b) Submillimeter

TECHNOLOGY DEVELOPMENT	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Facesheet Replication and Construction	Aperture : 1 m dia. Gr/Ep 1.0 μm rms (Figure and Roughness)	Composite Mirror Panel : Aperture : 2 m 1 μm rms (Figure & Roughness)	'96	'93 - '96
Thermal Stability	0.5 m Gr/Ep Composite ≤ 3 μm rms On Orbit at 80 K	0 CTE at 80 K (Thermal Stability) for 2 m Aperture 1 μm rms	'99	'93 - '98
Areal Density	10 kg/m^2	≤ 5 kg/m^2 for 2 m Panel 1 μm rms	'03	'93 - '03

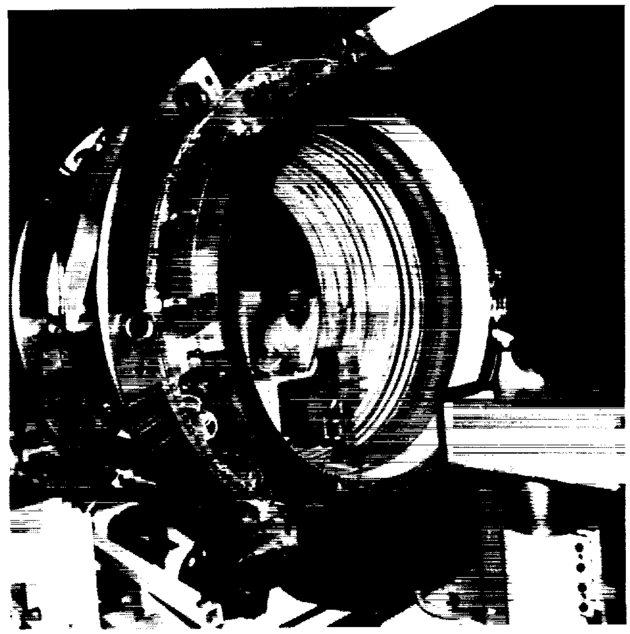


Figure 20. AXAF Parabola 1 (P1) – The P1 optic undergoes a grinding cycle on the Automated Cylindrical Grinder/Polisher (ACG/P) at Hughes Danbury Optical Systems, Inc. The manufacturing of the critical surface – the inside diameter of the cylindrical glass – is a lengthy process involving many grind/measurement and polish/measurement cycles. A cycle is defined as several rounds of grinding or polishing using different tools, followed by a series of various precision measurements. (Courtesy of Hughes Danbury Optical Systems, Inc.)

FIGURING LARGE OPTICS TO 1 NM RMS

A. Technology Assessment

Finishing aspheric surfaces to 1 nm accuracy represents the most challenging item for optical fabrication. Given a stable substrate, and techniques of in process testing, how does one bring the glass surface to the correct figure? In the past it has been common to first polish surfaces as accurate spheres, a relatively easy task, and then to gradually aspherize them by processes that preserve axial symmetry. New processes that are able to finish aspheric surfaces produced directly by precision generation (machining) are now being developed, and will likely be the preferred direction for space optics. Two currently operating state-of-the-art generating machines are the 8 m machine at the University of Arizona Mirror Laboratory, which achieves an accuracy of 3 μm rms, and the Kodak 2.5 m machine, which is expected to achieve an accuracy of 1 μm rms. On a much smaller scale, generating machines can achieve a specular finish by ductile grinding. However, this process is probably not well suited for extension to optics several meters in diameter.

The generation process, carried out with bound diamond abrasive, leaves on large mirrors a rough glass surface cracked to a depth of several to tens of microns. Such a surface must then be lapped and polished to yield a polished surface with no remaining cracks. At the same time it is figured to improve accuracy. Two processes under development have already demonstrated the capability of producing polished aspheric surfaces figured to better than 100 nm rms surface accuracy. These are the stressed lap method of the Mirror Laboratory and the membrane polishing method of Zeiss. Figure 21 shows the in-process test interferogram of a 1.8 m dia mirror with an extremely aspheric figure, f/1.0 paraboloid, currently being worked with a stressed lap at the University of Arizona Mirror Laboratory. With an rms surface error at this stage of 18 nm, the mirror already exceeds the quality and asphericity needed for the SOFIA primary.

