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ASTROTECH 21
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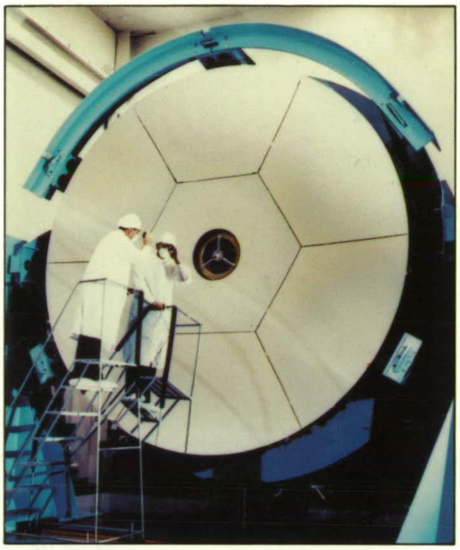
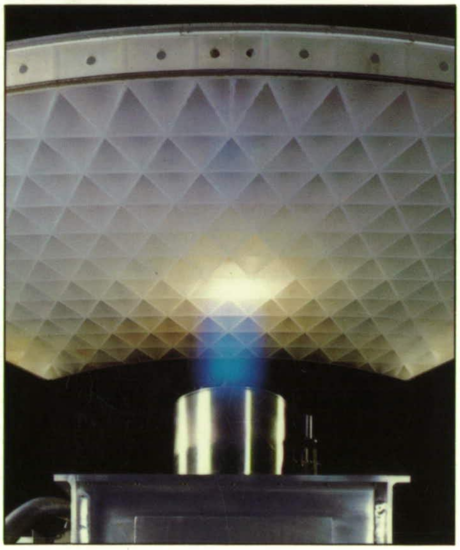
SERIES III INTEGRATED TECHNOLOGY PLANNING

Workshop Proceedings: Optical Systems Technology for Space Astrophysics in the 21st Century





August 15, 1992

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SERIES III INTEGRATED TECHNOLOGY PLANNING

Workshop Proceedings: Optical Systems Technology for Space Astrophysics in the 21st Century

Editor

J. A. Ayon

August 15, 1992

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This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).

Cover illustrations:

Top left: Large Adaptive Mirror Program (LAMP) – ITEK active segmented primary mirror 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. (Courtesy of ITEK Optical Systems.)

Top right: Space Infrared Telescope Facility (SIRTF) Concept – Concept for a space-based cryogenically cooled observatory for infrared astronomy. Designed to operate in High Earth Orbit (100,000 km) where it would achieve a 5-year lifetime and operate with better than 80% on-target efficiency. Advances in detector technology will enable gain factors of 100 to 10,000 in sensitivity over its predecessors. (Courtesy of Jet Propulsion Laboratory, California Institute of Technology.)

Bottom left: Ion Beam Figuring System at Eastman Kodak – Current system allows rapid correction of surface figure errors. Shown is a 1.5-m, off-axis, ultralightweight asphere in the ion chamber. This mirror was improved from 5 waves p-v to less than 0.20 wave p-v in only four iterations. (Courtesy of the Eastman Kodak Company.)

Bottom right: Advanced X-Ray Astrophysics Facility (AXAF) P1 Mirror – Quality Assurance inspectors from Hughes Danbury Optical Systems, Inc. perform a visual inspection of the P1 (Parabola 1) optic for NASA's AXAF. P1 is the first optical element for AXAF to have completed the polishing cycle. This will form the outermost and largest grazing-incidence mirror of the instrument. P1 measures 1.2 m in diameter by 1 m in length and weighs 520 lb. The wall of the optic is only 0.9 in. thick. (Courtesy of Hughes Danbury Optical Systems, Inc.)

ABSTRACT

In 1989, the Astrophysics Division of the Office of Space Science and Applications initiated the planning of a technology development program, Astrotech 21, to develop the technological base for the Astrophysics missions developed in the period of years 1995 to 2015. An infusion of new technology is considered vital for achieving the advances in observational techniques needed for sustained scientific progress. Astrotech 21 was developed in cooperation with the Space Directorate of the Office of Aeronautics, Exploration and Technology, which will play a major role in its implementation. The Jet Propulsion Laboratory has led the planning of Astrotech 21 for the agency.

The Astrotech 21 plan was developed by means of three series of workshops dealing respectively with: Science Objectives and Observational Techniques, Mission Concepts and Technology Requirements, and Integrated Technology Planning. Traceability of technology plans and recommendations to missions requirements and impacts was emphasized. However, breakthrough technologies, whose ultimate applications cannot be anticipated, were also considered. A Proceedings publication is published for each workshop. A summary report has also been prepared that synthesizes the results of the planning effort.

The Optical Systems Technology for Space Astrophysics in the 21st Century Workshop was one of the three Integrated Technology Planning workshops. Its objectives were to develop an understanding of future mission requirements for advanced optical systems, and to recommend a comprehensive development program to achieve the required capabilities. Workshop participants were briefed on the astrophysical mission set, with an emphasis on those missions that drive advancements in optics technology.

Program plans and recommendations were prepared in six optics technology areas: Wavefront Sensing, Control, and Pointing; Fabrication; Materials and Structures; Optical Testing; Optical Systems Integrated Modeling; and Advanced Optical Instruments Technology.

FOREWORD

A technology development program, Astrotech 21, is being proposed by the National Aeronautics and Space Administration (NASA) to enable the launching of the next generation of space astrophysical observatories in the two-decade period of years 1995–2015. Astrotech 21 is being planned and will ultimately be implemented jointly by the Astrophysics Division of the Office of Space Science and Applications and the Space Directorate of the Office of Aeronautics and Space Technology . The Jet Propulsion Laboratory is assisting NASA in developing the Astrotech 21 Plan.

The Astrotech 21 planning process has three phases. The first phase focused on the fundamental science objectives and the observational techniques used to realize these objectives. In the second phase, specific mission concepts were evaluated and their technology requirements were assessed. In the third phase, the technology needs and opportunities in various areas of technology were synthesized. A workshop on Optical Systems Technology, a part of this third and final phase in Astrotech 21 planning, was held in Pasadena, California on March 6–8, 1991, where more than 100 scientists and engineers from universities, industry, NASA centers, and other government laboratories participated.

This volume provides a summary of this Astrotech 21 Optical Systems Technology Workshop. The goal of this workshop was to identify areas of development within advanced optical systems that require technology advances in order to meet the science goals of the Astrotech 21 mission set, and to recommend a coherent development program to achieve the required capabilities. To accomplish this, six panels were assembled to address optics technologies across the electromagnetic spectrum from the gamma-ray to the submillimeter-wave regimes. The primary content of this proceedings publication is the set of workshop panel reports prepared by the six panel chairs and their team members. These reports describe the panels' analyses of the Astrotech 21 mission set requirements, an assessment of the current capabilities and future promise of the relevant optics technologies, and their specific recommendations to NASA for a development plan to achieve the desired system characteristics (performance). To place these reports in context, this volume first recaps the purpose and evolution of the Astrotech 21 Plan, the view of the mission set at the time of the workshop, and the structure and goals of the workshop itself. A listing of the panel participants, their affiliations, and a glossary of acronyms and abbreviations used in this Proceedings publication are provided in appendixes.

Astrotech 21 Workshop Proceedings:
Optical Systems Technology for Space Astrophysics in the 21st Century

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EXECUTIVE SUMMARY

The Astrotech 21 Optical Systems Technology Workshop was held in Pasadena, California on March 6 – 8, 1991. The purpose of the workshop was to examine the state of Optical Systems Technology at the National Aeronautics Space Administration (NASA), and in industry and academia, in view of the potential Astrophysics mission set currently being considered for the late 1990s through the first quarter of the 21st century. The principal result of the workshop is this publication, which contains an assessment of the current state of the technology, and specific technology advances in six critical areas of optics, all necessary for the mission set.

The workshop was divided into six panels, each of about a dozen experts in specific fields, representing NASA, industry, and academia. In addition, each panel contained expertise that spanned the spectrum from x-ray to submillimeter wavelengths. The workshop was chaired by J. B. Breckinridge of the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech). The six technology panels and their chairs were:

1. Wavefront Sensing, Control, and Pointing	Thomas Pitts	Itek Optical Systems, a Division of Litton
2. Fabrication	Roger Angel	Steward Observatory, University of Arizona
3. Materials and Structures	Theodore Saito	Lawrence Livermore National Laboratory
4. Optical Testing	James Wyant	WYKO Corporation
5. Optical Systems Integrated Modeling	Robert R. Shannon	Optical Sciences Center, University of Arizona
6. Advanced Optical Instruments Technology	Michael Shao	Jet Propulsion Laboratory, California Institute of Technology

This Executive Summary contains the principal recommendations of each panel.

1. Wavefront Sensing, Control, and Pointing

The Wavefront Sensing, Control, and Pointing panel defined six technology thrusts needed to support the mission set: active optics, active interferometry, pointing and attitude sensing and control, laser metrology, structures control, and system control architecture.

Active Optics is required to initialize and maintain optical elements in the optimal positions, orientations, and shapes to enable diffraction-limited performance and performance robustness. This will be especially critical for missions with large apertures or baselines. Figure and wavefront sensors will be needed to measure the quality of the wavefront at a representative location in the optical train in order to provide appropriate error signals to a wavefront control system. Deformable mirrors (or their segmented equivalents) will be needed to correct the wavefront errors introduced by motions and deformations of the optics and support structure. For positioning and aligning optical elements on orbit, space-flyable precision positioning actuators are needed.

Active Interferometry is required for future interferometric missions. Like active optics, the phase of this sampled wavefront must be sensed, and its phase adjusted, in order that the lights from the individual apertures are combined coherently. Three key areas for development within active interferometry require development are wavefront sensing, optical path length control, and beam combination. The first area, *wavefront sensing*, develops robust two-element systems for space qualification, high-rate fast-readout detectors, and efficient sensing architectures. The second area, *optical pathlength control*, focuses on delay line systems and metrology. The third area, *beam combination*, concentrates on the development of space-qualified systems that are consistent with the measurement goals, the wavefront sensing architecture, and space environment. The development of beam combiners that use interferometric cancellation of stray light to enable direct imaging of such high dynamic range objects, such as star-planet systems, is also a goal.

Pointing and Attitude Sensing and Control requirements for future astrophysics missions range widely and a variety of technologies must be brought to bear to address them. This development program is partitioned between pointing and attitude sensing and pointing and attitude control technologies. The first half of the program, *pointing and attitude sensing*, focuses on star trackers, fine guidance sensors, attitude transfer devices, and inertial attitude sensors. This program recommends the development of autonomous star trackers with an accuracy of better than 0.1 arcsec, the continued development of cryogenic visible fine guidance sensors along with an accurate star catalog in the UV/VIS/IR, the development of attitude transfer devices with nanoradian accuracy and very low thermal and radiation leakage, and the development of gyros capable of better than 0.0001 arcsec bias stabilities and lifetimes of greater than 15 years. The second half of the program, *pointing and attitude control,* concentrates on the development of actuators and fine pointing mirrors. An improvement of two orders of magnitude in torque capability and momentum capacity, with a simultaneous improvement of at least one order of magnitude in quietness along with high repeatability, is recommended for actuators. Fine-pointing mirror development should concentrate on the development of highly compensated (i.e., better than 99% in all degrees of freedom) steering mirrors assemblies with projected centers of rotation. It should also produce technology for cryogenically cooled mirrors needed for missions in the IR.

Laser Metrology development is divided into four areas: laser sources, fiducial references, active components, and innovative metrology architectures. For *laser sources*, frequency stability is a critical property in almost all applications. For the near term astrometry missions, the development of a frequency stability of $\sim 10^{-10}$ is recommended. There is also an immediate need for the development of a suitable stabilization scheme for solid-state lasers, and their packaging into a low mass, low power package for space qualification. Additionally, development is needed in the areas of tunable lasers (with precision tuning and high stability) and low mass beam launcher manifold designs. The program in *fiducial reference* development stresses concept development and manufacturing process technology to improve the properties of acceptance angle and pathlength invariance (to over 120 deg and 1 nm, respectively) for applications in optical truss structures. Fiducial references for mirrors are also needed. Additionally, *active components* such as Bragg or Pockels cells will need development along with new approaches and new design tools for *innovative metrology architectures*.

A comprehensive *Structures-Control* technology program is recommended, with development efforts in six areas: vibration isolation systems, damping augmentation methods, control structure interaction (CSI), modal control, smart structures, and integrated structures-control design optimization. *Vibration isolation systems* are needed to isolate the structure from disturbance sources and the optics from the structure. Advances are needed in performance and low temperature operation. New techniques in *damping augmentation methods* are needed to lower vibration levels due to persistent disturbances and to hasten settling after transient excitations. Improvements are needed in performance and temperature ranges. Moreover, developments are needed to enable operation in the radiation environment of space for long periods and to practicable methods of design and the identification of appropriate control architectures for the class of problems of interest to the optical community be supported. Furthermore, it is recommended that this work include the development of relevant system testbeds to serve as proving grounds for the technology. *Modal control* research is recommended on controlled structure system identification, self-tuning structural control, and systematic robust controller design. Additionally, it is recommended that reliable, flight-qualifiable components be developed, and that the system concept be demonstrated within a realistic testbed (*smart structures*) along with the development of a practical design tool for integrated optimization of the structure, control system, and optics (*integrated structure-control design optimization*).

System Control Architecture addresses the unprecedented dimensional complexity of spaceborne active optics and structures. New control theory and algorithm types will be needed to cope with the challenges. In particular, fundamental but highly focused research on systematic design and analysis methods, adaptive control, system identification, robust control, multiobjective optimal control and control of high dimensional systems are needed. Methods of suppressing optics control system interactions need to be developed along with the development of massively parallel architectures, algorithms, and hardware. Development of general tools (e.g., such as Matrix$_x$ or the Matlab Control System toolbox) for design, analysis, and simulation of optical system control elements are necessary. Finally, research in optimal design, leading to multiloop optics control system design optimization techniques, is recommended. Specific problems in need of attention include simultaneous optics and control design optimization, minimum time figure and alignment initialization, and wavefront error minimizing figure and alignment maintenance.

2. Fabrication

The Fabrication panel made technology development recommendations in six areas: replicated optics, figuring large optics to 1 nm rms, lightweight cryogenic aspheric mirrors, systems issues in optical fabrication, innovative techniques, and facility needs and development.

Replicated Optics are required for both x-ray and submillimeter missions. Six critical developments are needed. X-ray applications require advancements in automated cylinder polishing, improvement in mandrel materials and lifetimes, and improved speed in cylinder production. Essential to the submillimeter missions are large, smooth, accurate composite face sheets that are supported on a lightweight sandwich construction. Once the surface quality can be met at ambient temperature, the technology will need to be pushed to the cryogenic regime required by submillimeter telescopes (80 K) since it will be necessary for the telescope panels (≈ 2 m) to maintain their qualities at operational temperature. To support the very large submillimeter missions in the latter part of the Astrotech period, panel areal densities of less than 5 kg/m^2 will also be needed.

Figuring Large Optics to 1 nm rms accuracy represents the most challenging item for optical fabrication. Once a stable substrate has been provided, and suitable in process testing has been defined, there remains the task of bringing the surface to the correct figure. At scales of less than 1 cm, development is needed of smoothing processes for large aspheric surfaces that will give the desired control of microroughness and small scale figure at the 1 nm level. At scales of 1 cm to tens of cm, development is needed of non-contact methods such as ion beam polishing for correction at the 1 nm level. At scales larger than tens of cm, active control techniques of the mirror will be required.

Developments will also be required in precision generation of large lightweight blanks.

The manufacture of *Lightweight Cryogenic Aspheric Mirrors* (with diameters of 4 m or larger) figured to 2 to 3 nm, which preserve their figure and radius of curvature to a temperature of 80 K, is a critical step in technology development required by several missions. Key developments include blank materials with effective coefficients of thermal expansions (CTEs) of zero at 80 K, lightweighting, gravity release compensation, active figure control, polishing, non-contact figuring, in-process testing, and the development of cryogenic testing facilities.

Systems Issues in Optical Fabrication were also addressed. 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, include smart structures, on-orbit alignment, figure control, rigidity scales, segment fabrication, and mounting considerations.

Innovative Techniques covered basic research and development activities in the early stages of development that offer potential. These topics include advanced techniques for monitoring and measuring material removal, continuously adaptive thin film and membrane optical systems, high throughput optics for high energy astronomy, prototype fabrication of innovative optical designs for high energy astronomy, advanced techniques for refractive optics including binary optics, and advanced techniques to reduce the number of fabrication and metrology cycles (manufacturing determinism).

In addition to the technology activities previously discussed, *Facility Needs and Development* of appropriate education programs were also recommended.

3. Materials and Structures

The Materials and Structures panel made technology recommendations in five specific areas: vacuum coatings, materials science and engineering, environmental protection, reflector substrates, and structures.

The *Vacuum Coatings* technology requires development of optical coatings resistant to atomic oxygen that are durable, and that provide high performance over a large spectral range. Additionally, the behavior of coatings at low temperatures needs characterization along with the development of analytical tools necessary to support advanced coatings technology.

Advancements in *Materials Science and Engineering*, which develops, characterizes and demonstrates materials, test methods and predictive models for new materials, are required. This is particularly important to achieve dimensionally stable materials, interfaces, joints, and contact surfaces.

Required developments in *Environmental Protection* have the objective of monitoring and maintaining performance in the presence of a hostile space environment and self-contamination from the spacecraft. Development of coatings and metrology systems is required to enable the lifetimes expected by the large scale missions of next century astrophysics missions. Also required is an enlarged ground and space test program.

Required developments in *Reflector Substrates* include low areal density, high surface accuracy and smoothness, varying size, shapes, and operating temperatures. Continued development of composite materials to produce optically stable structures is recommended along with increased emphasis in lightweight material substrate fabrication technology for optics replication. Also necessary is the development of substrates for active/adaptive optics.

Developments in *Structures* technology are critical. Optical positioning structures for the next century astrophysics missions will in general be larger, lighter, and more susceptible to jitter and vibration by at least an order of magnitude of current experience. Development of these advanced structures and the development of techniques to characterize and verify their performance in the laboratory before committing them to a mission are the principal objectives of this thrust. This includes the development of structures and mechanisms techniques that will facilitate precision erection, alignment, and control of large telescopes. Necessary will be the advancement of modeling analysis capabilities and the development of a microdynamics structure and control breadboard to allow measurements of critical parameters.

4. Optical Testing

The Optical Testing panel made development and testing recommendations in six areas: surface figure, surface roughness, alignment, image quality, radiometric quantities, and stray light suppression.

Current capabilities in testing *Surface Figure* measurements of figure quality and shape with high spatial resolution and high speed are surprisingly limited and need development. New interferometric technology must be developed that will allow for the detection and interpretation of more complicated fringe patterns to reduce the requirements placed on existing detectors and null optics. In addition, improved calibration procedures are needed to push the accuracy of these tests towards the 1 nm level from their current level of about 10–20 nm. Specifically, the testing of aspheric surfaces, large convex secondaries, cryogenic measurements, sources and detectors for optical measurements, and grazing-incidence x-ray mirrors needs development.