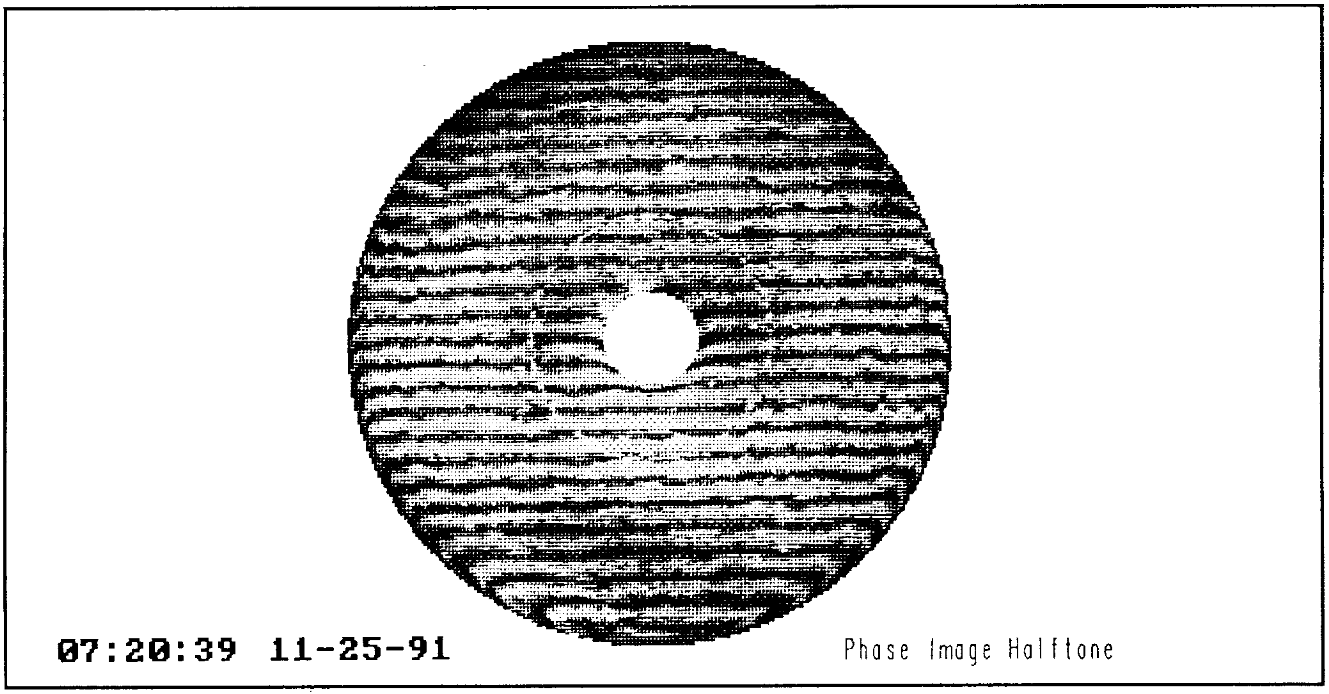


Figure 21. Test Interferogram of 1.8-m Mirror With Extremely Aspheric Figure – This is an in-process test interferogram at 633-nm wavelength of a 1.8-m f/1.0 asphere being polished by the stressed-lap method at the Steward Observatory Mirror Laboratory. The surface error is currently 18 nm rms. (Courtesy of Steward Observatory Mirror Laboratory.)

The above mechanical polish processes should be developed to produce very smooth surfaces with 10 nm accuracy. However, they are not suited to figuring or controlling very small errors on small scales, such as may occur on cryogenic cooling, or from deformation of a thin facesheet under the polishing pressure. The final steps to realize 1 nm accuracy must then be taken with a non-contact process that cannot in itself make a rough surface smooth, but can remove material from a polished surface in such a way as to correct the figure without losing the surface finish. Two such processes, ion polishing and PACE (Plasma Assisted Chemical Etch), warrant further development.

The use of chemical etching techniques (such as PACE) as an optical fabrication process is currently being investigated at OCA Applied Optics, Inc., under a contract with NASA and at Hughes Danbury Optical Systems. Initial results show promise but there are several critical issues that must be addressed before the process can be effectively utilized. The PACE process is an etching procedure in which a chemical reaction removes material in the presence of a plasma discharge. The plasma discharge is formed under a porous electrode in an appropriate gas mixture and acts as the fabrication "tool". In any precision fabrication procedure, the material removal function must be deterministic and repeatable. In the PACE process there are several constraints that dramatically affect the material removal profile. The gap between the electrode and the substrate is directly related to the width and overall shape of the removal profile as well as the rate. In general, the removal rates decrease and the profile broadens as the electrode-substrate gap is increased. Therefore, since a consistent removal profile is desired, the gap must be maintained at a constant distance. This may be difficult to achieve on optical surfaces with large departures. In addition, the removal profile shows some dependence on the local thickness of the substrate material. The etch rate generally decreases as the substrate thickness increases because the secondary electrode is located beneath the sample. The other major consideration is the effect of the PACE procedure of the surface roughness. The process does not degrade the surface finish but may uncover subsurface damage that was introduced in the previous processing steps for small etching depths. If these problems can be resolved or compensated for, the PACE process could be successfully utilized for precision optical fabrication.

It is well known that optical fabrication of large axisymmetric and non-axisymmetric aspheric optical elements to tight surface figure tolerances using conventional methods is generally difficult. Ion figuring is a state-of-the-art deterministic optical fabrication process for final error correction of previously polished optical surfaces. This method employs a directed, inert, and neutralized ion beam to physically sputter material from an optic surface in a controlled manner by varying the beam dwell time at grid points in the surface error array. The ion beam removal function, or characteristic material removal distribution, is scanned in an x-y (cartesian grid) motion across the optic to selectively remove material. The physical sputtering process results from direct momentum transfer of the beam ions striking the target surface; the ion beam comprises inert gas ions and externally supplied electrons for charge neutralization.

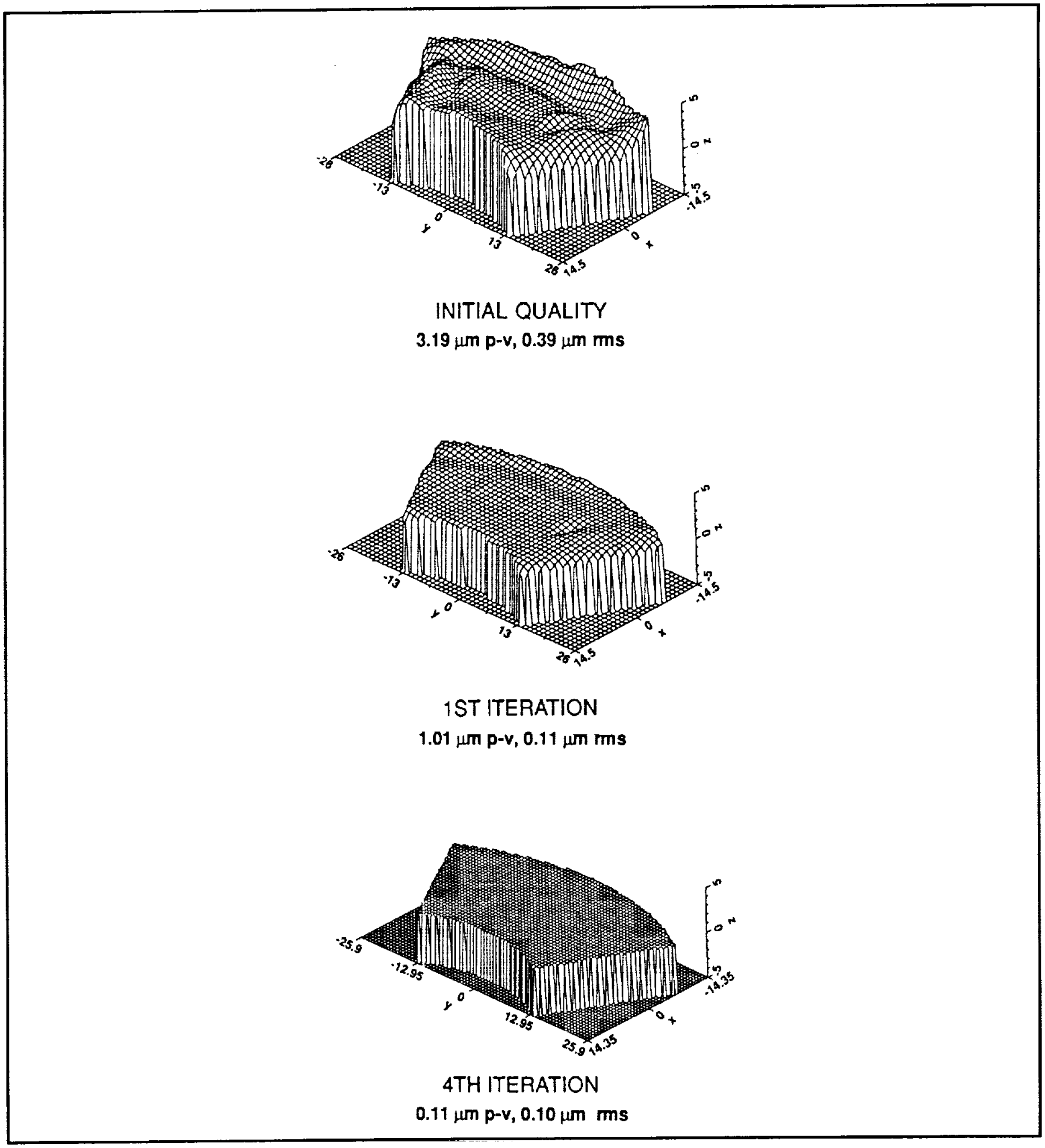
The ion figuring process offers significant advantages over current mechanical polishing processes, which ultimately allow for the final error correction of most optics to optical test limits in a few process iterations, in that:

- the removal function is insensitive to the optic construction and edge geometry
- removal is not affected by aspheric departure
- the removal function can be well characterized and is constant for a given material

Optics with maximum dimensions of 2.5 m x 2.5 m x 0.6 m can be processed in the Kodak 2.5 m Ion Figuring System (IFS). This system is currently the only facility which has demonstrated a large optic processing capability. The IFS hardware comprises three basic subsystems: the vacuum chamber and pumping equipment, the ion beam mechanical translation and positioning system, and the ion beam source itself. Here, the ion beam is projected vertically upward towards the optic surface. At the present time, Litton Itek Optical Systems is developing a 1 m capacity system, and the University of New Mexico has a nominally 1 m development system, in which much of the early research work was completed.

Current ion figuring process technology can be applied to several key optical materials, including fused silica, ULE™, and PYREX™ glasses, Zerodur™, CER-VIT™ and Corning Code 9600 glass-ceramics, and silicon carbide. Generally speaking, a multiple-iteration process is required to most efficiently remove various figure error spatial wavelengths present; spatial wavelengths as low as 4 to 5 cm have been corrected.

Several large, complex optical elements have been completed at Kodak during the past two years, demonstrating the full capability and utility of the ion figuring process. These include ion figuring a 1.3 m ULE™ off-axis, aspheric petal-shaped mirror and three W.M. Keck Observatory Telescope Zerodur™ 1.8 m primary mirror hexagonal segments. One hexagonal mirror segment, serial number 038, was recently finished in October 1991 using a single ion figuring process iteration. The mirror segment was ground, polished, shaped, and tested by Itek Optical Systems under a contract from the California Association for Research in Astronomy (CARA). The surface error prior to ion figuring was 1.46 µm p-v, 0.303 µm rms, without application of the mirror warping structure. After a single correction cycle, the as-tested surface quality for segment 038 was reduced to 0.31 µm p-v, 0.055 µm rms, an improvement by a factor of 5.5. With theoretical warping applied, the mirror quality was further improved to 0.14 µm p-v, 0.013 µm rms. At the present time segment 038 is the best mirror segment fabricated for CARA's Keck I telescope in terms of surface figure quality (both unwarped and warped values), and is the first segment to meet the encircled energy specification. Figure 22 shows the result of ion-polishing an off-axis segment of around 1 m in size to a figure error of 10 nm, which was about the test limit.



INITIAL QUALITY
3.19 μm p-v, 0.39 μm rms

1ST ITERATION
1.01 μm p-v, 0.11 μm rms

4TH ITERATION
0.11 μm p-v, 0.10 μm rms

Figure 22. 1-m Off-Axis Segment Ion Polishing

B. Development Plan

For the purpose of this section, we will ignore all the problems of testing and support to better than 1 nm, and focus on the processes used to shape the glass to this accuracy, all of which must go beyond the state of the art (see Table 19) to reach the goal in a large non-spherical surface. Figure 23 illustrates the state of the art relative to the development that must take place. The surface accuracy on different spatial scales is controlled by three different processes:

1. *Small scale, less than 1 cm.* On these scales, the smoothness will be that yielded by the smoothing process,

stressed lap or membrane polishing. Development is needed to ensure these processes can handle large aspheric surfaces, and yet still give the desired control of microroughness and small scale figure at the 1 nm level.

2. *Mid scale errors, 1 cm to tens of cm.* These scales are controlled by the non-contact figure correction, ion polishing, or PACE. Development is needed to prove that these methods can correct at the 1 nm level. The challenges are to control the removal geometry to match exactly the error map produced by precision metrology.

3. *Large scale errors, larger than tens of cm.* On approximately these scales, the mechanical rigidity of the substrate will not be adequate to hold 1 nm tolerance. Gravity release, errors in support forces applied during fabrication or long term material creep will produce errors of more than 1 nm. It will be necessary to correct the figure in space, by mechanical or other means. Active control must form an essential element of future optical systems if the demanding requirements (outlined in Table 14 and discussed in more detail in the introductory section on visible UV optics) are to be met.