Surface Roughness measurements define the surface properties at smaller scales than those met by surface figure measurements. Optical profilers for cylindrical and general aspheric surfaces need to be developed. The spatial frequency of roughness measurements needs to be extended to near atomic dimensions to support development of new fabrication techniques. Also requiring development are the measurement tools that will establish the relation of subsurface damage to final achievable surface roughness.

Alignment is perhaps in the most primitive state of all the optical testing technologies. The procedures used to align complex, multimillion dollar optical systems are essentially ad hoc, with little or no model verification of the procedure before or during the alignment process. Development of partially assembled system alignment techniques is required for the assembly and test of optical systems containing large numbers of components. Segmented optics initialization development is required for phasing large segmented optical systems. The effort will be to simulate the various algorithms, the operating software, and the mirrors, including distortions, diffraction, and high- and low-frequency spatial errors to demonstrate the ability to initialize a system. Improvements in laser gauges by a factor of 10 are necessary to reach the 0.1 nm level. Developments in optical and mechanical software interactiveness are necessary to provide fast and accessible to varied users.

Image Quality measurements on partially assembled systems as well as complete systems will allow verification of system performance. Image quality metrics include: encircled energy, Strehl ratio, the optical transfer function, and quality of the transmitted wavefront. Collimated sources with the requisite wavefront flatness and radiometric uniformity must be available for many different wavelengths with development especially needed in the UV. In those cases where it is not feasible to measure the wavefront across the entire aperture, and therefore subaperture measurements will be required, improved stitching software is required to go from the sub-aperture wavefront to the full-aperture system wavefront. Additionally, improvements in diffraction analysis modeling are needed to reduce the number of measurements required and to reduce the effects of noise sources and number of misalignments.

Radiometric Quantities such as transmittance, reflectance, radiance, and polarization are difficult to measure, particularly at the outer wavelength regimes of the Astrotech mission set. Two major technology areas require development. The first is to develop the material data bases that allow proper build designs, tested and validated. Significant tests are required of the complex refractive index and reflectivity, particularly of ultraviolet and x-ray materials. There is no empirical polarization property data base available to system designers. The necessary test of materials must be made and documented in a usable catalog. The second technology development is to increase the accuracy and capability of the measurement instruments. An order of magnitude improvement is needed in absolute radiometric calibration, polarization, and radiometric quantities.

Many of the Astrotech missions will require very good *Stray Light Suppression.* Stray light measurement is limited in dynamic range, near angle scatter and wavelength region. Space-based cleaning holds the promise of decreasing background noise on systems like the Space Infrared Telescope Facility (SIRTF) by a factor of 100. This type of return should be further developed. Bidirectional Reflectance Distribution Function (BRDF) data below wavelengths of 0.4 µm and above 20 µm is almost nonexistent. Funding is necessary for the enhancement of existing facilities and the fabrication of vacuum UV BRDF instruments. Then data should be accumulated on mirrors, filters, lenses, and black coatings so that stray light analyses in the future will have realistic BRDF data to work with. Funding should be provided for the development and characterization of Lambertian reference materials for the UV, IR, and far IR wavelength regions. Very near angle scatter measurements are an important part of many of the missions. None of the existing BRDF instruments measure high quality, low scatter surfaces at angles less than about 0.5 deg. New methods are probably needed to evaluate the BRDF at angles much less than 0.5 deg. Additionally, techniques need to be developed that prevent scattered light from a bright "point-like" stellar sources from reaching the detector, be it the detector of the BRDF instrument or the science sensor.

5. Optical Systems Integrated Modeling

The Optical Systems Integrated Modeling panel identified four critical areas for further development: integrated package for initial design, interface development for detailed optimization, validation, and modeling research.

An *Integrated Package for Initial Design* addresses the need for a high level optimization tool. Accessible software tools are needed that allow initial designs to be characterized quickly and inexpensively. The characterization must include the system's response to dynamic and thermal perturbations as well as static performance. These tools must also be capable of providing an early and reasonably accurate understanding of the expected imaging and radiometric performance of the system.

Interface Development for Detailed Optimization addresses modeling for detailed system and subsystem optimization. Existing software is available to carry out major portions of the modeling effort, but these components of software are generally separate dedicated packages that address the geometrical design, physical optics analysis, structural analysis, and thermal effects separately. Since future missions will be dominated by the size and complexity of the optics, these separate areas must be tied together to permit system-level evaluation of future design concepts. Integration of existing software and the development of advanced codes are required to enable end-to-end system performance evaluation. This includes the development of an integrated modeling computer program for initial design of large and complex advanced space optical systems.

Also critical to integrated modeling is *Validation.* All modeling software must be validated as part of the development effort. Software that cannot produce experimentally corroborated answers is useless. Additionally, since most of the advanced modeling capabilities required are very limited or nonexistent, validation with experimental demonstrations or hardware has not occurred and is necessary.

Modeling Research is recommended for development. While most concepts covering optical propagation are well founded, there are some critical areas that need basic development for incorporation into an integrated modeling process. Additional research and development into specific types of models (diffraction, scattered light, image inversion) and modeling techniques is required to improve model performance, relevancy, and clarity to a broad technical community.

6. Advanced Optical Instruments Technology

Six technologies that need to be developed in Advanced Optical Instruments are directly related to specific scientific measurements: gratings, tunable filters, interferometer beam combiners, optical components, starlight suppression, and fibers.

Gratings are needed with improved diffraction efficiency, particularly in the UV. Reduced scatter at all wavelengths is required to increase measurement signal-to-noise ratio. Aspheric, x-ray, and holographic blazed gratings of large size are also required to support the instrument concepts of the Astrotech mission set.

Tunable Filters encompass acousto-optic tunable filters (AOTF), Piezoelectric-tuned Fabry-Perot filters, and birefringent filters. These filters need further development for detecting the velocity distribution of extended emission line objects by looking at the spectral shifts of their emission lines in the UV, visible, and near IR.

Interferometer Beam Combiners, necessary for the new emerging scientific instruments called interferometers, exist in a number of forms: pair-wise pupil combiners, n-wise pupil combiners, and image plane combiners. The only developed beam combiner is the pair-wise pupil combiner. All of the others are required for the large scale multiple aperture interferometric measurements of future missions.

Optical Component technology is essential for the continued development of science instruments. The Advanced Optical Instruments group identified a number of components required for new science measurement capabilities. These include x-ray and ultraviolet windows, grids and gratings, binary optical elements, narrow band filters, tunable filters and advanced fiber optic systems.

The *Stray Light Suppression* effort focuses on the development of coronagraphs, nulling interferometers, and Woods filters. The coronagraph and nulling interferometer development would advance suppression levels to 10^{-4} – 10^{-6} for the visible and UV regimes. Suppression in the IR at 10^{-4} levels would also be developed.

The *High Potential Fiber* development program will focus on advancing fiber technology. The initial phase of the development will address the characterization of fiber materials (e.g., polarization, attenuation, dispersion, transmittance, etc.) applicable to the IR and UV regimes. Research will also concentrate on new and advanced materials and the fabrication processes necessary for fiber development.

Juan Ayon
February 1992

SECTION I
ASTROTECH 21 PROGRAM OVERVIEW

James A. Cutts, Jet Propulsion Laboratory, California Institute of Technology

Jess E. Fordyce, Jet Propulsion Laboratory, California Institute of Technology

Space astronomy is about to embark on a period of great discovery. During the 1990s, four great observatories will be launched to probe the universe in spectral regions ranging from gamma radiation to the far infrared. But NASA is already looking beyond the Great Observatories to even more challenging missions to be launched during the first few decades of the next century. New technology advances that enable observations with higher angular resolution, greater sensitivity, and the exploration of new spectral regions are viewed as vital for continued scientific progress. In 1989, the NASA Office of Space Science and Applications Astrophysics Division in cooperation with the NASA Office of Aeronautics, Exploration, and Technology created Astrotech 21 to devise a technology development plan for the astrophysics missions for the 21st century. The resulting plan was developed through three series of workshops that had different, yet related, goals.

The first series consisted of three workshops that addressed the science objectives and architectures for future missions in the disciplines of High Energy Astrophysics, Optical Interferometry, and Submillimeter Interferometry. In these forums, scientists and engineers met to discuss the astrophysical phenomena that could be observed with enhanced observation capabilities, the performance measurements required for these observations, and the various possible observatory architectures.

After developing science objectives and architectures for the New Century Astronomy Program in the first workshop series, a second series was held to better develop the mission concepts and identify specific technology requirements. Four such workshops were held and attended by participants involved in point mission design studies in the areas of: optical interferometry, laser gravitational wave observatories, advanced orbiting very long baseline interferometry (OVLBI), and large filled-aperture telescopes.

To synthesize the disparate technology requirements from the Astrotech 21 mission set in a coherent fashion, a third series of three integrated technology planning workshops were held concerning the critical areas of information systems, sensors, and optics. The goal of these workshops was to evaluate the new requirements in the context of existing and projected capabilities, and to recommend technology development programs whose justifications are directly traceable to the science goals of the mission set. This Proceedings publication summarizes the analyses and recommendations of the workshop on optics technology.

The proceedings of each workshop have been documented in separate volumes of this series; the final volume integrates all workshops and planning activities into a single technology development program plan for future space astrophysics missions.

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SECTION II
THE NEXT CENTURY ASTROPHYSICS PROGRAM

Paul N. Swanson, Jet Propulsion Laboratory, California Institute of Technology

The Astrophysics Division within the NASA Office of Space Science and Applications (OSSA) has defined a set of flagship and intermediate missions that are presently under study for possible launch during the next 20 years. These missions and tentative schedules, referred to as the Astrotech 21 Mission Set in this proceedings, are summarized in Figure 1. The missions are in three groups corresponding to the cognizant science branch within the Astrophysics Division. Phase C/D (in white) refers to the pre-launch construction and delivery of the spacecraft, and the Operations Phase (in black) refers to the period when the mission is active in space. Thus, the mission launch date is at the white/black boundary. Approximately 1.5 years before the start of Phase C/D, a non-advocate review (NAR) is held to ensure that the mission/system concept and the requisite technology are at an appropriate stage of readiness for full scale development to begin. Therefore, technology development is frozen (usually) as of the date of a successful NAR.

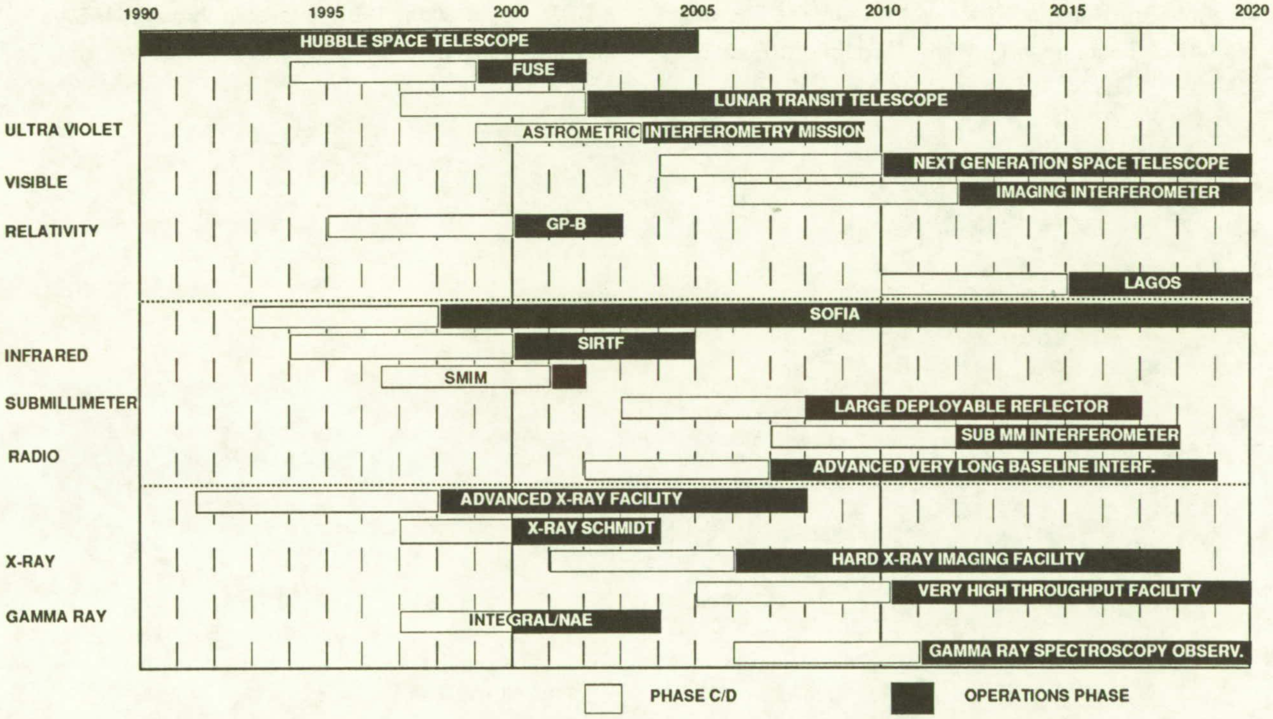

Figure 1. Next Century Astrophysics Program: Candidate Flagship and Intermediate Missions for Launch During 1995–2020 (for technology planning purposes only)

Figure 2 is a plot of wavelength coverage versus angular resolution (resolving power) for the set of missions as a function of the wavelength or frequency of observation. The 200–in. Hale telescope, the premier ground-base optical telescope during most of the latter 20th century, is included for comparison. For space telescopes in the wavelength range from the radio through to the

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ultraviolet, resolution is limited by diffraction and therefore varies linearly with wavelength. The Hale telescope resolution is limited by atmospheric turbulence and is approximately flat over its operational wavelength range. The shaded regions of the chart are regions where observations can nominally be made from the ground, i.e., regions where the atmosphere is essentially transparent. The unshaded regions, where most of the missions are focused, indicate where observations must be made from space because the earth's atmosphere is largely opaque at these wavelengths.

Figure 2 also plots wavelength coverage versus angular resolution (resolving power) for representative missions in the high energy range of the mission set. Their resolving power is flat over the energy ranges of interest in the case of the x-ray missions [Advanced X-ray Astrophysics Facility (AXAF), Einstein, Very High Throughput Facility (VHTF)] because they are limited by optical aberrations in the x-ray telescopes. The resolutions show for VHTF and Hard X-ray Imaging Facility (HXIF) are somewhat conjectural. If multilayer, normal-incidence mirrors replace glancing incidence mirrors, then significantly higher resolution is possible but with a penalty of limited spectral bandwidth. The gamma-ray telescopes, which have significantly poorer resolution than x-ray telescopes, do not use optical focusing.

An overview of the technology advances required for each of the three wavelength groups is provided in the following paragraphs, along with a brief description of the individual missions. Queries for more detailed information on any particular mission should be referred to the appropriate study or project manager [see Astrophysics Missions Payload Data Handbook, BDM Corporation, 1991 (available through NASA's Astrophysics Division, Code SZ)].

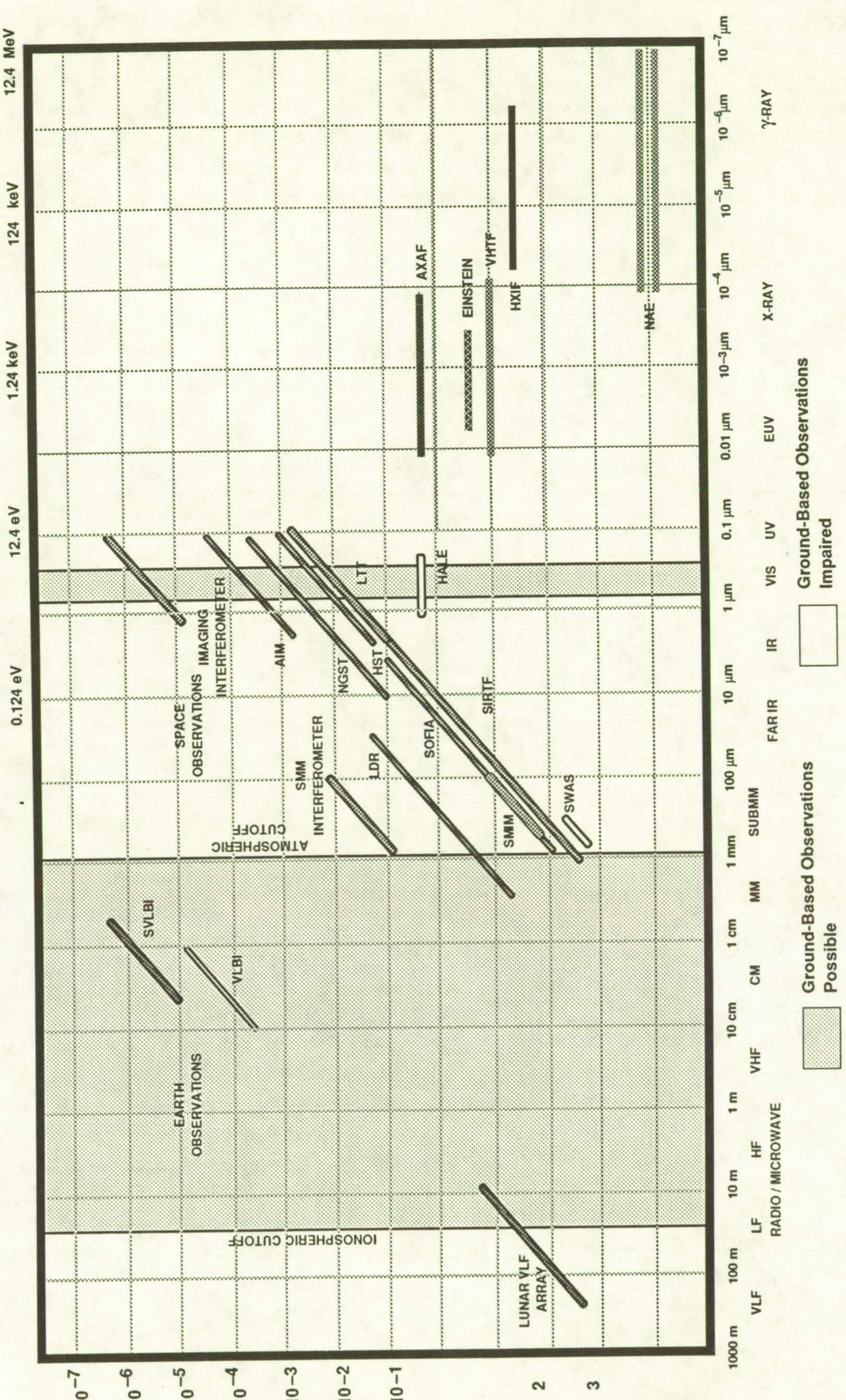

Figure 2. Angular Resolution versus Wavelength for Future Astrophysical Instruments

HIGH-ENERGY MISSIONS

The relevant parameters for the planned and proposed high-energy astrophysics missions are shown in Table 1. High-energy optics technologies are still in their infancy. In the x-ray regime, orders of magnitude enhancements in the throughput and collector area are desired, and potentially possible with an appropriately focused development program. The lack of conventional optics for the highest energy ranges places special demands on a technology program and the development of innovative optical systems for x-ray spectroscopy and imaging. The status of new techniques and technologies for x-ray imaging are discussed in Ref. 2.

Table 1. X-Ray and γ-Ray Mission Parameters

MISSION	Advanced X-Ray Astrophysics Facility (AXAF)	Integral/Nuclear Astrophysics Explorer (Integral/NAE)	Hard X-Ray Imaging Facility (HXIF)	Very High Throughput Facility (VHTF)	Gamma-Ray Spectroscopy Observatory (GRSO)	X-Ray Schmidt Telescope (WFXT)
LOCATION	600 km Earth Orbit	Low Earth Orbit	Space station attached or free flyer	Moon or free flyer	Moon or free flyer	TBD
MISSION DURATION	15 years with servicing	2 – 4 years	10 years	20 years	10 years	≈ 4 years
WAVELENGTH/ ENERGY RANGE	0.09 to 10 keV	15 keV to 10 MeV	20 keV to 2 MeV	0.15 to 40 keV	1 keV to 10 MeV	0.2 to 5 keV
MEASUREMENTS	Imaging, Spectroscopy	High-resolution imaging, spectroscopy	Coded-aperture and direct X-ray imaging, time-resolved photometry	Spectroscopy, imaging, time-resolved photometry	High-resolution spectroscopy	Imaging, high-resolution spectroscopy
SENSORS	Large imaging array, X-ray calorimeter spectrometer	High spatial resolution 9 Ge detectors 325 cm^2 area	Position sensitive, high-sensitivity, time resolved	High spatial and energy resolution, high dynamic range	High sensitivity 19 Ge detectors 1000 cm^2 area	High energy resolution imaging sensors
SENSOR TEMPERATURES	≈ –200 K, 0.1 K	85 K	Ambient	Ambient	Cooled	Cooled
APERTURE	1,700 cm^2 grazing incidence mirrors	Coded aperture	Up to 30 m^2 coded aperture	Up to 30 m^2 modular array	2.5 m^2 coded aperture	Few hundred cm
OPTICS TEMPERATURE	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient

Advanced X-Ray Astrophysics Facility (AXAF)

AXAF will be the third of the Great Observatories and will have an expected mission lifetime of 15 years with on-orbit servicing to support second- and third-generation instruments. It will provide high-resolution imaging in the x-ray region of the spectrum. Science objectives include the study of highly energetic sources, such as stellar black holes, clusters and superclusters of galaxies, neutron stars, and supernovae. The telescope will consist of a nested array of grazing-incidence mirrors with an effective collecting area of 1700 cm^2. The energy response will be 0.09 – 10 keV. The focal plane detectors consist of a 200 K Charged Coupled Device (CCD) array and a 0.1 K calorimeter. AXAF will be placed in a 600-km, 28-deg Earth orbit in 1998.

X-Ray Schmidt [Wide-Field X-ray Telescope (WFXT)]

The X-Ray Schmidt Telescope has been conceived to perform moderate spectral resolution surveys in the x-ray regime over large, contiguous areas of the sky at high sensitivity and high angular resolution. This will allow investigation of both the properties of the sources (galaxies, clusters, and AGN) and the large-scale structures they define over a broad range of red shift. The flight system is an integrated telescope/satellite system optimized for surveys. Its optics design (60 cm outer mirror) provides high angular resolution (better than 5 in. half power radius) over a full 1 deg diameter field of view. By using a CCD detector, moderate resolution spectroscopy ($E/\Delta E \approx 10$) will be achievable for thousands of sources. Two surveys are planned (100 sq. deg at a limiting sensitivity of $\approx 5 \times 10^{-15}$ erg s^{-1} cm^{-2}, 1000 sq. deg at limiting sensitivity of 10^{-14} erg s^{-1} cm^{-2}), yielding approximately 50,000 sources. The observatory would be launched into an equatorial Earth orbit of approximately 550 km, with a 4-year design life.

Integral/Nuclear Astrophysics Experiment (Integral/NAE)

The Integral/Nuclear Astrophysics Experiment (NAE) is an orbiting, high-resolution, gamma-ray telescope that will provide much higher spectral resolution and sensitivity than previous gamma-ray missions. It will investigate nucleosynthesis in supernovae, and study neutron stars, black holes, annihilation radiation, gamma-ray bursters, X-ray pulsars, and sites and rates of galactic nucleosynthesis. The collecting aperture will be an ambient temperature bulk detector of 325 cm^2 area and 2600 cm^3 volume. The cooled Ge detectors will be sensitive from 10 keV to 10 MeV. Two possible operational orbits are being considered. If the mission evolves as "integral," the flight system would operate in a high Earth orbit (approximately 48 hr). Should the NAE option evolve, the flight system would operate in low Earth orbit with a 2 – 4 year mission lifetime.

Hard X-Ray Imaging Facility (HXIF)

HXIF is a hard x-ray imaging telescope. It will complement AXAF by extending sensitivity into the hard x-ray region from 20 keV to 2 MeV. It will study quasars, galactic cores, physical properties of neutron stars and black holes, as well as make high time-resolution observations of black-hole emission. The original plan was for HXIF to be a space station attached payload. However, due to Space Station program restructuring, an alternate plan is for a free flyer. The telescope will consist of an array of large imaging telescopes (total of 30 m^2), each with a coded mask, shielded detector and position-sensitive readout. The telescope and detectors will be at ambient temperature. Launch is in 2005 with a 10-year mission duration.

Very High Throughput Facility (VHTF)

This telescope will provide high-sensitivity spectroscopy as well as high-time-resolution observations of faint x-ray sources. It will study dark matter in galaxies, star formation in molecular clouds, and rapidly changing signals from compact objects. Similar to AXAF, the telescope will be sensitive to radiation from 0.15 to 15 keV, but it will have a much greater collecting area of up to 30 m^2 and a high spectral resolution of $10^{-3} - 10^{-4}$ with an angular resolution of 10 arcsec. The telescope and detectors will be at ambient temperature. Launch into Earth orbit is planned for about 2010.

Gamma-Ray Spectroscopy Observatory (GRSO)

This gamma-ray telescope, located on the Moon (or as a low Earth free flyer), will use a distant, coded aperture mask to obtain sub-arcsecond angular resolution. The mask, which may be up to 5 km away (in the case of the lunar surface option), can be movable for source tracking.

High sensitivity will come from an array of 19 Ge detectors of large volume. The high angular resolution will provide positive identification of gamma-ray sources with their optical counterparts. Highly energetic, compact sources such as the postulated black hole at the center of our galaxy are candidate objects for study by the GRSO.

VISIBLE, ULTRAVIOLET, AND RELATIVITY MISSIONS

The relevant parameters for the missions in the visible and UV that require advances in sensor technology are summarized in Table 2. Future space-based observatories will place primary emphasis on end-to-end system analysis, wavefront sensing and control, advanced materials and structures, fabrication techniques, validation and testing, and advanced components and instruments.

Table 2. Ultraviolet/Visible Mission Parameters

MISSION	Hubble Space Telescope (HST)	Far Ultraviolet Spectroscopic Explorer (FUSE)	Lunar Transit Telescope (LTT)	Astrometric Interferometry Mission (AIM)	Next Generation Space Telescope (NGST)	Imaging Interferometer (II)
LOCATION	Low Earth Orbit	Earth Orbit	Moon	900 km Earth Orbit	Moon or Earth Orbit	Moon or Earth Orbit
MISSION DURATION	15 years with servicing	≈ 4 years	10 years	5 – 10 years	15 years	10 years
WAVELENGTH/ ENERGY RANGE	0.1 to 1 μm, upgrade to 2.5 μm	0.01 to 0.12 μm	0.1 to 2.5 μm	0.1 to 2.5 μm	0.1 to 10 μm	0.1 to 10 μm
MEASUREMENTS	Imaging, spectroscopy, photometry	High resolution spectroscopy	Imaging	Interferometric astrometry, imaging	Imaging, spectroscopy	High resolution spatial imaging, spectroscopy
SENSORS	Large format arrays, high dynamic range, low noise	High energy resolution, high sensitivity, photon counting	Large format arrays, high sensitivity, low-noise	High sensitivity array, fast frame rate, low noise photon counting	Large format array, fast frame rate, low read noise photon counting.	High sensitivity array, high frame rate, low-noise, photon counting
SENSOR TEMP.	80 K	TBD	≈ 100 K	≈ 200 K	< 100 K	TBD
APERTURE	2.4 m	70 m	1 – 2 m	50 cm apertures, 2 – 30 m baseline	10 – 16 m	1.5 m apertures 1 km baseline
OPTICS TEMP.	Ambient	Ambient	100 K	Ambient	<100 K	Ambient

Hubble Space Telescope (HST)

The HST was launched in 1991, but new instruments will be installed periodically during the planned 15-year lifetime of the mission. The HST has a 2.4-m primary reflector and operates from the visible into the ultraviolet. Future upgrades are expected to extend the coverage to 2.5 μm. There are four focal-plane instruments, each of which is designed to be serviceable. The first instrument replacement is scheduled for 1993. Spherical aberration of the primary reflector has so far prevented fully diffraction-limited operation; however, future replacement instruments will internally correct for this shortcoming, eventually providing 0.1 arcsec angular resolution.

Far Ultraviolet Spectroscopic Explorer (FUSE)

The FUSE is an orbiting far-ultraviolet telescope which will operate primarily between 90 and 120 nm and secondarily down to 10 nm. It will carry out high-resolution spectroscopic observations of energetic sources such as quasars, active galactic nuclei, stellar and accretion discs, and the foreground interstellar medium. The FUSE will have a 70-cm-dia glancing incidence telescope, and will be launched into Earth orbit in 1999. Mission lifetime is planned for 4 years.

Lunar Transit Telescope (LTT)

The LTT may be the first astronomical telescope placed on the surface of the Moon under NASA's Space Exploration Initiative (SEI). The LTT will be a wide field of view, visible-wavelength telescope with a fixed pointing near the lunar zenith direction. The slow rotation of the Moon will allow the LTT to map out a strip of sky perhaps 1–2 deg wide. The long integration times provided by this scheme allow extremely deep observations over a limited area of the sky. The telescope will be about 1 m in diameter, with a large-format CCD array at the ambient temperature focal plane. Emplacement on the Moon could be as early as 2002, with a 10–15-year lifetime.

Astrometric Interferometer Mission (AIM)

The AIM will be the first optical interferometer in space. It will be used primarily for astrometry and can measure the distance to Cepheid variables directly, can determine the presence of extra-solar planets through the star's orbital perturbations, and can detect supermassive galactic cores. An imaging capability would permit the imaging of protostellar objects, the surface of supergiant stars, and solar system objects such as comets and asteroids. It will operate over a wavelength range of 0.12 to 2.5 μm, with an interferometric baseline of 2–20 m. The interferometer may be made up of as many as six individual telescopes, each with up to a 50 cm aperture. Measurement of angular distances between objects with exceedingly high accuracies will require ultra-precise metrology within the instrument. The architectural features of various astrometric instrument concepts are discussed in Ref. 3, which includes the Orbiting Stellar Interferometer (OSI) and the Precision Optical Interferometer In Space (POINTS).

Next Generation Space Telescope (NGST)

The planned 15-year lifetime of the HST will be completed in 2005. The NGST is the follow-on mission. It will have a larger aperture and will operate from 0.1 to 10 μm, and may take advantage of passive cooling of the optics to < 100 K. The science objectives include the study of the formation of the nature of the early universe at red shifts $Z > 1$. The radiatively cooled aperture will be approximately 6–8 m in diameter. The detectors will also be cooled to < 100 K. The launch date is approximately 2010, with a planned 15-year lifetime. The NGST can either be placed in Earth orbit or on the surface of the Moon. Technology requirements for this mission are described in Ref. 4.

Imaging Optical Interferometer (I I)

The Imaging Optical Interferometer will be the second-generation space optical interferometer following AIM. It will be used primarily for high-spatial resolution imaging rather than astrometry as in the case of AIM. It can image binary star systems, supergiant stars and Cepheid variables, can determine the structure of quasars and active galactic nuclei, and can detect extra-solar planets. It will operate from 0.1 to 10 μm, have a baseline of up to 1 km, and as many as ten 1- to 1.5-m individual apertures. It may be placed in Earth orbit, but the larger baselines would benefit from lunar basing. The launch date is beyond 2010 with a 10-year mission duration. Three potential mission configurations were examined at the Astrotech 21 workshop on technologies for optical interferometry in space: the Folding Fizeau Telescope (FFT), the Lunar Optical Interferometer (LOI), and the Visible Interferometer with Separate Telescope Assemblies (VISTA) (see Ref. 5.)

Gravity Probe - B (GP-B)

The Gravity Probe-B is a highly specialized satellite to test two of the lesser known predictions of general relativity: frame dragging and the geodetic effect. Both have the effect of causing a gyroscope axis to slowly change direction in space when orbiting a massive object. The GP-B uses four precision gyroscopes suspended in a magnetically shielded, drag-free environment. Less than 1 year in the planned 400-km, polar Earth orbit should be sufficient to measure the relativity effects.

Laser Gravity-Wave Observatory in Space (LAGOS)

The LAGOS is an experiment designed to detect gravitational radiation, one of the most important predictions of general relativity. It will be capable of detecting gravitational radiation from galactic close binary stars, and possibly from the capture of stars by supermassive black holes to strain levels of 10^{-23}, and 10^{-5} Hz oscillation rates. The configuration is an "L" shaped optical interferometer in heliocentric orbit with legs ~ 10^{7} kilometers long. When a gravitational wave passes, the local space is strained, and the interferometer measures a change in distance between the widely spaced elements. These measurements require active sensing systems with very stable lasers. The main technical challenge in the optics area is the extreme precision required. Thermal control, vibration suppression, and control systems well beyond existing technology must be developed. Technology requirements for LAGOS are described in Ref. 6.

INFRARED, SUBMILLIMETER AND RADIO MISSIONS

Table 3 summarizes the relevant parameters for the missions in the infrared (IR), submillimeter (submm) and radio regime. Advances in replication techniques, modeling, figure initialization and maintenance, ultrastable structures, materials, and cryogenic optics technologies are required for these missions to enable low background, high dynamic range measurements.

Table 3. Infrared / Submillimeter / Radio Mission Parameters

MISSION	Stratospheric Observatory For Infrared Astronomy (SOFIA)	Space Infrared Telescope Facility (SIRTF)	Submillimeter Intermediate Mission (SMIM)	Large Deployable Reflector (LDR)	Submillimeter Interferometer (SMMI)	Space Very Long Baseline Interferometer (SVLBI)
LOCATION	747 Aircraft	High Earth Orbit	70,000 x 1,000 km elliptical Earth Orbit	100,000 km Earth Orbit	Moon	Highly elliptical Earth Orbit
MISSION DURATION	> 20 years 120 – 200 flights/year	3 – 6 years	1 – 2 years	10 – 15 years	10 years	10 years
WAVELENGTH/ ENERGY RANGE	IR - submillimeter	2.5 to 1200 µm	100 to 800 µm	30 to 3000 µm	100 to 800 µm	1.5 mm to 3 cm
MEASUREMENTS	Testbed for new IR and submm sensors	Imaging spectroscopy, photometry	Imaging high-resolution spectroscopy	Imaging, high-resolution spectroscopy	First submm interferometry in space	Interferometry, high precision astrometry
SENSORS	Wide variety of state-of-the-art non-coherent and coherent detectors	High sensitivity, large array formats, low noise	High sensitivity direct and heterodyne	First submm array, high-sensitivity, broadband back end spectrometer, high power LO	High sensitivity and broadband back end spectrometer	High sensitivity and ultra-stable Local Oscillator
SENSOR TEMPERATURES	0.1 to 80 K	0.1, 0.3 and 2 – 5 K	0.1, 0.3 and 2 – 5 K	0.1, 0.3 and 2 – 5 K	0.1 and 2 – 5 K	2 – 5 K
APERTURE	2.5 m	1 m	2.5 – 3.6 m	10 – 20 m	4 – 5 m apertures, 1 km baselines	25 m
OPTICS TEMPERATURE	Ambient	Liquid He cooled	Ambient	Ambient	Ambient	Ambient

Stratospheric Observatory for Infrared Astronomy (SOFIA)

SOFIA is an advanced aircraft facility for infrared and submillimeter astronomy. It will replace the highly successful Kuiper Airborne Observatory. SOFIA will provide a high-altitude platform for infrared through submillimeter astronomical observations above the troposphere, developing and testing the next generation space instruments, and for training new astronomers. A 2.5-m, ambient temperature telescope will be installed in a Boeing 747 aircraft. It will operate throughout the infrared and submillimeter bands with cryogenically cooled detectors in an easily accessible focal plane. The system is planned to be operational in 1998.

Space Infrared Telescope Facility (SIRTF)

SIRTF is the second-generation cryogenically cooled infrared telescope after the successful Infrared Astronomy Satellite (IRAS). It will be the fourth of the Great Observatories. The scientific objectives are high-sensitivity photometry, imaging and spectroscopic observations of primitive bodies in our solar system, brown dwarfs, infrared-emitting galaxies, and quasars. The telescope will be ~ 1 m in diameter and cryogenically cooled to liquid He temperatures to reduce background radiation. The liquid He cooled focal plane detectors will operate over 2.5 – 1200 µm. SIRTF will be in a circular, high Earth orbit with a 28 deg inclination. The planned launch date is in the year 2000. Mission duration will be 3 – 6 years, limited by the lifetime of the liquid cryogen supply.

Submillimeter Intermediate Mission (SMIM)

This mission is an orbiting observatory to conduct a complete, high resolution, spectral line search throughout the far infrared and submillimeter spectral regions. It will study the physical conditions and compositions of the interstellar gas, star formation regions, early galaxies, and infrared galaxies at cosmological distances. The telescope will have a 2.5–3.6-m, ambient temperature aperture, diffraction limited at 100 µm. The orbit will be highly elliptical with a 70,000 km apogee and 1,000 km perigee, inclined at 28 degrees. The focal plane detectors will cover the range from 100 – 800 µm, with detectors cooled to liquid He temperatures. Launch date is planned for 2002. The mission lifetime, limited by the stored cryogen supply, is 1–2 years. Technology requirement for SMIM are covered in Ref. 7.

Large Deployable Reflector (LDR)

The LDR is the Great Observatory class mission in the submillimeter spectral range. The science objectives are the study of the early universe, the interstellar medium, the formation of stars and planets, anisotropy in the cosmic background, and the chemistry, distribution and energetics of molecular, atomic and ionic species. The 10–20 m, ambient temperature reflector will be placed in a circular 10,000 km Earth orbit. The focal plane instruments will cover the range from 30 to 1000 µm with both superconducting heterodyne and noncoherent (direct) detectors. The focal plane will be cooled to liquid He temperatures. Launch date is about 2012 with a 10–15 year duration, depending on the lifetime of cryogenic system.

Submillimeter Interferometer (SMMI)

The lunar-based submillimeter interferometer may be an alternative to the Earth-orbiting LDR. If NASA's Space Exploration Initiative continues, it may be possible to construct a large submillimeter interferometer on the Moon with a baseline > 1 km. Science objectives would include high spatial-resolution studies of star-forming regions and protogalaxies, starburst phenomena in distant galaxies, and fine-structure anisotropy in the cosmic background. Six to twelve elements, made up of approximately 4-meter reflectors in a "Y" (or ring) configuration, would make up the interferometer. The cryogenically cooled detectors would operate at selected wavelengths from 100 to 800 µm. Operation on the Moon would begin in 2012. Technology requirements for SMMI are described in Ref. 8.