NASA can make a major contribution by investing in these three fabrication technologies listed above for the three spatial domains. At this time these technologies seem particularly applicable to mirrors for the UV and optical although they may have much broader application.

Table 19. Large Optics Figuring to 1 nm rms Enabling Technologies Program

TECHNOLOGY DEVELOPMENT	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES [a]	TECH. DEV. TIME FRAME [b]
Lightweight Blank Fabrication (Generated Surface)	2.5 m at 1 μm rms 8 m at 3 μm rms	8 m at 1 μm rms	'92, '97, '02, '04	'92 - '02
Surface Polishing	200 nm rms	Methods to Convert Generated Surface to Polished Figure Accuracy : ≤ 10 nm rms	'92, '97, '02, '04	'92 - '02
Metrology	10 nm, 256 Pixels	Surface Contour Measurements to 1 nm, Mid Spatial Frequencies and High Resolution, > 1000 Pixels	'99	'92 - '94
Deterministic Finishing	10 nm rms	Finish to 1 nm rms at Mid-Spatial Frequencies Accuracy Better Than 5% of Removal Per Step Demonstrate Rapid Progression to Final Figuring	'94	'92 - '93

[a] Milestone date in the development program at which some form (i.e., phased development) of capability is required.

[b] The time frame over which the technology program/development occurs.

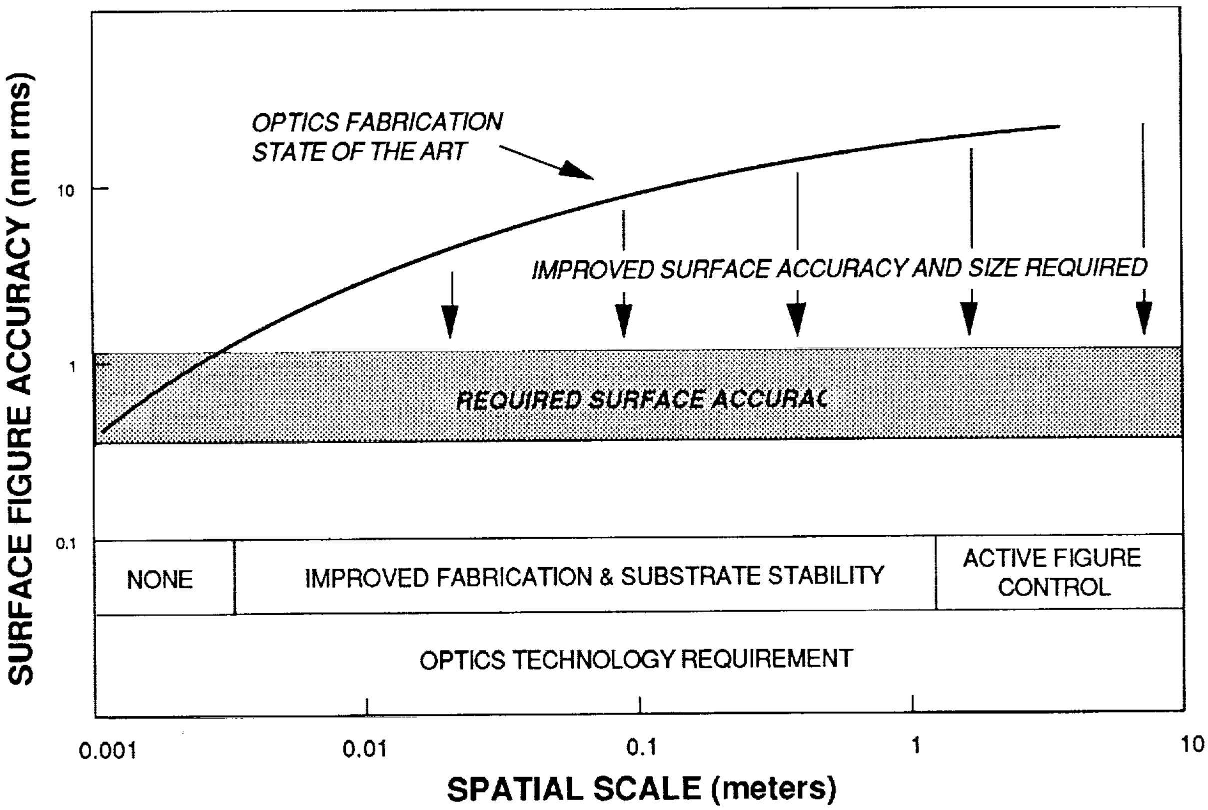


Figure 23. Technology for Surface Figuring to 1 nm rms

FABRICATION OF A 4-m MIRROR

A. Technology Assessment

The panel identified the actual manufacture of a lightweight 4-m mirror to 2–3 nm rms as a critical step in technology development. The mirror would weigh 500–1000 kg, and would be required to meet specification when tested at 80 K. Because such a mirror requires so many different areas to be pushed beyond the present state of the art, the only way to have confidence that they will all come together is to actually do it. The critical new areas are:

- blank material with effective CTE of zero at 80 K
- making the ultralightweight 4 m blank
- support of the mirror to ensure 1 nm accuracy after gravity release
- active control of figure on large scales
- polishing of a large asphere to achieve low microroughness and small scale figure to 1 nm
- non-contact figuring to achieve mid-scale tolerance to 1 nm
- in-process testing to better than 1 nm at 80 K
- non-contact figuring at room temperature to correct for thermal release.

The Hubble Space Telescope mirror represents the state of the art in large lightweight mirror structure (Figure 24). It is 2.5 m in diameter, weighs 200 kg/m^2. Inhomogeneity in the glass (ULE) probably limits its accuracy to around 10 nm.

Figure distortion on cooling has been investigated only on a scale of 0.5 m mirrors, and only to about 10 nm accuracy (NASA Ames Research Center).

Testing of large mirrors has not achieved accuracy of better than 10 nm. Present state of the art is represented by the 1.5 m facility at the Rome Air Force Development Center (RADC), which operates down to 80 K. The tolerancing and manufacture of null lenses to 1 nm is well beyond current state of the art. Additionally, the verification in space also challenges the state of the art.

State of the art in optical fabrication is discussed in the previous section.

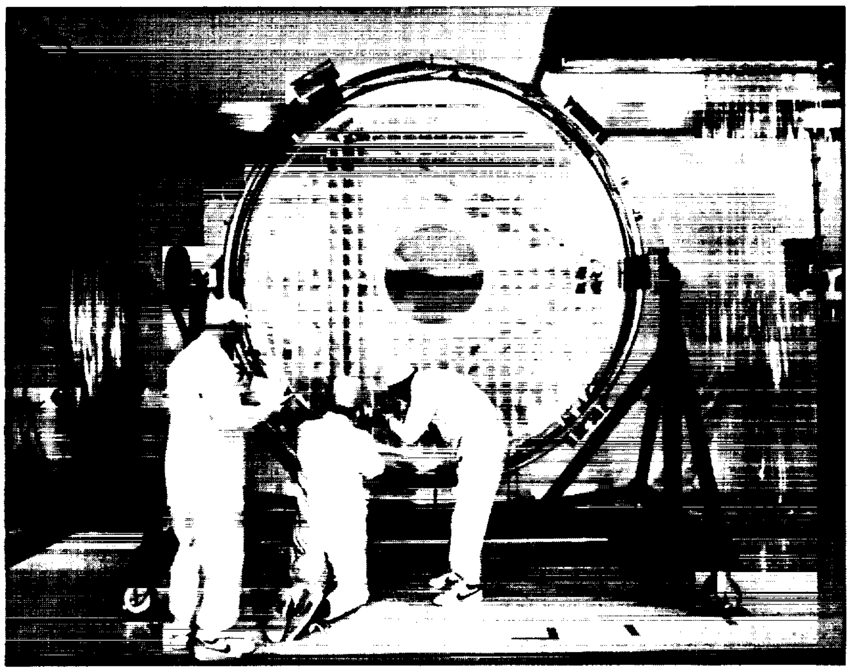


Figure 24. Lightweight 94 in. Primary Mirror – The final-polished 94 in. primary mirror is inspected prior to application of the reflective coating. The cellular hollow-cored structure of the primary mirror provides for maximum lightweighting. Solid face sheets cover the structure. During final shaping and polishing the approximately 1-ton primary mirror was reduced to a weight of about 1,825 lb. (Courtesy of Hughes Danbury Optical Systems, Inc.)

B. Development Plan

Table 20 summarizes the technology development within this area. The most pressing item to get this mirror started will be the development of the material with an effective CTE of zero at 80 K. This would probably be doped silica, made by flame deposition like ULE. Glass chemistry considerations indicate such a glass will be also more stable against devitrification than ULE. Design and manufacture of the blank would run in parallel, with manufacture following when the material was ready (1994).

A capability must be developed to generate and polish the mirror close to the final figure. This will involve building a polishing support that best compensates for the polishing load, and the stressed or membrane laps to carry out the polishing at the 4 m size (1995).