Space Very Long Baseline Interferometer (SVLBI)

The second-generation VLBI experiments, after Radioastron and VSOP, are already being planned. The highly elliptical Earth orbit will provide angular resolution in the radio region better than that from the lunar Imaging Interferometer, as well as having superior UV plane coverage. The space component of the SVLBI will be a 15-m ambient temperature reflector in a highly elliptical orbit. Cooled receivers will cover the microwave to millimeter wave bands from 10 to 200 GHz. Launch is planned for about 2000. Technology requirements for SVLBI are described in Ref. 5.

OPTICAL CONFIGURATIONS

Another way of looking at the mission set that is particularly relevant to the present consideration of optical systems technology requirements appears in Table 4. In this table, the missions are divided not by wavelength but on the basis of optical configuration. The filled-aperture telescopes have a single collecting area, typically near circular. The smaller nearer-term telescopes generally have monolithic primary mirrors with minimal provisions for figure control on orbit. The large telescopes may be segmented and will almost certainly include some form of active figure control. For some missions, such as the Imaging Interferometer (II), alternative configurations exist. These configurations may fall into different categories.

Interferometers consist of a set of individual mirrors or telescopes that sample parts of the wavefront from the astrophysical object. The interferometer closest in concept to a conventional filled aperture telescope is the Fizeau design. In essence, this is a conventional telescope for which large segments of the primary mirror have been removed. The only example in the current mission set is the Folding Fizeau Telescope (FFT), which is one of three candidates considered for the Observatory-Class Imaging Interferometer (Ref 1). The aperture of the FFT is 20 m but only about 5% of this is occupied by reflector. Snapshot images with this telescope have diffraction-limited resolution corresponding to the full 20-m aperture, but the image is corrupted by sidelobes. By taking successive images with the telescope rotated to several different angular positions around an axis pointed at the target object, a synthetic aperture image of high dynamic range can be reconstructed in which the sidelobes are substantially reduced.

The Michelson interferometer group includes the other two candidate concepts for the Imaging Interferometer: the Lunar Optical Interferometer (LOI) and the Visible Interferometer With Separate Telescope Assemblies (VISTA). The Michelson architecture is also be used in the two concepts being considered for an Astrometric Interferometer Mission (AIM): Orbiting Stellar Interferometer (OSI) and Precision Optical Interferometer in Space (POINTS). Michelson and Fizeau interferometries demand exacting knowledge and control of optical pathlengths but are the techniques of choice for high resolution observations at ultraviolet, visible, and infrared wavelengths.

The heterodyne interferometer group consists of the Space Very Long Baseline Interferometery (SVLBI) mission, which observes millimeter waves and the Submillimeter Interferometer (SMMI) mission. In a heterodyne interferometer, the starlight signal is mixed with a fixed locally-derived reference frequency at each telescope in the array and the difference signal is used to reconstruct the wavefront. Heterodyne interferometry does not demand the same degree of control of the optical path as either a Michelson or a Fizeau interferometer. It is the preferred approach for wavelengths longward of the submillimeter and is in routine use in ground based microwave interferometers.

Grazing incidence telescopes are specialized telescopes for x-ray imaging or spectroscopy. Soft x-rays incident near normal incidence are heavily absorbed in mirror materials but if they impinge at a sufficiently shallow angle they reflect and can be sucessfully focused. Normally, this class of telescope is limited by figure errors or aberrations and grazing incidence telescopes do not normally approach the diffraction limit.

Finally, the Laser Gravitational Observatory in Space (LAGOS) is in a class of its own, not just in terms of the kind of radiation that it observes but in the optical configurations that are applicable.

Gamma-ray and hard x-ray missions that do not require optical focusing are excluded from this list.

Table 4. Optical Configurations of Missions in Next Century Astrophysics Program

MISSION	APERTURE/ BASELINE	WAVEFRONT QUALITY	POINTING KNOWLEDGE	POINTING CONTROL
		FILLED APERTURE TELESCOPES		
FUSE	1 m	1 nm	2.5 µrad	1.25 µrad
SIRTF	1 m	140 nm	300 nrad	300 nrad
SMMM	3.65 m	10 µm	2.5 µrad	1.25 µrad
LTT	2 m	12 nm		
NGST	10 m	10 nm	50 nrad	5 nrad
LDR	20 m	500 nm	250 nrad	125 nrad
		FIZEAU INTERFEROMETERS		
II/FFT	30 m	10 nm	0.8 nrad	0.8 nrad
		MICHELSON INTERFEROMETERS		
AIM/OSI	20 m	1 nm	15 µrad	170 nrad
AIM/POINTS	2 m		10 µrad	10 NRAD
II/VISTA				
II/LOI	10 km	10 nm		
		HETERODYNE INTERFEROMETERS		
SVLBI	TBD	15 µm	500 nrad	500 nrad
SMMI	TBD	10 µm		
		GRAZING INCIDENCE TELESCOPES		
AXAF		NA		
VHTF		NA		
WFXT	.6 m	NA		
		LASER GRAVITATIONAL WAVE DETECTION		
LAGOS	10^7 km	0.5 pm		0.3 prad

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SECTION III
WORKSHOP STRUCTURE AND GOALS

James B. Breckinridge, Jet Propulsion Laboratory, California Institute of Technology

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The Optical Systems Technology Workshop was held in Pasadena, California, March 6–8, 1991, as part of the Series III of the Astrotech 21 planning workshops. The charter of this workshop was to identify technology needs of the Astrotech 21 mission set in the area of optical systems technology, and to recommend a plan to develop the required capabilities that are not currently available. To accomplish this, a set of panels was selected, and a 2-day meeting was convened in Pasadena. Optical system performance requirements spanning the entire mission set (and electromagnetic spectrum) were addressed by six panels, with responsibility for: wavefront sensing, control, and pointing; fabrication; materials and structures; optical testing; optical systems integrated modeling; and advanced optical instruments technology.

Prior to their arrival at the meeting, panel members received a briefing package which contained information on the Astrotech 21 mission set and science goals, and summaries of: (a) the optical requirements not met by current technology, and (b) the relevant technologies offering promise in providing these capabilities in the future. Starting from this material, and from the results of any previous studies with similar focus, the panel chairs compiled strawman versions of their recommendations to provide a framework for discussion at the workshop. The first (half) day of the meeting consisted of a review of the Astrotech 21 program, followed by presentations by the panel chairs. During the second (full) day, the panels split into separate sessions to carry out their assignments. To ensure coordination of the recommendations from the workshop, panels with similar development topics participated in presentations to, and/or joint discussions with, other panels. Following the day of splinter sessions, the chairs prepared a summary of their panels' findings and presented it at a plenary session during the final (half) day. The final reports prepared by the panel chairs following the workshop appear in Section IV of this proceedings publication.

The panel reports first describe the optics capabilities desired for future astrophysics missions, and the performance specifically required to achieve the science goals of the Astrotech 21 mission set. Current state-of-the-art capabilities are then examined in this context, in order to determine the areas in which advances are required, and the relative importance of the desired capabilities to the mission goals. The reports also discuss approaches that offer promise in eventually overcoming remaining shortcomings in optics technology capabilities vis-a-vis the Astrotech 21 mission requirements, if further development is supported.

Finally, within the context of the Astrotech 21 mission needs, the history of optics technology development in that wavelength regime, and the analysis of emerging technologies, the reports recommend to NASA a set of specific development plans to achieve the capabilities desired to meet the challenges of the Astrotech 21 science goals. Recommended dates are defined for each development program. To ensure uniformity among the recommendations generated by the six different panels, a definition of program scope was identified at the workshop to help the panels better gauge each item. It was decided that the most uniformly defined parameter is the number of lead technical personnel involved in a particular effort, rather than the financial resources required, which may vary considerably depending on the institution overhead, salary scales, etc. However, some allowance was made if significant build up of capital equipment was deemed necessary.*

It is important to keep in mind that the panels' charter was specifically to focus on those technologies and optics capabilities relevant to the Astrotech 21 mission set. Thus, the deliberations and reports exclude any consideration of other technologies, regardless of how important they may be to other classes of missions. They also exclude technologies that may be of value to future astrophysics missions but are not expected to be ready in time to benefit the particular mission set highlighted here. These restrictions naturally result in an arbitrary ramping down of the development plans as the relevant technology freeze dates of the Astrotech 21 mission set are approached. In fact, as time goes on, more distant missions, undoubtedly with even more demanding specifications, will be defined, requiring continued development beyond the limited scope considered here.

It is recognized that the Astrotech 21 mission set is part of an evolving plan. Consequently, mission definitions, priorities, and requirements have continued to change during the period in which this proceedings publication was being prepared. As much as possible, references to these missions have been updated to reflect their status as of February 1992.

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* Note: Specific funding and dollar levels are not included in this publication. All panels addressed the funding and capital investments required for their technologies, and this information was provided to NASA Headquarters under separate cover.

SECTION IV
WORKSHOP PANEL REPORTS

This section contains the following final workshop panel reports:

1. Wavefront Sensing, Control, and Pointing
2. Fabrication
3. Materials and Structures
4. Optical Testing
5. Optical Systems Integrated Modeling
6. Advanced Optical Instruments Technology

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SECTION IV
WORKSHOP PANEL REPORT:

1. WAVEFRONT SENSING, CONTROL, AND POINTING

Thomas Pitts, Itek Optical Systems, a Division of Litton, Chair

George Sevaston, Jet Propulsion Laboratory, California Institute of Technology, Co-Chair

Wavefront Sensing, Control, and Pointing Panel Participants

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Pierre Bely	Space Telescope Science Institute
Mark Colavita	Jet Propulsion Laboratory, California Institute of Technology
Mark Clampin	John Hopkins University
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Paul Idell	Phillips Laboratories
Dave Sandler	Thermo Electron Corp.
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INTRODUCTION

A majority of future NASA astrophysics missions from orbiting interferometers to 16-m telescopes on the Moon have, as a common requirement, the need to bring light from a large entrance aperture to the focal plane in a way that preserves the spatial coherence properties of the starlight. Only by preserving the phase of the incoming wavefront, can many scientific observations be made, observations that range from measuring the red shift of quasi-stellar objects (QSOs) to detecting the IR emission of a planet in orbit around another star. New technologies for wavefront sensing, control, and pointing hold the key to advancing our observatories of the future from those already launched or currently under development.

As the size of the optical system increases, either to increase the sensitivity or angular resolution of the instrument, traditional technologies for maintaining optical wavefront accuracy become prohibitively expensive or completely impractical. For space-based instruments, the low mass requirement and the large temperature excursions further challenge existing technologies. The Hubble Space Telescope (HST) is probably the last large space telescope to rely on passive means to keep its primary optics stable and the optical system aligned. One needs only look to the significant developments in wavefront sensing, control, and pointing that have occurred over the past several years to appreciate the potential of this technology for transforming the capability of future space observatories.

Future developments in space-borne telescopes will be based in part on developments in ground-based systems. Telescopes with rigid primary mirrors much larger than 5 m in diameter are impractical because of gravity loading. New technologies are now being introduced, such as **active optics**, that address the scale problem and that allow very large telescopes to be built. One approach is a segmented design such as that being pioneered by the W.M. Keck telescope now under construction at the Mauna Kea Observatory. It consists of 36 hexagonal mirror segments, supported on a framework structure, which are positioned by actuators located between the structure and the mirrors. The figure of the telescope is initialized by making observations of a bright star using a Shack Hartmann sensor integrated with a white light interferometer. Then, using sensed data from the mirror edges to control these actuators, the figure of the mosaic of 36 segments is maintained as if it were a rigid primary mirror. Another active optics approach is the use of a thin meniscus mirror with actuators. This technique has been demonstrated on the European Southern Observatory's New Technology Telescope (NTT) and is planned for use in the Very Large Telescope (consists of four 8-m apertures), which is now entering the design phase. Figure 3 illustrates the interrelation of key technologies necessary to wavefront sensing, control, and pointing.

The control bandwidth for active optics systems is measured in periods of seconds to minutes. To correct for atmospheric distortion of the wavefront in ground-based applications, the U.S. Department of Defense (DoD) has developed **adaptive optics** systems whose technology has recently been declassified. Because of the much higher control bandwidth, wavefront control is performed at a pupil plane using a small active mirror. Systems with as many as 2000 actuators have been built and demonstrated for use on the ground. The STARLAB Wavefront Control Experiment (WCE) is a 69 degree of freedom system designed for use in space that incorporates a shearing interferometer as a wavefront sensor.

Both adaptive and active optics systems are concerned with maintaining or restoring wavefront fidelity over a single contiguous aperture. Interferometers, which sample the wavefront at discontinuous points, have also been developed for ground-based astronomy. Narrow band systems using heterodyne techniques are applicable for the wavelength range from microwave to submillimeter wave (as previously discussed in the mission set review by Swanson in Section II). However, for observation of wide spectral bands at visible or near infrared wavelengths, the control and knowledge of

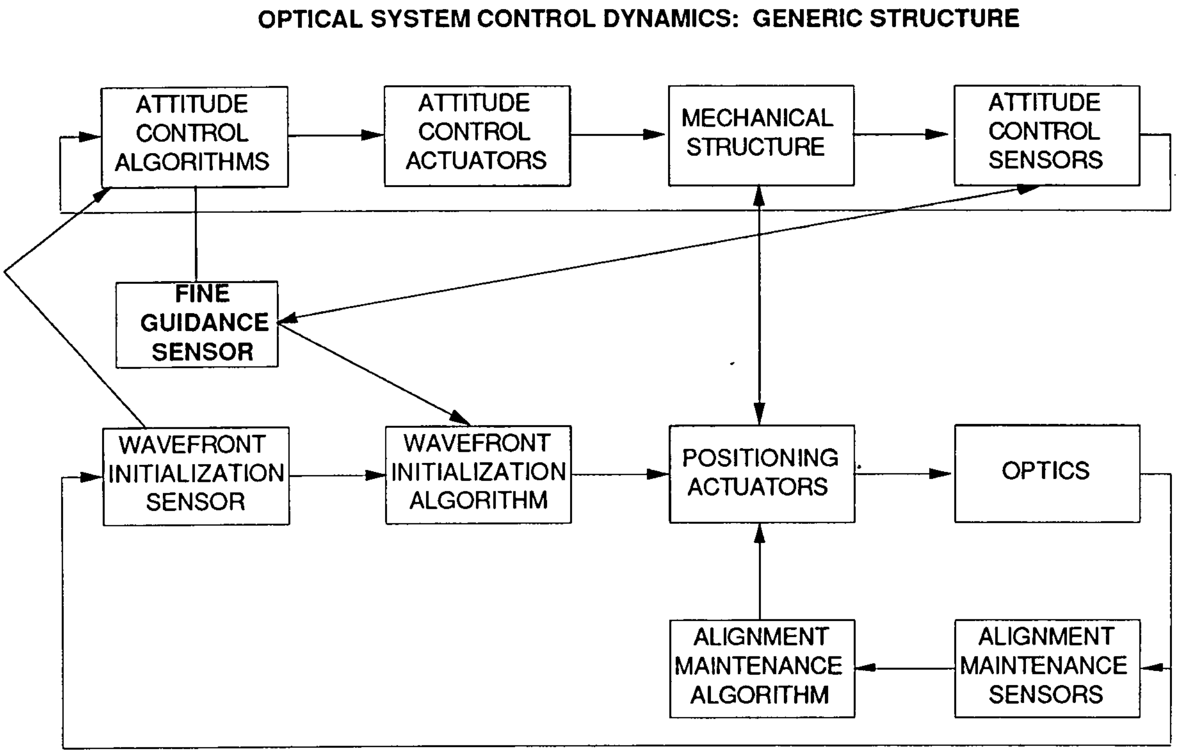


Figure 3. Interrelation of Key Technologies in Wavefront Sensing, Control, and Pointing

the wavefront is extremely demanding. The first Michelson interferometer to implement active white light fringe tracking through control of laser monitored delay lines (Mark III interferometer) is currently operating at Mt. Wilson Observatory, California and is designed primarily for astrometry. Other much more powerful systems are now being planned for visible and near infrared interferometric imaging, including the W.M. Keck Interferometer at Mauna Kea, Hawaii, and the Very Large Telescope (VLT) Interferometer planned by ESA.

The space missions in the Astrotech 21 mission set include filled-aperture telescopes, partially filled-aperture telescopes, heterodyne interferometers, starlight Michelson interferometers with astrometric and imaging capabilities, and the laser gravitational wave detection mission which uses laser interferometry between spacecraft to detect the space time perturbations introduced by the passage of gravitational waves. The characteristic aperture and baseline, rms wavefront error, pointing accuracy, and pointing stability for these missions are summarized previously in Table 4 of Section II. Although atmospheric perturbations are clearly not a source of wavefront errors and gravity loading will only be important for lunar observatories, there are several sources causing time variable wavefront and pointing perturbations. These include thermal or dynamic changes in telescope support structures, in the optical elements, or in the alignment and spacing of discrete elements.

Previous Astrotech 21 workshops, one on technologies for space-based interferometry identified developmental needs in wavefront sensing, control, and pointing. Characteristics of the interferometer concepts are extreme path length control (3 nm visible, 0.3 nm UV). This requires metrology systems; ultra-quiet structures; measurement of spacecraft disturbance sources to nanometer levels; actuator responses to millinewton level; and development of quasi-static, lightweight, space-qualified set-and-forget actuators with step sizes of 10 nm at 1 nm accuracy and a dynamic range of 100 mm. Large filled-aperture concepts require pointing control systems with >10 Hz bandwidth and slew rates >20°/min; active optics actuators with sub-micron accuracy at 100 K; segment sensing of 10 nm rms at 10 Hz bandwidth and 100 K; and validation of sensing techniques. Additionally, the LAGOS workshop identified a laser pointing requirement of 3×10^{-9} $(f/1\ \mathrm{Hz})^{-1/2}$ rad $\mathrm{Hz}^{-1/2}$ for 10^{-3} to 1 Hz.

In many cases, a given problem has many solutions, and the challenge is not just to find an answer but to find the optimal choice. Technologies involved in the solution can be broken down into six categories: (1) Active Optics, (2) Active Interferometry, (3) Pointing and Attitude Sensing and Control, (4) Laser Metrology, (5) Structures Control, and (6) System-Control Architecture. Table 5 summarizes the technology needs for future astrophysics missions, and Table 6 summarizes the recommended technologies, identified by the panel, in light of the mission needs.

Table 5. Wavefront Sensing, Control, and Pointing Mission Technology Needs for Astrophysics Missions

	ACTIVE OPTICS	ACTIVE INTERFER-OMETRY	POINTING AND ATTITUDE SENSING AND CONTROL	STRUCTURES CONTROL	LASER METROLOGY	SYSTEM CONTROL ARCHITECTURE
Filled-Aperture Telescopes						
FUSE						
SIRTF	●[1]		●			
SMIM	○		○	○	○	○
LTT						
NGST	●		●	●	●	●
LDR	●		●	●	●	●
Fizeau Interferometer						
II/FFT	●		●	●	●	○
Michelson Interferometers						
AIM/OSI		●	○	●	●	●
AIM/POINTS		●	○	○	●	●
II/VISTA		●	○	○	●	●
II/LOI		●	○	○	●	●
Heterodyne Interferometers						
SVLBI	○		○	○	○	○
SMMI	○		○	○	○	○
Grazing Incidence Telescopes						
AXAF						
VHTF						
WFXT						
II/LOI		●	○	○	●	●
Laser Gravitational Wave Detection						
LAGOS	●		●	●	●	●

● = Enabling Technology

○ = Supporting Technology

= (Blank) Not Required or Unknown

[1] SIRTF pointing mirror is considered here as active optics

Table 6. Wavefront Sensing, Control, and Pointing Technologies for Astrophysics Missions : 1992–2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Active Optics	To Achieve and Maintain Diffraction Limited Performance in Large Optical and Submm Systems Employing Active Optical Techniques	Figure Sensing	NGST	'02
		Phase Sensors	II/FFT	'04
		Deformable Mirrors	SMMI	'05
		Precision Actuators	LDR	'01
		Line of Sight Stabilization	SVLBI	'00
			LTT	'95
			SMIM	'96
			SIRTF	'96
Active Interferometry	To Develop Systems and Elements for the Active Sensing of Wavefronts, Pathlength Control, and Beam Combination for Physically Separated Collection Elements	Wavefront Sensing	AIM/OSI	'97
		Optical Pathlength Control	AIM/POINTS	'97
		Beam Combination	II/LOI	'04
		Stray Light Cancellation	II/VISTA	'04
Pointing, Attitude Sensing and Control	Precision Pointing (Optical Axis) and Attitude (Interferometer Baseline), Knowledge, and Control for Large Optics and Structures	Star Trackers	SMIM	'92 - '08
		Fine Guidance Sensors	NGST	
		Attitude Transfer Devices	LDR	
		Inertial Attitude Sensors	II/FFT	
		Attitude Actuators	II/VISTA	
		Fine Pointing Mirrors	II/LOI	
			NGOVLBI\SMMI	
			AIM/OSI	
			AIM/POINTS	
			LAGOS	
Structures Control	Control Vibration and Changes in Lightweight Flexible Structures to a Level Consistent With the Performance Envelope of Optical Control and Pointing Control Subsystems	Isolation	NGST	'02
		Damping	II/AII	'04
		Control Structure Interaction	LDR	'01
		Modal Control	SVLBI	'00
		Smart Structures	SMIM	'96
		Control Design Optimization	LAGOS	'08
			SMMI	'05
Laser Metrology	Precision 3-D Measurement and Control Over Large Distances for Long Baselines and Optical Trusses	Laser Sources	NGST	'02
		Fiducial References	AIM/AII	'97
		Components	II/AII	'04
		Innovative Architectures	LDR	'01
			SMMI	'05
			LAGOS	'08
System-Control Architecture	Integration of Component Technologies (Optics and Structures) for Optical System Control	Vibration Isolation Systems	SMIM	'92 - '08
		Damping Augmentation	NGST	
		Control Structure Interaction	LDR	
		Modal Control	II/AII	
		Smart Structures	SVLBI	
		Integrated Structure Control Design Optimization	SMMI	
			AIM/AII	
			LAGOS	

ACTIVE OPTICS

A. Technology Assessment

The only foreseeable approach to the construction of very large filled-aperture telescopes and long baseline interferometers in space includes the concept of active control of the optical surface figure and the alignment of the supporting structure. Active, segmented optical systems that are space deployable or erectable offer the possibility of essentially unlimited aperture size which would otherwise be limited by manufacturing and launch constraints to 4 m diameters or less. Active systems also allow the use of low areal density materials and structures. Densities of 10–20 kg/m^2, a factor of 10 reduction over the Hubble Space Telescope optics, are achievable in very large sizes.

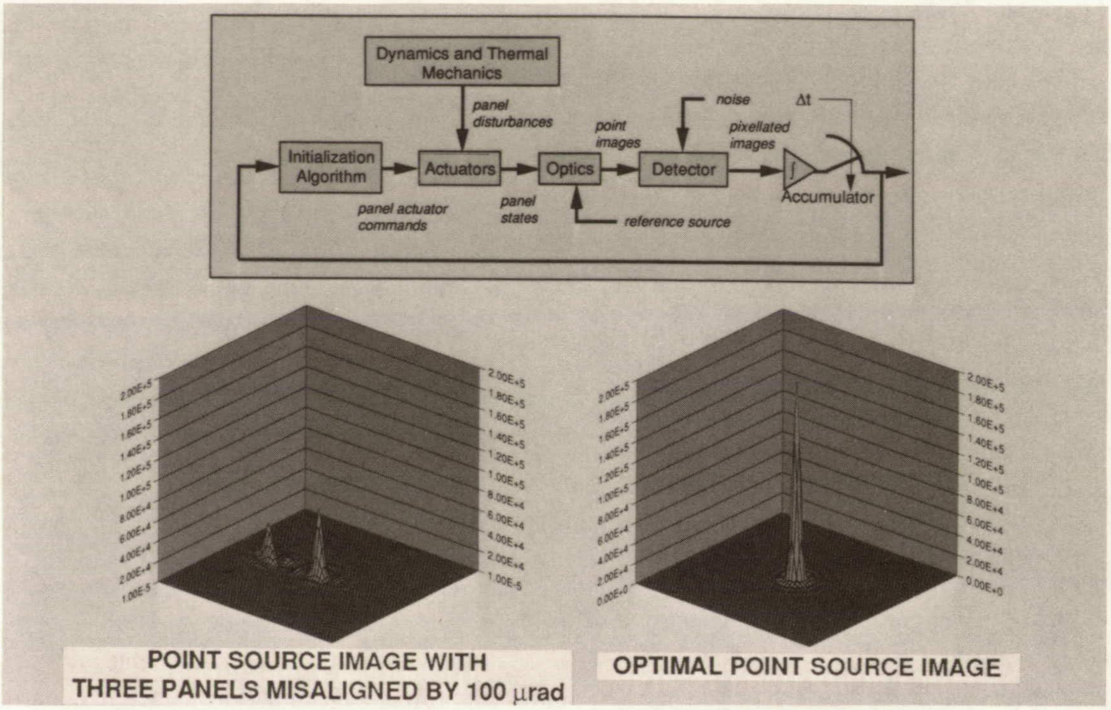
Active optics can be realized using one of two distinct wavefront control system architectures. The most accessible of the two, from the standpoint of required new technology, is a two phase approach in which initialization and maintenance are accomplished by separate but nested control loops. Initialization is accomplished by periodically slewing the system to a sufficiently bright illumination source and actively optimizing the configuration of the optics (e.g., by image sharpening or image inversion). Between initialization times, the configuration is maintained by a faster control loop using information from a dedicated maintenance sensor (e.g., an optical truss of laser metrology sensors). Further into the future is a single phase approach in which initialization and maintenance are accomplished by the same control loop using one sensor. This can be accomplished, for example, by introducing an illumination source on board that can be used continuously for wavefront control without interrupting science observations. Although the required level of technology development is greater than that of the two stage approach, the benefits are obvious. Figures 4 and 5 illustrate techniques for figure initialization and maintenance.

Considerable progress has been made in the area of active optics for laser beam control and military surveillance. This technology has direct applications to astrophysics, however many of the Astrotech 21 mission needs will drive the technology well beyond the state of the art defined by DoD requirements.

Wavefront Sensing – DoD resources have been invested in pupil plane wavefront sensors including the Shack Hartmann device and shearing interferometers, such as the device developed for the WCE adaptive optics system. Recently, wavefront sensing based on near image plane curvature and image inversion data has been developed. The comparative advantages of these various techniques have not been fully investigated and their ultimate reliance on new detector and optics technology remains speculative. The basic issues to be investigated include the number of subapertures that must be independently controlled, the control bandwidth and the required brightness of the control signal (natural or artificial).

Wavefront Control – Wavefront control includes two subsystems: a reconstructor that converts the wavefront sensor output into actuator drive signals, and the actuator arrays that adjust the optical path between each subaperture and the controlled image. Most reconstructors integrate wavefront tilt (slope) information to produce phase errors and associated control signals. They require supplemental information about the relative positions of the individual control actuators in order to form the final control signals.

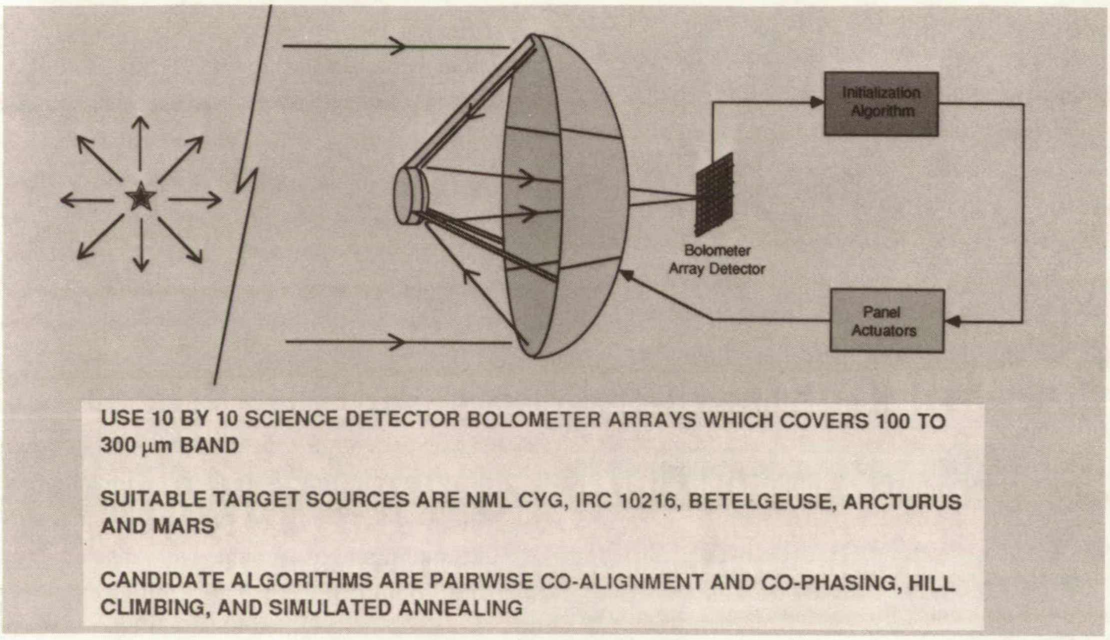
The actuator arrays drive the individual mirror segments or sections of continuous surface deformable mirrors in response to the control signals. The key requirements are areal number density of actuators, response bandwidth, displacement range, and operating temperature and cost. High yield fabrication techniques have not been developed and therefore costs are high. Space applications will require actuator materials that produce large displacements while operating at low temperatures to cryogenic temperatures.



POINT SOURCE IMAGE WITH THREE PANELS MISALIGNED BY 100 μrad

OPTIMAL POINT SOURCE IMAGE

(a)



USE 10 BY 10 SCIENCE DETECTOR BOLOMETER ARRAYS WHICH COVERS 100 TO 300 μm BAND

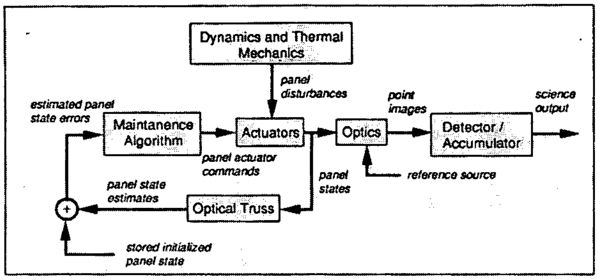
SUITABLE TARGET SOURCES ARE NML CYG, IRC 10216, BETELGEUSE, ARCTURUS AND MARS

CANDIDATE ALGORITHMS ARE PAIRWISE CO-ALIGNMENT AND CO-PHASING, HILL CLIMBING, AND SIMULATED ANNEALING

FOCAL PLANE IMAGE SHARPENING

(b)

Figure 4. Figure Initialization



Optical Truss

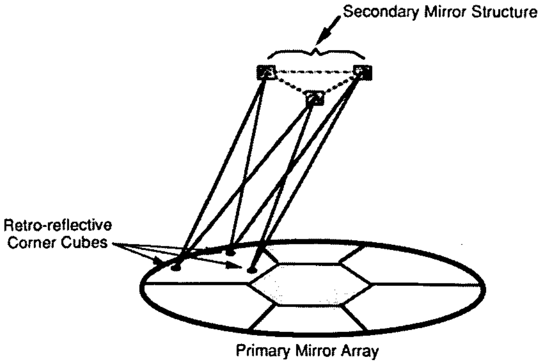


Figure 5. Figure Maintenance

B. Development Plan Needs

Future astrophysical missions will require active optics to initialize and maintain their optical elements in the optimal positions, orientations, and shapes to enable diffraction-limited performance and performance robustness. This will be especially critical for missions with large apertures or baselines. Table 7 is a summary of the active optics technology areas requiring significant advances to meet the Astrotech 21 requirements for 1998 and beyond.

Wavefront Sensing – Figure and wavefront sensors will be needed to measure the quality of the wavefront at a representative location in the optical train in order to provide appropriate error signals to a wavefront control system. Current technology is characterized by low-resolution (i.e., a few hundred samples over the aperture) pupil plane techniques (i.e., shearing interferometers and Shack-Hartman sensors). The use of pupil plane sensors (which measure wavefront slope) on segmented telescopes necessitates the use of edge matching sensors as well, which adds to the cost and complexity of the system. Future large optical systems will require spatial resolution in excess of 10,000 over the aperture consistent with the correlation length of anticipated wavefront errors. The sensors must be capable of operating from natural (perhaps even extended) broadband sources to maximize their utility. The use of focal plane techniques will minimize the amount of special purpose hardware required, thus minimizing mass, cost and complexity, and maximizing reliability. Moreover, it will support segmented optics without the need for special provisions. Fast reconstruction algorithms (e.g., neural nets) will be required to solve for the controlled variables (e.g., segment coordinates and deformation states) in real time. Finally, the use of onboard sources and associated optics will eliminate the need to have specific targets within the field of view, thus maximizing operability of the system.

Table 7. Active Optics Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Figure Sensing	Low Resolution Pupil Plane Techniques, Shearing Interferometers, Hartman Sensors	Real Scene White Light Sensors Fast Reconstruction Algorithms (e.g., Neural Nets) Focal Plane Sensors Onboard Sources	'95 - '06 '95 - '06 '96, '04 '10	'93 - '04
Phase Sensing	Breadboards Electronic Sensors : 10 nm	Optical and Electronic Sensors : < 1 nm Space Qualifiable Prototype Phasing Mirror	'95 - '05 '06	'93 - '06
Deformable Mirrors	Operations at IR Wavelengths Low Resolution, mm Range	High Resolution, Long Stroke Deformable Mirror Operation at VIS Wavelengths	'04 '95 - '05	'93 - '04
Actuators	0 -100 mm Stroke 0.01 mm Precision < 1 Hz Bandwidth Non Cryogenic	0 - 10 mm Stroke 1 nm Precision > 10 Hz Bandwidth Cryogenic	'95 - '05 '96, '04, '10	'93 - '10

Wavefront Control – Deformable mirrors (or their segmented equivalents) will be needed to correct the wavefront errors introduced by motions and deformations of the optics and support structure. The displacement and spatial resolution will have to be smaller than 1 nm and 10,000 actuators per aperture (10-m structure with 10 cycles over aperture), respectively. The stroke will have to be on the order of 100 mm, and the bandwidth will have to exceed 1 kHz. The state of the art deformable mirror contains of a few hundred actuators and is capable of stokes of a few microns. Major advances are needed to reach the required level of development. One promising approach is to apply micro-machining principles to this class of problem.

For positioning and aligning optical elements on orbit, space flyable precision positioning actuators are needed. These will require strokes up to 10 mm, precision better than 1 nm, and bandwidths in excess of 10 Hz. Furthermore, they must be capable of operating at temperatures down to 1 K in a vacuum. Currently available positioners are roughly an order of magnitude away in performance, and cryogenic device development is in its infancy.

ACTIVE INTERFEROMETRY

A. Technology Assessment

Active interferometry, as used here, refers to the same process of wavefront sensing and control between the elements of a Michelson interferometer as is provided by active optics for a filled or partially filled aperture telescope. In one sense, active interferometry is a limiting case of active optics, with a very sparse aperture sampling the incident wavefront at a small number of points. Like active optics, the phase of this sampled wavefront must be sensed, and its phase adjusted, in order that the light from the individual apertures combine coherently. However, compared with active optics, active interferometry incorporates some key differences in both wavefront sensing and wavefront control. It also imposes some special requirements on the recombination of the wavefronts that are unique to interferometry. For reference, Figure 6 provides a schematic of a simple two-element Michelson stellar interferometer.

Wavefront Sensing – Wavefront sensing for active interferometry is similar to wavefront sensing for a segmented (non-monolithic aperture), in that wavefront continuity cannot be used to reconstruct the wavefront from slope measurements — the phase of the white-light fringe must be measured directly. Thus, there will be an initial

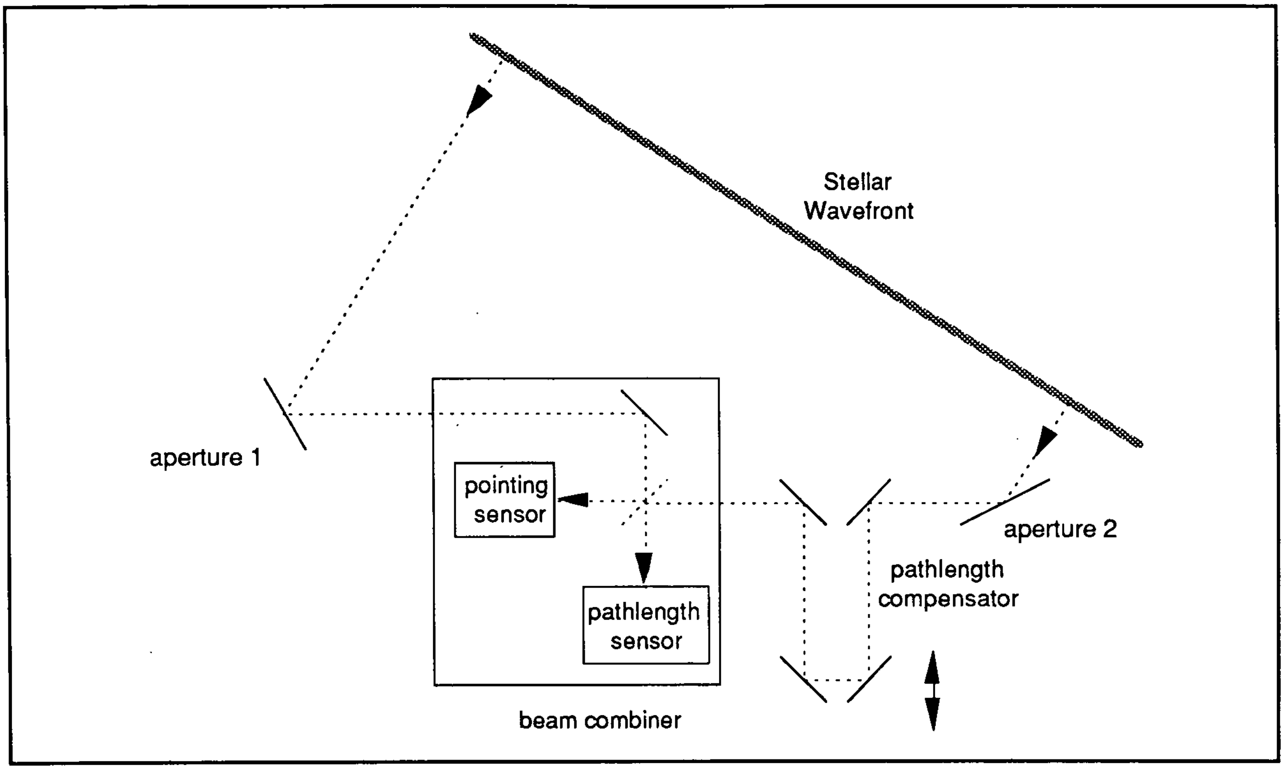


Figure 6. Essential Components of a Two-Element Stellar Interferometer. (Courtesy of Mark Colavita.)

uncertainty in the wavefront phase, which could be ~10–1000 μm, depending on the calibration of the geometry of the instrument. As quasi-monochromatic sensing leads to 2 pi ambiguities in the measured phase once the fringe is found, for active interferometry it is necessary to use broadband (white) light ($\lambda/\Delta\lambda < 5$), and to incorporate acquisition techniques to find the white-light envelope and determine the central white-light fringe. Photon-efficient techniques are essential because signal fluxes are always low.