A test facility to handle in-process metrology of 4 meter mirrors at 80 K will be required, (1996-1997), along with the facility for non-contact final figuring, ion polishing, or PACE. These facilities should be together. Experience with finishing the Keck segments has shown it is very inconvenient to ship the mirror for even a few iterative cycles of final finishing.

Table 20. Lightweight, Cryogenic, Aspheric Mirror Enabling Technologies Program

TECHNOLOGY DEVELOPMENT	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Cryogenic Testing Facility	1.5 m Panel to 10 nm at 80 K	4 m Panel to to < 5 nm at 80 K	'98	'94 - '98
Lightweight Blank fabrication	HST, 2.5 m Diameter $\alpha = 0$ at 300 K 200 kg/m^2	4 m Diameter $\alpha = 0$ at 80 K 60 – 80 kg/m^2	'94	'92 - '94
Nanometer Figuring	10 nm for 2.5 m Diameter 20 – 30 nm for 4 m Diameter	2 – 3 nm rms for 4 m Diameter	'97	'94 - '97
Fabrication Testing	Accuracy : 5 nm for 1.5 m Diameter	Accuracy : 2 nm for 4 m Diameter Develop Interferometric Test Capability for In-Process and Cryogenic Testing	'95	'92 - '95

SYSTEMS ISSUES IN OPTICAL FABRICATION

A number of systems issues were raised by the panel (Table 21). These issues explore the relation of the fabrication process to the overall telescope system and mission design process. Most of these issues were explored in more depth in other panels, but areas of significant overlap, where system decisions have the greatest impact on the fabrication process and cost are:

1. *Smart Structures* to simplify optical fabrication alignment and test. Research is currently being supported under NASA's CSI program and should be continued.

2. *On-Orbit Alignment and Figure Control* is the province of the Wavefront Sensing, Control and Pointing section. Obviously the more that can be done in supplying the figure control actively, the less that needs to be done in the fabrication process, and the lighter the mirror substrate needs to be. A second issue may be the impact of wavefront control system flexibility requirements on the ability to achieve a smooth surface during the fabrication process.

3. *Rigidity Scales* again related to the on-orbit alignment and control of optics. It is likely that the mirror systems will have a combination of stiffness and flexibility requirements with varying spatial frequencies. The specification of these properties and the translation of the specifications into practical materials and structural designs is still in its infancy.

4. *Segment Fabrication Optical Technology* has traditionally been concerned with the fabrication of circular blanks. The trend in recent years is toward hexagonal blanks or radial segments. These new blank shapes present challenges to the standard figuring techniques. Commonly incurred during the fabrication process are unusual edge effects, which must be solved on a case by case approach. A systematic view of the edge effects problem needs investigation. Additionally, the technology required by, and the practicality of, the identified solutions need exploration.

5. *Mounting Considerations* both in fabrication and final application must be considered for an optimal design to result. The present state of integrated system design generally determines (or greatly impacts) the final mirror size (design). Because it has become necessary for the mirror fabrication process and system design process to proceed in parallel with the active optics system design, future designs must actively consider the mounting requirements during fabrication as equal to those for final use.

Table 21. Systems Issues in Fabrication

TECHNOLOGY DEVELOPMENT	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Smart Structures	NTT	Develop Smart Structures to Simplify Optical Fabrication and Test	'96	'92 - '03
On-Orbit Techniques	HST	Develop On-Orbit Figure Initialization and Control	'96	'92 - '96
Rigidity	HST (2.5 m Rigid, 10 nm)	Determine Relationships Between Scale and Rigidity and Control Understand Spatial Scale of Transfer	'96	'92 - '96
Segment Fabrication	Keck (50 nm)	Investigate Edge Effects vs. Segment Shape	'03	'92 - '03
Mounting	LOS (30 nm)	Develop Techniques for Fabricating and Mounting of Adaptive Thin Meniscus Mirrors Goal ; < 30 nm	'03	'92 - '03

INNOVATIVE TECHNIQUES WITH LONGER RANGE POTENTIAL

It is not yet possible to define a road map to an ultimate application. Some of these technologies will enable future missions and will provide back-up approaches to some of the technologies discussed above. In addition to the set of focused technology developments with specific quantitative objectives, also needed is innovative research into processes and techniques with even greater potential but more uncertain outcome. The concepts are outlined in Table 22.