For a two-element interferometer, the wavefront is usually sensed with pathlength-modulation or dispersed-fringe techniques. With pathlength modulation (Figure 7(a)), as is used on the Mark III interferometer (and would be used in AIM/OSI), a systematic modulation of the optical path is introduced into one arm of the interferometer. This modulation sweeps the interference fringe across a detector, producing a temporally modulated intensity, from which the phase of the interference fringe can be determined. The fringe phase can also be detected using dispersed-fringe techniques, which use a spectrometer to disperse the interfered light across an array detector, producing fringes in wavenumber space (Figure 7(b)) as in AIM/POINTS.

For an interferometer with more than two beams, the sensing problem becomes more complicated, and is different depending on the beam combination method. For example, with Michelson combination (e.g., II/LOI), the phase of each baseline pair is measurable, and pathlength modulation or dispersed-fringe methods are applicable. However, their application becomes far more complicated: with pathlength modulation, multi-frequency or multi-cycle modulation is required to separate the various baselines, while for dispersed-fringe techniques, fiber-fed array detectors are required to accommodate the various baselines. At the other extreme, with Fizeau combination (e.g., II/FFT), phasing information may not be directly available in the image plane if the array geometry is partially redundant, and a auxiliary Michelson combiner may be needed for phasing.

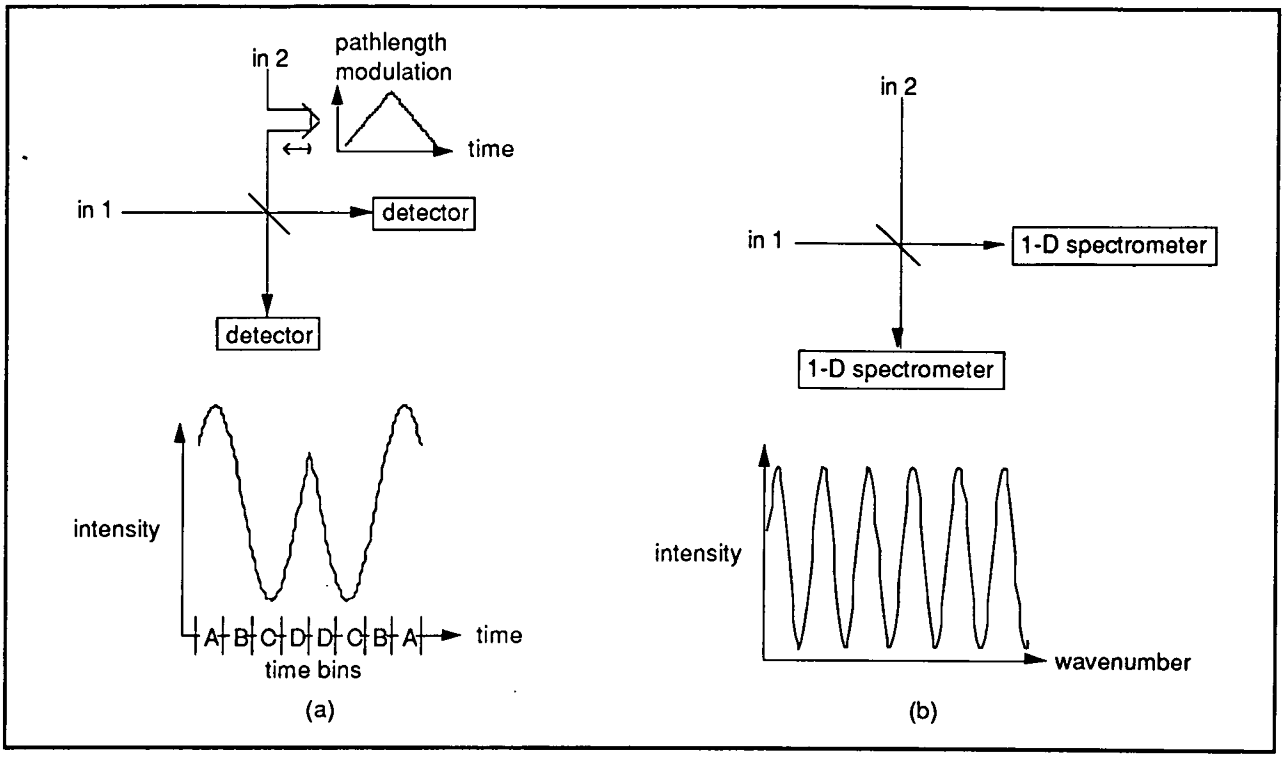


Figure 7. Wavefront Sensing, using: (a) pathlength modulation – the bin counts A-C and B-D are proportional to the sine and cosine quadratures of the interference fringe; the fring ephase is just the arctangent of these quantities, and (b) a dispersed fringe – the optical pathlength error is proportional to the frequency of the interference in wavenumber space. (Courtesy of Mark Colavita.)

Optical Pathlength Control – While the individual elements of an interferometer could employ active optics, wavefront control of the interferometer does not require deformable mirrors. Rather, piston control of the phase at each subaperture is normally all that is required. Unlike active optics systems where phase errors can be compensated with motions of a small number of wavelengths, for some interferometer architectures, where the subaperture telescopes must be pointed relative to the baseline (e.g., AIM/OSI, II/LOI), the phasing mirrors must be mounted on delay lines. The total travel of these delay lines may be a substantial fraction of the total baseline, and phase must be maintained in the vibration environment generated by motion of the delay line. Even for designs where the interferometer is pointed as a solid body (e.g., AIM/POINTS, II/FFT), short-travel delay lines could be used to compensate for pointing errors, although this may not be required. For very long delay line travels, it frequently makes sense to partition the delay function into two parts, a coarse correction with a large dynamic range, and a fine correction over a smaller range. Figure 8 gives the schematic of a delay line developed for a ground-based stellar interferometer.

Control bandwidths for pathlength control vary depending on the application. For free-flying space applications, high control bandwidths can be used to compensate for structural deformations and vibrations. Essentially, the measured fringe phase from observation of some target is a function of both the orientation of the baseline vector and the delay-line position. If laser metrology is used to monitor the baseline motions, the baseline error can be converted to an equivalent optical path error and fed forward to the delay line in order to synthesize a stable structure. Similarly, for a system with coarse and fine delay lines, errors in the coarse delay can be compensated by the fine system. However, as an optical delay line is essentially a one-element deformable mirror with a stroke measured in meters,

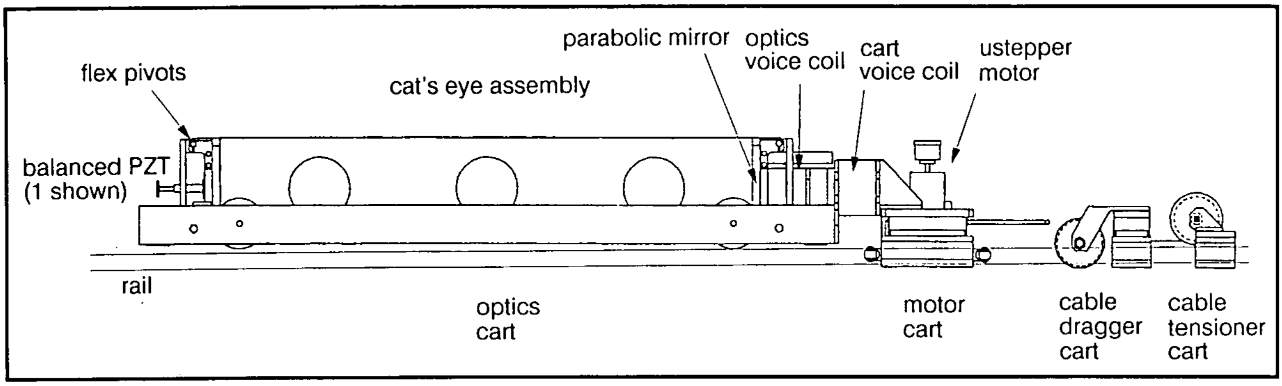


Figure 8. Schematic of a Delay-Line System Developed for a Ground-Based Interferometer. (Courtesy of Mark Colavita.)

high bandwidths, which are normally applied to only one element of the delay-line system, can be achieved.

Beam Combination – In an active optics system with a monolithic primary, the combination of light at a focus presents no special optical problems; the measure of success is the ability to concentrate light from a point source into a spot with a high Strehl ratio. For a two-element interferometer, the beam combination is also relatively straightforward, and has been demonstrated on ground-based interferometers, although the current combiner designs are very bulky relative to the constraints of space missions.

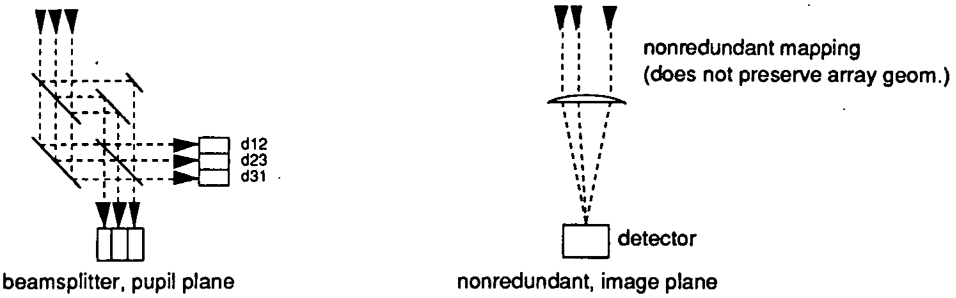
However, in a multiple-element (e.g., II/LOI, II/FFT) interferometer, the combination of beams at either an image plane or a pupil plane presents substantial optical challenges. There are two broad types of beam combiners for interferometry: 'Fizeau' and 'Michelson'. Examples of these combiners are shown in Figure 9. Fizeau combiners (e.g., II/FFT) preserve the geometry of the projected interferometer pupil and produce a direct image. In the case of II/FFT, the image is created at the focal distance of the equivalent full-aperture system. Alternatively, a scaled image of the interferometer pupil as seen by an incident wavefront can be reimaged onto the pupil of a combining telescope that produces the image. In exchange for a large field of view, Fizeau techniques have tight tolerances on not only the piston, but also the translation and magnification of the individual (or reimaged) subapertures. If the telescopes are individually pointed, the reimaging needs to be dynamic.

Multiway Michelson combiners (e.g., II/LOI), on the other hand, do not aim to produce a 1:1 mapping of object spatial frequencies to image spatial frequencies, and are more similar to radio techniques (aperture synthesis imaging). The field of view for imaging with a Michelson combiner is set by the spectral resolution. One variant of the Michelson technique reimages the input pupils onto a combining telescope in such a fashion that the resulting Fourier components of the image correspond to unique baseline pairs. Alternatively, a pupil-plane technique can be used which employs beamsplitters to interfere the beams pairwise. With both Fizeau and Michelson techniques, the incorporation of spectral resolution, guiding, infrared observation, and passive cooling, complicates the design.

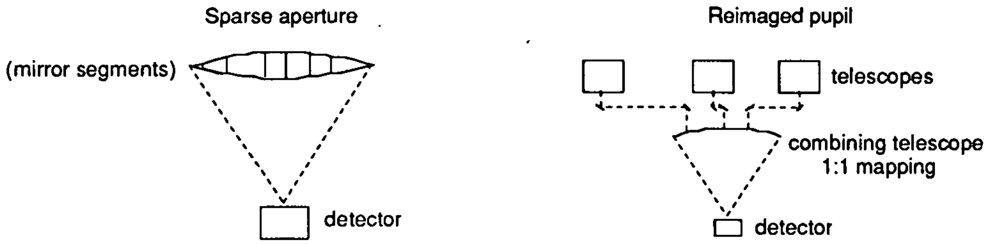
B. Development Plan

A list of enabling technologies in active interferometry is given in Table 8.

Wavefront Sensing – Photon-noise limited wavefront sensing has been demonstrated on the ground for two-element systems. However, while the systematic phase accuracy necessary on the ground is only ~0.1 rad, space astrometric interferometers require systematic errors of 0.001 (AIM/POINTS) – 0.009 rad (AIM/OSI). Thus the development goals for two-element, visible-wavelength sensing includes the control of



(a) Michelson Beam Combination--Conceptual



(b) Fizeau Beam Combination--Conceptual

Figure 9. Geometries for: (a) Michelson (pairwise) beam combination, using beamsplitters or nonredundant pupil remapping, and (b) Fizeau beam combination, using a spares-aperture and reimaged pupils. Lenses are illustrated for combination instead of telescopes for simplicity. (Courtesy of Mark Colavita.)

systematic phase errors, robustness, and space qualification. Detectors are also a key area, especially high-rate, solid-state photon-counting devices for pathlength-modulation methods, and fast-readout, low-read-noise CCD detectors for dispersed-fringe methods. For multi-element combiners, goals include the development of sensing architectures that are photon efficient and are consistent with science constraints on observation wavelength, cooling, and sensing bandwidth, and that are robust enough for space application. These architectures may include the development of hybrid pupil-plane/image-plane techniques that partition the wavefront sensing and science observation components for application to II/FFT (dependent upon whether II/FFT implements edge sensors or whether the individual parts are sensed as individual sparse aperture interferometers).

Optical Pathlength Control – Optical pathlength control is key to all interferometers. While active delay lines have been developed for ground-based applications with acceptable optical performance, these designs tend to be massive, exploiting their large inertia, in part, to provide isolation from external vibrations. In addition, as they assume a massive mounting structure that serves as a reaction mass, the actuators are usually not momentum balanced, nor are they designed to minimize random vibrations induced into the supporting structure. For space applications (e.g., AIM/OSI, II/LOI), these shortcomings need to be addressed, and a robust, space-qualifiable, low vibration system is among the development goals. In addition, for high sensitivity observations in the thermal infrared, interferometers, like any observational system, require cooling of all optics in the beam train, including the delay lines. Thus, delay lines for such missions as II/LOI require a design compatible with the proposed passive cooling systems. Also, for long-baseline systems such as II/LOI, it makes sense to partition the path-delay

Table 8. Active Interferometry Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Wavefront Sensing	Fringe-scanning or dispersed-fringe techniques for 2-element systems	Phase-measurement accuracies of 0.03 (AIM/POINTS) – 0.5 (AIM/OSI) deg	'97	'93 - '05
		High dynamic range (1 – 10 MHz) photon-counting systems for high bandwidth astrometry: AIM/OSI, II/LOI, II/VISTA	'96	
		Fast readout, low-read-noise CCD detectors: all		
		Stray light efficient wavefront sensing for multi-element systems: II/FFT, II/LOI	04	
Optical Pathlength Control	3–4 stage active delay lines for ground-based applications	Lightweight, momentum-compensated, low induced vibration delay lines: AIM/OSI, II/VISTA, II/LOI	'97, '04	'93 - '05
		Cryogenically cooled (or coolable) delay lines: II/VISTA, II/LOI	'04	
		Switched delay lines with absolute pathlength measurements: II/VISTA, II/LOI	'04	
Beam Combination	Two-way pupil-plane beam combiners for ground-based applications at visible wavelengths	Lightweight, compensated or self-aligning 2-way combiners: all	'97, '01, '02, '04	'93 - '06
		2-way combiners incorporating laser metrology for astrometry: AIM/POINTS, AIM/OSI, II/LOI	'97, '04	
		Multiway combiners with spectroscopic capability: II/LOI, II/FFT	'04	
		Low emissivity beam combiners for IR observations: II/VISTA, II/LOI	'04	
		Stray light cancellation (rotational shearing interferometers): II/VISTA, II/LOI	'04	

function into a coarse, switched system with a large range, plus a fine system of the type described above. For the former, an absolute metrology system enables continuous monitoring of the optical path when switching among segments. Even for smaller baseline systems like AIM/OSI, absolute metrology can be employed to monitor beam reconfigurations, enhancing imaging performance.

Beam Combination – Most of the proposed space interferometers require a two-beam combiner as one of their back-end instruments. The development goals and technology challenges for a visible-wavelength combiner are mostly in the area of space qualification and robustness, and in particular, the development of designs that are alignment compensated or else present only minimal requirements on active alignment. For infrared observations, the requirement for optics cooling makes the development of the beam combiner more challenging. However, the greatest challenges arise when multiway combiners are considered, and the choices for combination are greatly increased, as discussed above. Thus, the development goals for beam combination also include the development of detailed optical configurations for beam combination that are consistent with the measurement goals, the wavefront sensing architecture, and space environment. A final goal is the development of beam combiners that uses interferometric cancellation of starlight to enable direct imaging of such high dynamic range objects as star-planet systems.

POINTING AND ATTITUDE SENSING AND CONTROL

A. Technology Assessment

The pointing and attitude sensing and control requirements for future astrophysics missions range widely and a variety of technologies must be brought to bear to address them.

The need for accurate and stable pointing of telescopes is basic. Large diameter visible and UV filled-aperture and partially filled-aperture telescopes (NGST and II/FFT) present the most exacting sensing and control requirements (see Table 4 in Section II). Infrared and submillimeter telescopes need not usually be pointed as accurately but, as we shall see, this does not necessarily make the task easier.

In the case of an interferometer, it is important to distinguish between the pointing requirements for the individual telescopes and the requirements on attitude knowledge and control for the baselines connecting elements of the interferometer array. Typically, the pointing requirements are comparable to the requirements for a telescope of that aperture used singly. The orientation of the baseline, on the other hand, typically must be known to much greater accuracy for performing high dynamic range imaging and astronomy.

If the telescopes comprising the interferometer are mounted on a single space structure, knowledge of the orientation of the baseline must derive from metrology of the structure and measurements of its attitude in space. If the telescopes orbit separately, then baseline knowledge must include measurements between the spacecraft and perhaps reference stations on the earth also.

Measurement of gravitational waves using laser metrology between free flyers spacecraft places extreme demands on both the pointing of the telescopes uses as laser beam directors and collectors and the metrology techniques for determining changes in their spacing.

We now consider the status of techniques and technologies for sensing of pointing and attitude.

Pointing and Attitude Sensing – The fundamental reference is always a star field although inertial measurements of angular drift are becoming increasingly important as these techniques can be made more accurate. The guidance system used on the Hubble Space Telescope (HST) represents the state of the art, circa 1980, and will be used as a reference for this discussion. The HST guidance system consists of orthogonal star trackers for initial orientation. The Fine Guidance Sensor (FGS), which shares the main telescope focal plane with the science instruments, is able to locate reference stars close to the targeted science object that are bright enough for accurate angular positional measurements. The HST FGS is shown in Figure 10.

Fine Guidance Sensors – The use of fine guidance sensors like the HST/FGS, which share the main telescope optics with the science payload, presents special challenges for infrared and submillimeter telescopes. The use of a reference frame of infrared stars is not currently practical because there are no infrared star catalogs comparable to the visible catalog used for HST. There may not be a sufficient number of suitable stars in some regions of the sky. The alternative is to use tracking in the visible range. This introduces two kinds of problems. In some missions, such as Submillimeter Intermediate Mission (SMIM) and the Large Deployable Reflector (LDR), the telescope is not figured to operate in the visible and so the approach is clearly not practical. In other missions, such as Space Infrared Telescope Facility (SIRTF), the telescope is figured adequately to operate in the visible, but the telescope and instruments are also cooled with superfluid helium, and visible star sensors designed with current technology will not function at the temperature of the helium bath. Accordingly, the SIRTF project has embarked on a technology program to develop a cryogenic fine guidance sensor that can be located internal to the telescope.

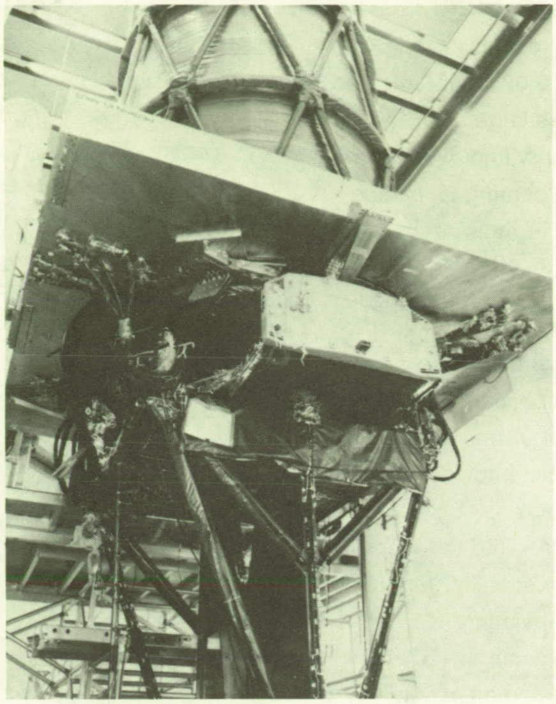


Figure 10. HST Fine Guidance Sensor

Star Trackers – The alternative to guidance systems that share the primary optics is the use of a coaligned external tracker. In this case it is necessary to cross calibrate the sensors and minimize the drift in this calibration as a function of changing thermal conditions for example.

Inertial Attitude Sensors – Sensors are needed for targets where there are no nearby reference stars. The key parameters are the accuracy with which pointing information can be transferred from the nearest reference star field which will depend among other things on the time required to slew and the exposure time on the science object. Current gyros have drift rates of 0.003 degrees per hour which is unacceptable for high precision pointing. Development of inertial attitude sensors is necessary to enable initialization, slewing and nodding of future astrophysics systems.

Pointing and Attitude Control – The requirements on telescopes pointing range from rapid slewing between science targets to accurate low-jitter stabilization on the science target for the duration of the integration. In addition, infrared and submillimeter telescopes require a nodding motion to facilitate background subtraction. This involves a sequence of small slews punctuated by rapid settling of pointing for the integration on the science object and the background scene. In all cases, there is a requirement for low noise and vibration so that wavefront (figure) control and in some cases inertial pointing knowledge are not disturbed by the operations.

Slewing Actuators – To maximize observational efficiency, astrophysical instruments have to be slewed rapidly between science targets. The infrared and submillimeter instruments also have to be nodded for background suppression. Since future instruments will be large, attitude actuators capable of high torque and large momentum capacities will be required. Interferometer slewing poses the problem of moving large structures quickly, quietly, and efficiently. Actuators that give high rates, low jitter, and low mass do not exist.

Quiet Attitude Actuators – What makes this a difficult challenge is that the actuators must, at the same time, be extremely quiet. The state of the art in quiet attitude actuators is characterized by a peak torque of 0.82 N-m, a momentum capability of 264 N-m-sec, a torque ripple of about 0.02%, and emitted force and torque vibration levels as large as 0.5 N and 0.1 N-m, respectively. Evolutionary improvements in noise properties by advances in bearing technology, balance, and new isolation techniques are a possibility.

Control of telescope pointing can involve pointing the telescope as a rigid structure as is done on the HST or using an active secondary as is being considered for the SIRTF. For X-ray telescopes, where photon flux rates are low and photon detectors are standard, pointing control can be relaxed considerably. Thus with the AXAF, the telescope is allowed to drift with a 0.5 arcsec stability (half-cone angle) over 10 sec. Frequent pointing knowledge updates are acquired to allow accurate positional reconstruction of the time-tagged photon events.

B. Development Plan

Table 9 is a summary of the pointing and attitude sensing and control technology needs to meet the Astrotech 21 requirements for 1998 and beyond. Details of the recommended development program are given below.

Pointing and Attitude Sensing – The pointing and attitude sensing technology program focuses on star trackers, fine guidance sensors, attitude transfer devices, and inertial attitude sensors. Developments in these areas are key to the success of future astrophysics missions.

Star Trackers - Star trackers are needed to establish absolute attitude in space. Today's star trackers have accuracies of about 1 arcsec. In the future, more accurate star trackers will be needed not only to support pointing of telescopes but also to support orientation of the interferometer array. Today's star trackers rely on complex ground interaction for acquisition. In the future, the need to lower operations costs will make autonomous operations costs a necessity. The panel recommends development of autonomous star trackers with accuracy of better than 0.1 arcsec.

Fine Guidance Sensors – Sensors are needed to maintain accurate and stable pointing with long integration times for all locations on the sky for large UV, visible, and IR/submillimeter telescopes. The most advanced visible fine guidance sensor today has an accuracy of 0.003 arcsec, uses a visible star catalog, operates at relatively warm temperatures, and has a very narrow capture range (i.e., about 0.02 arcsec). Development efforts are recommended to advance the state of the art by more than an order of magnitude in accuracy (to 0.0001 arcsec) and to increase the capture range to 60 arcsec. Continued development of cryogenic visible fine guidance sensors for missions like the SIRTF is urged along with the development of an accurate star catalog in the UV/VIS/IR.

Attitude Transfer Devices – Devices are needed to relay attitude information between components, such as the main telescope and an auxiliary star tracker, bypassing the dimensional instabilities of mechanical structure. The technology of such devices is currently at an immature stage of development. Prototypes that have been built are accurate to approximately 1 µrad and have poor control of thermal radiation leakage across the interface. Both the Air Force Weapons Laboratory (now Phillips Laboratories) and the Charles Stark Draper Laboratories have (or had) state-of-the-art development programs at the breadboard stage. The development of attitude transfer devices with nanoradian accuracy and very low thermal and radiation leakage is recommended.

Inertial Attitude Sensors – Sensors are needed to relay attitude information in time to allow pointing in areas where there are no suitable reference stars. Future missions demand very stable inertial attitude sensors. The panel recommends the development of gyros capable of better than 0.0001 arcsec bias stabilities and lifetimes of greater than 15 years.

Table 9. Pointing and Attitude Sensing and Control Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Star Trackers	Resolution : 1 as Ground Commanded	Resolution : < 0.1 as Autonomous Star Trackers	'94, '96	'93- -'96
Fine Guidance Sensors	Resolution : 0.003 as Visible Guide Stars Warm Focal Plane Very Narrow Capture Range (i.e., ≈ 0.02 as)	Resolution : ≤ 0.0001 as Cryogenic, Visible Fine Guidance Sensor Accurate UV-VIS-IR Correlated Star Catalog Wide Capture Range : > 60 as	'94, '96, '10	'93 - '10
Attitude Transfer Devices	Accuracy : 1 mrad Poor Thermal and Radiation Leakage Control	Accuracy : 10 nrad Negligible Thermal and Radiation Leakage	'94, '96	'93- -'96
Inertial Attitude Sensors	Drift : 0.003°/hr Lifetime : 10 years	Drift : < 0.0001°/hr Lifetime : > 15 years	'97, '10	'93 - '10
Attitude Actuators	Peak Torque; 0.82 N-m Momentum Cap: 264 N-m-s Torque Ripple: 0.02% Emitted Force Vib: 0.5 N Emitted Torque Vib: 0.1 N-m	Peak Torque; 82 N-m Momentum Cap: 26400 N-m-s Torque Ripple: 0.002% Emitted Force Vib: 0.05 N Emitted Torque Vib: 0.01 N-m	'97, '10	'93 - '10
Fine Pointing Mirrors	Moderately Compensated Steering Mirrors Non-Cryogenic	Large Diameter, Projected Center of Rotation, Highly Compensated Steering Mirror, Space Qualifiable Cryogenic	'95 - '05 '96, '04, '06 '96	'93 - '07

Pointing and Attitude Control – Two areas are encompassed by the pointing and attitude control technology program. These are the development areas of actuators and fine pointing mirrors.

Actuators – An improvement of two orders of magnitude in torque capability and momentum capacity, with a simultaneous improvement of at least one order of magnitude in quietness is recommended. This may be achievable by modifying existing large actuators to make them quieter (e.g., by improving bearings and balance properties, and by incorporating appropriate isolation mechanisms). Another feature that will need improvement is repeatability. High repeatability will make nodding possible without driving attitude control bandwidths, which are generally limited to about 1 Hz by control-structure interaction (CSI) and saturation avoidance concerns, to unsupportable levels. This may indeed be mission enabling. Repeatabilities of about 1 part in 1,000,000 are called for. An effort is recommended to study this issue and, if necessary, to develop ways improving attitude actuator repeatabilities to these levels.

Fine Pointing Mirrors – Line of sight or pointing error is equivalent to a tilt error in the wavefront at the telescope output. As such, the task of controlling or regulating a telescope line of sight requires a wavefront tilt sensor and a tip-tilt wavefront corrector (e.g., a tip-tilt mirror). To date, steering mirror assemblies for large mirrors have been relatively slow, massive devices, which generate rather large mechanical disturbances. High bandwidth operation and momentum compensation has only been achieved in small mirror assemblies (i.e., on the order of 2 inches across). In either case, the center of rotation in current technology devices is near the center of mass of the mirror, a point that is generally sub-optimal from an optical performance point of view. This panel therefore recommends that efforts be applied toward the development of highly compensated (i.e., better than 99% in all degrees of freedom) steering mirrors assemblies with projected centers of rotation. The effort should include technology for large mirrors (i.e., on the order of 1 m) as well as small mirrors. It should also produce technology for cryogenically cooled mirrors needed for missions in the infrared.

LASER METROLOGY

A. Technology Assessment

Laser metrology is the most widely applicable of the technologies considered by the panel. It plays a role in implementing capabilities in active optics, active interferometry, pointing and attitude sensing, and structures control. It is also important for ultra-accurate ranging within a constellation of instrumented spacecraft.

In active optics, laser metrology may play a role in the two stage approach for wavefront maintenance. However, for advanced single stage techniques, laser metrology is essential. This requires absolute measurements over distances of the order of tens of meters with an accuracy of better than 50 nm. In addition, it requires innovations in transferring the metrology measurements and knowledge about the wavefront originating from the science object. Some work on single stage techniques using lasers has been performed in the NASA's Precision Segmented Reflector program but no demonstration has been performed.

In active interferometers, laser metrology is critical to monitoring the interferometer baseline and internal optical paths, which is important for precise astrometric measurements in particular. Tolerances on the order of 10^{-3} μm over distances of 10 to 100 m are required for imaging interferometers and absolute ranging is also required. The tolerances will be tighter for an active astrometric interferometer (e.g., AIM/OSI). However, laser interferometry is also useful in interferometers that do not use active components for calibrating the interferometers internal geometry (e.g., AIM/POINTS). Here the requirement is 20 pm accuracy and accurate transfer of the metrology measurements to the science wavefront. Innovative homodyne techniques have been developed and laboratory measurements have now shown <20 pm consistency between two lasers over the same path. However, these demonstrations are far from the demonstration of a complete system.

In pointing and attitude sensing, laser technology may be exploited in new technologies for inertial pointing using the Sagnac effect and in attitude transfer devices.

In structures control technology, laser metrology is important in sensing and verification. Laser metrology is planned for verification of ground demonstrations in the NASA's Control Structure Interaction program. Deployment on complex three dimensional structures is generally a required part of implementing laser metrology in support of the other three technologies.

A final application is ranging between spacecraft in a constellation. This is important in the Imaging Interferometer implemented with the VISTA approach and for gravitational wave detection with the Laser Gravity-Wave Observatory in Space (LAGOS) mission.

B. Development Plan

Technology needs have been classified into four areas: laser sources, fiducial references, active components, and innovative metrology architectures.

Laser Sources – the requirement on laser sources for the variety of applications considered here are quite diverse. For most applications, the power requirements are modest; as in most other respects, the LAGOS application is an exception. Frequency stability is a critical property in almost all applications. For the near term astrometry missions, the frequency stability requirements are best defined with AIM/OSI and AIM/POINTS having similar requirements of $\sim 10^{-10}$.

Recent work on the development of lasers for AIM/OSI and AIM/POINTS has confirmed the feasibility of being able to use lasers for ultraprecise distance measurements using a variety of approaches (see Figure 11). However, while certain laboratory lasers, such as a HeNe laser with an iodine absorption cell, can meet the required stability, such

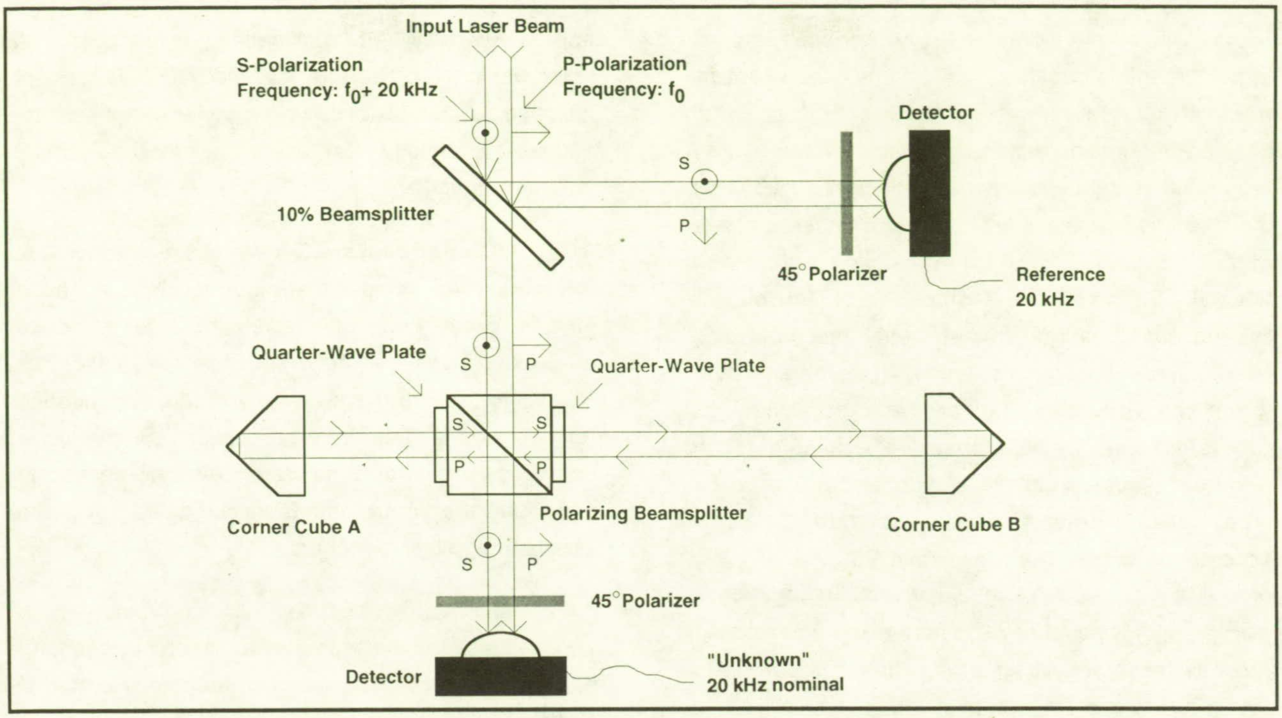


Figure 11. Point-to-Point Laser Metrology Using a Dual-Frequency Heterodyne Technique. (Courtesy of Mark Colavita.)

systems cannot be readily space qualified, are limited in optical output, and consume significant power. High efficiency diode-pumped solid-state lasers are far more promising for space applications. The immediate need is for the development of a suitable stabilization scheme for the solid-state laser, and the packaging into a low-mass, low-power package for space qualification.

For absolute distance measurements, tunable lasers are required. However, the tuning must be precise, either instantaneously, or else between well known frequency markers. In addition, the larger the tuning range, the higher the absolute range accuracy. Current techniques using tuned dye lasers have both insufficient accuracy and are not feasible for space applications. Thus a goal for the program is the development of tunable solid state lasers, with similar stability (or frequency knowledge) specifications as above; such a laser, with the tuning disabled, could also serve as the primary frequency source. The tuning range should be at least 1 part in 10^{-5}, which should allow 10–100 mm absolute accuracies over ranges of ~10 m. With a greater tuning range, absolute metrology to ~1 mm may be possible, which would resolve all ambiguities in a relative metrology system.