The specific technologies that would most benefit by immediate support were listed by the fabrication panel:

1. Advanced techniques for monitoring and measuring material removal over spatial scales ranging from micrometers to meters with angstrom level accuracy.
2. Continuously adaptive thin film and membrane optical systems.
3. High throughput optics for high energy astronomy – the targeted capabilities are collecting area greater than 100 m^2 with high resolution (< 0.1 arcsec) in the energy range up to 10 keV.
4. Prototype fabrication of innovative optical designs for high energy astronomy (e.g., Kirkpatrick Baez, Foil, Off-plane Imaging, Lobster Eye, Hard X-ray Grazing Incidence Optics, etc.).
5. Advanced techniques for refractive optics, including binary optics, etc. A major problem here is the development of techniques in which two elements are combined to obtain one corrected element.
6. Advanced techniques to reduce the number of fabrication and metrology cycles. Specific developments that are needed are:
   a. Bound abrasive polishing.
   b. Loose abrasive polishing (this is used in the stressed-lap polishing technology).
   c. Mechanochemical polishing: controlled, chemical, improved abrasives, finer, purer, and more uniform.
   d. Non-contact figuring.
   e. Post polish figuring.

Table 22. Innovative Techniques Technology Program

TECHNOLOGY DEVELOPMENT	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Material Removal	Ion Milling : Convergence : 0.1 – 0.05 Removal/Pass : 250 nm rms	Advanced Techniques for Monitoring/Measuring Material Removal Over Large Areas Ion Milling : Convergence : 0.04 – 0.02 Removal/Pass : 10 nm rms With No Subsurface Damage Ion Flux Stability : 1 – 2% Spatially and Temporally	'92 - '02	'92 - '02
Adaptive Thin Film Systems	Being Assessed	Advanced Techniques for Continuously Adaptive Thin Films	'92 - '02	'92 - '02
High Energy Optics	PACE Ion Beam	Advanced Techniques : Replication of Smooth Foils for 40 – 100 keV Regime Advanced PACE and Ion Beam Area : > 100 m^2 Resolution : < 0.1 as at 10 keV	'92 - '02	'92 - '02
High Energy Optical Designs	AXAF	Proof of Concept Fabrication : Kirkpatrick-Baez Optics Off Plane Imaging Foil Mirrors Lobster Eye Hard X-Ray/Grazing Incidence	'92 - '02	'92 - '02
Refractive Elements	Refractive Elements On a Large Scale Not Fully Developed	Advanced Techniques for the Development of Complex Refractive Elements (e.g., Binary Optics)	'92 - '02	'92 - '02
Processing Techniques	TBD	Advanced Processing Techniques for Fabricating and Testing Aspherics : Bound Abrasive Loose Abrasive Mechanochemical Post Polish Figuring	'92 - '02	'92 - '02

FACILITY NEEDS

Large Aperture Cryogenic Vacuum Facilities

The large reflector panels and mirror segments needed for future far infrared and submillimeter missions will characteristically operate at temperatures below 80 K. In order to select materials for these mirrors, full scale prototypes must be tested to insure that thermal hysteresis and long term material instabilities are within acceptable limits. In advance of final optical figuring, the thermal contraction characteristics of the individual substrates must be accurately mapped so that a compensating shape can be designed for each segment. Final testing and acceptance must be based on data obtained at the design operating temperature.

All of these activities require test facilities that are capable of supporting precision optical testing of highly aspheric mirrors up to 4 m in characteristic dimension. Such facilities would include an appropriately large and seismically stable high vacuum chamber with liquid nitrogen cooled work space and shrouds; long path optical test space; a clean room environment surrounding the chamber and test area; vacuum and cryogenic support equipment;

and a substantial near-real time data analysis capability in order to minimize the cost of re-testing and other delays associated with data quality confirmation.

EDUCATIONAL ISSUES

Investments in optical fabrication technology will be unproductive unless they are accompanied by investments in education to provide the human resources needed to make progress in the technology. Specific needs include graduate fellowships in optical fabrication and upgraded undergraduate teaching laboratories and programs. NASA/University/Industry collaborations on basic research should be sponsored. One form that this might take is a NASA Space Engineering Research Center (SERC) in Optical Fabrication.

DEVELOPMENTAL METHODOLOGY

The Optical Fabrication Panel sees the interactive development of science goals with technology advances as critical to future missions. The history of discovery in astronomy is one in which instrumental advances have led, not followed. The present paradigm for space astronomy in which astronomers develop science requirements, missions are defined, and new technology is developed to meet a production schedule, is very inefficient. The result is the huge lag between mission and technology definition and launch, endless cost overruns, and instruments flown with obsolete designs. Both problems would be greatly aided if a variety of possible missions with soft edges were continuously refined, balancing evolution in technology along with that in scientific opportunity. Ideally, this process should be carried through to the point where, upon selection of well optimized and thought out missions with the key technology already in hand, the time to launch would be as short as 5 years.

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