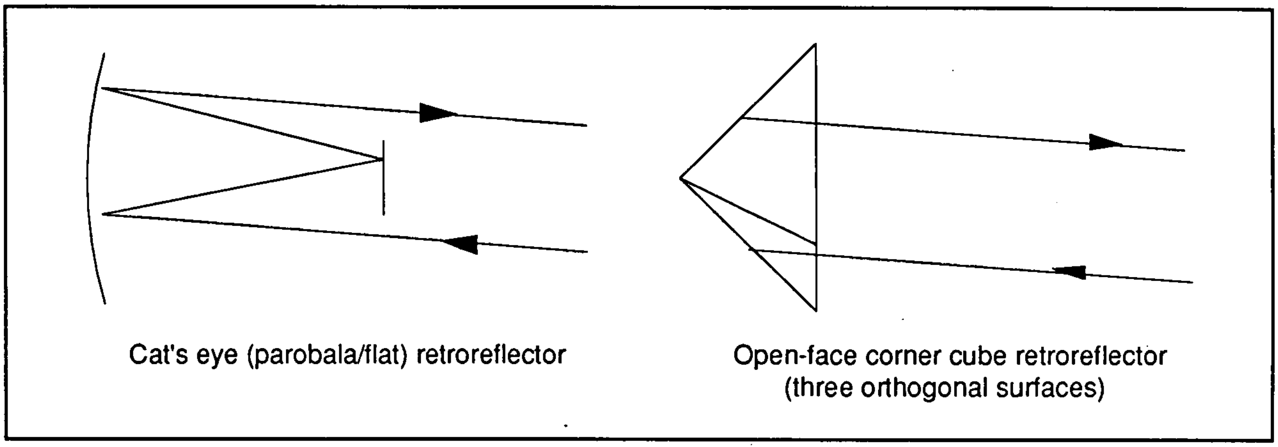
For both relative and absolute distance measurement, packaging of the metrology interferometers (fed from the stabilized laser) will be important. Many metrology system designs require clusters of beam launchers with accurate and stable pointing. Manifolds of beam launchers are currently just a glimmer in the eyes of large optical system designer, and existing hardware is little more than massive assemblies of individual beam launchers. Much work is needed to demonstrate small low mass manifolds. Beam launchers that provide beams tailored to the configuration of the fiducial references will also be needed, but the exact specifications of these devices await specifics on the system design.

Fiducial References – In order to use lasers to perform accurate metrology, fiducial references that define the geometry to be monitored are required. Retroreflectors represent one class of fiducial reference. Although they only generate point to point range information, they can be used in optical truss structures to determine three dimensional position information within the optical system. Key requirements on metrology retroreflectors include that the measured pathlength be invariant under rotations of the fiducials and beam translation across the fiducial. To minimize restrictions on the overall system configuration, the retroreflectors must also have a wide acceptance angles (i.e., angles over which they operate efficiently and accurately as retroreflectors). Devices that are available today (Figure 12 shows cat's eye type and corner cube type) are characterized by relatively narrow acceptance angles (i.e., less than 90 deg) and low precision (i.e., about 0.1 μm). The panel recommends a program of concept development and manufacturing process technology to improve these properties to over 120 deg and 1 nm respectively for applications in optical truss structures. Retroreflectors in innovative configurations have been conceived for specialized applications such as AIM/POINTS, which uses a complex corner cube structure (Figure 13).

Fiducial references for mirrors are also needed. For active optics systems using single stage wavefront sensing, retroreflectors within the primary mirror will be needed. Holographic approaches may have applications in this case. A holographic filled-aperture metrology (FAM) concept has also been investigated for transfer of the science and laser metrology reference frames for the POINTS interferometer.

Components – Certain active components will be needed in laser metrology systems. These include Bragg cells or Pockels cells to introduce modulation necessary for frequency stabilization, as well as to provide the frequency modulation needed for heterodyne metrology schemes. Single-mode fiberoptics and fiber couplers also will be needed to distribute the metrology laser signal among the various metrology launchers.

Innovative Metrology Architectures – New approaches and new design tools are needed for putting together the elements of metrology systems. Optical truss configuration design, for example, is currently done by trial and error. The design objectives include maximum observability of degrees of freedom, minimum sensitivity to parameter uncertainties, minimum number of individual beams, avoidance of obscurations, and satisfaction of component placement restriction (e.g., due to stray light and thermal consideration) thus the design



Cat's eye (parobala/flat) retroreflector

Open-face corner cube retroreflector
(three orthogonal surfaces)

Figure 12. Cat's Eye and Corner Cube Retroreflectors. (Courtesy of Mark Colavita.)

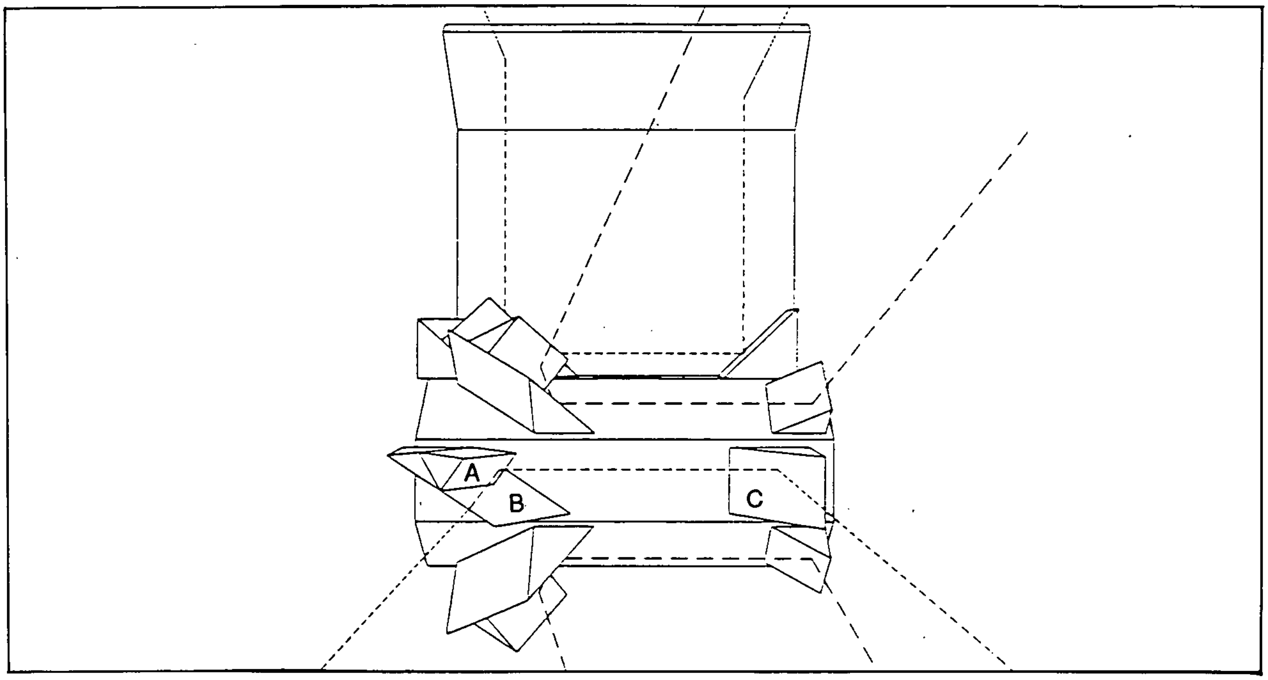


Figure 13. AIM/POINTS Retroflector Assembly (Courtesy of Mark Colavita.)

problem is a multiobjective constrained optimization. Computer-aided design tools are needed to streamline the design process and, more importantly, to allow true optimal designs to be produced.

Table 10 summarizes the laser meterology technology area.

STRUCTURES - CONTROL TECHNOLOGY

A. Technology Assessment

As the optical system size increases to 4 m and beyond, and the precision of these systems increases by 10 to 100 times that of the Hubble Space Telescope, precision lightweight structures of a kind never employed before will be required. These structures will be needed for filled aperture telescopes, partially filled-aperture telescopes, and interferometers. The materials will need to be very lightweight with very low coefficients of thermal expansion. The stiffness, damping, and dimensional stability of these structures will have to be actively controlled to achieve the nanoradian pointing stability and nanometer positioning accuracy needed after a system slew, and to compensate for the thermal effects of the space environment. These structures will also be very susceptible to vibration from onboard disturbances. This is an area where, due to complex non-linear control systems and control system interaction, a testbed is essential to prove the technology feasibility down to optical tolerances and validate models for system design. Table 11 summarizes previous flight system capabilities and the future direction of structures control.

Table 10. Laser Metrology Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Laser Sources	Tunable Lasers: Prototype Units Frequency Stabilization: Lab Demos Large and Massive Beam Launcher Manifolds	Tuning Range: 1 part in 10^5 Frequency Stability: 10^{-10} Low Mass Manifold Designs	'97, '08	'93 - '10
Fiducial References	Narrow Acceptance Angle : < 90° Precision: 0.1 mm	Wide Acceptance Angle : 120° Precision : 1 nm Rotation Invariance Beam Translation Invariance	'97, '08	'93 - '10
Active Components	Temporally Unstable Bragg Cells Temporally Unstable Optical Fibers	Stable Space Qualified Bragg Cells Stable Space Qualified Optical Fibers	'97, '08	'93 - '10
Innovative Metrology Architectures	Ad Hoc	Metrology System Optimization Tool Optical Truss Design Tool	'97, '08	'93 - '10

Table 11. Previous, Current, and Planned Structures Control Capabilities

TECHNOLOGY AREA	PREVIOUS FLIGHT SYSTEMS	HUBBLE SPACE TELESCOPE	CURRENT TECHNOLOGY	LOW LEVEL DEVELOPMENT PROGRAM		AGGRESSIVE DEVELOPMENT PROGRAM	
				5 years	10 Years	5 years	10 Years
ACTIVE STRUCTURE CONTROL	NONE	NONE	Ground Testbeds Local Feedback Low Authority (10 dB Vibration Suppression)	Ground Testbeds Global Feedback Mod. Authority (20 dB Vibration Suppression)	Ground Testbeds Global Feedback Limtd. Bandwidth (30 dB Vibration Suppression)	Flight Ready Global Feedback Mod. Bandwidth (40 dB Vibration Suppression)	Flight Proven Global Feedback Wide Bandwidth (60 dB Vibration Suppression)
PASSIVE STRUCTURAL DAMPING	Galileo - Single Viscous Damper for Mag Boom	NONE	Viscoelastics- Temp. Sensitive, Nonlinear (10 dB Vibration Suppression)	Ground Testbeds Distributed Viscous Dampers	Ground Testbeds Improved Viscoelastics (20 dB Vibration Suppression)	Viscous struts flight ready (30 dB Vibration Suppression)	Viscoelastics flight ready (30 dB Vibration Suppression)
ACTIVE MEMBERS	NONE	NONE	Ground Testbeds 50 mm Stroke Signif. Hysteresis	Ground Testbeds 50 mm Stroke Mod. Hysteresis	Ground Testbeds 100 mm Stroke Slight Hysteresis	Flight Ready 100 mm Stroke High Linearity	Flight Proven 1 - 10 mm Stroke High Linearity
VIBRATION ISOLATION	Hubble passive RW isolator	Passive/ Viscous (10 dB Isolation)	Passive (10 dB Isolation)	Passive/Active (15 dB Isolation)	Active/Passive (20 dB Isolation)	Tuned Active (40 dB Isolation)	Tuned Active (60 dB Isolation)
OPTICAL ELEMENT ARTICULATION CONTROL	Secondary Mirror Angular Articulation on STS-borne Telescope (200 Hz Bandwidth)	NONE	Flight Proven Mod. Bandwidth (200 Hz) Angular Articulation Ground Testbeds Translational Control (300 Hz)	Ground Testbeds Improved Bandwidth Translational Control (1 kHz)	Ground Testbeds High Bandwidth (2 kHz) 90% Reactionless Actuation	Flight Ready High Bandwidth (5 kHz) 99% Reactionless Actuation	Flight Proven Very High Bandwidth (10 kHz) Adv. Dig./Analog Implementation
SIMULTANEOUS STRUCTURE CONTROL OPTIMIZATION	NONE	NONE	No Capability	No Capability	Ground Testbeds 10% Weight Savings At Nominal Perf.	Flight Ready 20% Weight Savings At Nominal Perf.	Flight Proven 40% Weight Savings At Nominal Perf.
DISTRIBUTED ACTUATOR PLACEMENT	NONE	NONE	Ground Testbeds Heuristic Energy Methods	Ground Testbeds Heuristic Energy Methods	Ground Testbeds Systematic Energy Methods (10 dB Perf. Improvement)	Flight Ready Systematic Input/Output Methods (20 dB Performance Improvement)	Flight Proven Systematic Input/Output Methods (30 dB Performance Improvement)

B. Development Plan

A comprehensive structures-control technology program is recommended, with development efforts in isolation systems, damping augmentation methods, control-structure interaction suppression, modal control, smart structures, and integrated structure-control design optimization. An overview of the proposed program is shown in Table 12.

The structure of an optical system supports the optics, and thus has a central role in determining the quality of the output wavefront. It also supports the internal mechanical disturbance sources such as reaction wheels and chopping mechanisms. Structure-related wavefront errors arise because of temperature variations and gradients, mechanical vibrations and aging. As the threats are manifold, a corresponding multi-tier technology approach is recommended.

Vibration Isolation Systems – Isolation systems are needed to isolate the structure from disturbance sources and the optics from the structure. These devices must be stiff at low frequencies to preserve alignment, yet soft at high frequencies to be effective isolators. The transition must be sharp and predictable. Moreover, the properties of the device must be preserved over a wide temperature range, including temperatures below 100 K. In general, the devices must function as isolators in some degrees of freedom but must be transmissive in others. The state of the art in this technology is represented by the HST reaction wheel isolators and the Space Active Vibration Isolation (SAVI) prototypes. Advances are needed in performance and low temperature operation. Furthermore, the active techniques required for very high performance must be made practical in terms of mass, power, complexity, and reliability.

Damping Augmentation – New techniques are needed to lower vibration levels due to persistent disturbances (e.g., momentum wheel bearing rumble) and to hasten settling after transient excitations (e.g., slews). In addition, damping augmentation is required to lower structural resonance peaks, thus enabling higher control

Table 12. Structures Control Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Vibration Isolation Systems	Special Purpose Prototypes and Passive Techniques Isolation : 80 dB 1 – 1000 Hz	10 X Improvement, Low Temperature Operations Isolation : 100 dB, 0.1 – 10^4 Hz Active Techniques, Magnetic Suspension	'97, '04	'93 - '10
Damping Augmentation	Room Temperature Operations Only, None Space Qualified, Passive Techniques	10 X Improvement Low Temperature Passive and Active Damper Active Techniques	'97, '04	'93 - '10
Control Structure Interaction	Analytical Studies	Testbed Demonstrations	'97, '04	'93 - '05
Modal Control	Analytical Studies, Demonstration Under Idealized Conditions	Robustness Against Modelling Errors Modal Control System Testbed Demonstration	'97, '04	'93 - '97
Smart Structures	Breadboards Exist	Structural Shape Control Full Scale System Demonstration	'97, '04	'93 - '97
Integrated Control Structure Design Optimization	Analytical Studies	Control Structure Optimal Design Tool System Demonstration	'97, '04	'93 - '10

system (e.g., pointing system) bandwidths and hence better control system performance. Both passive and active damping treatments are currently limited to operation near room temperature, and are capable of delivering only a few percent damping. The technology is generally not space qualified. Thus, improvements are needed in performance and temperature range. Moreover, developments are needed to enable operation in the radiation environment of space for long periods. Active techniques, which promise to overcome the limitations of passive methods, must be refined in terms of reliability, low temperature operation, and operation off of low voltage power supplies, which are less susceptible to arcing than the high voltage supplies that are currently required.

Control Structure Interaction – Closed loop electromechanical control systems generally interact dynamically with the structure that supports them. This interaction may effect control system performance and may even give rise to unbounded structural resonances. A great deal of analytical work has been done on methods of preempting undesirable control structure interaction (CSI), however, no generally successful design architecture or procedure exists. Therefore, current practice relies on wide separation of control and structure bandwidths, which is obviously very limiting in terms of performance. It is recommended that support be given to the development of robust yet practicable methods of design and to the identification of appropriate control architectures for the class of problems of interest to the optical community. Furthermore, it is recommended that this work include the development of relevant system testbeds to serve as proving grounds for the technology. To provide realistic test environments for space missions, these testbeds should include high vacuum and gravity off-loading capabilities.

CSI technology is being cooperatively developed at three NASA centers: Langley Research Center (LaRC), Jet Propulsion Laboratory (JPL), and Marshall Space Flight Center (MSFC). The technology is being developed to quiet large space optics, reduce stringent design/operation constraints, and increase the probability of mission success. Quieting is achieved to the nanometer level by inserting progressive layers of passive and active structure/optical control. Each CSI layer (disturbance isolation, structural quieting, optical motion compensation) reduces critical motions by one to two orders of magnitude, enabling overall quieting factors of up to 10,000. Work on quieting microprecision structures of large space optical systems is being carried out at JPL. A precision structural actuator design has been built and a Honeywell heavy-viscous damper (D-Strut) has been adapted for precision structure control. Both have shown excellent and repeatable behavior at the tens-of-nanometer level. A microprecision component tester has been built for component and material characterization and a measurement facility has been made available to the effort. Additionally, new integrated structure/control design methods have been in development, and results from these methods have been used to design control systems for the JPL Precision Truss Testbed. Future plans include an advanced "Phase 1 Testbed" if funding can be solidified.

Modal Control – One very promising method of active structural quieting is modal control. This method attempts to regulate the natural vibration modes of a structure by extracting energy from it at fixed or adaptively tuned frequencies. As it is not restricted to applying force feedback from collocated rate sensors, it offers the potential of great effectiveness. Indeed, the method has been shown to be highly effective in analytical studies and laboratory demonstrations where the structural dynamics are well understood. What is needed in the future is improved robustness against modelling errors and demonstration in dynamically rich realistic test environments. Research is recommended on controlled structure system identification, self-tuning (i.e., multi-variable adaptive or phase locked loop) structural control, and systematic robust controller design (i.e., H_∞ or μ synthesis).

Smart Structures – By actively accommodating thermal deformations, so called smart structures can maintain their overall shape while individual structural elements undergo dimensional changes. Thus, smart structures, in conjunction with good thermal control and thermally stable materials, are required to achieve the very high levels of dimensional stability needed by future missions. To date, only breadboard components exist, and complete systems exist only as concepts. It is recommended that reliable, flight qualifiable components be developed, and that the system concept be demonstrated within a realistic testbed.

Integrated Structure Control Design Optimization - The standard practice in structure and control system design consists of individual design efforts which respond to independent requirements. Iteration between the disciplines is generally limited to mutual expressions of preferences. The stringent requirements of future space-based optical systems will require that designs eke out all the performance possible from a given system. This will make it necessary to optimize the structure, control system, and even the optics simultaneously. Such an integrated optimal design discipline is currently in the formative stage. A practical design tool is needed. Moreover, experience on representative systems is essential, and robustness on real systems must be demonstrated.

SYSTEM-CONTROL ARCHITECTURE

A. Technology Assessment

Active optics, interferometric phase control, and active structures in space represent control problems of unprecedented dimensional complexity. Most of the current work in this area is limited to theory with very little hardware verification. As the control systems become a more integral part of the payload and spacecraft, new methods must be found to detect and compensate for component failures. The control architectures must be robust enough to deal with a wide range of conditions and changes This is another critical area where a system-level testbed capable of control experiments at optical tolerances is essential. Testing control systems at these levels requires special isolated test facilities and diagnostic tools capable of interferometric accuracies.

B. Development Plan

Table 13 is a summary of the system-control architecture technology areas requiring significant advances to satisfy the Astrotech 21 mission set requirements. Each is discussed in the following paragraphs.

The large astrophysical missions in the Astrotech 21 mission set will generally require active control of optics, structures, and pointing. The level of required performance and complexity is without parallel within control system engineering practice. Existing control theory and algorithm design methods are poorly equipped to deal with this challenge. Furthermore, they do not address the unique interdependencies among optics, structures, and pointing control. New control theory and algorithm types will be needed to cope with these challenges. These developments are closely tied to, and essential for, the end-to-end simulation capability of the integrated modeling technology development effort. In particular, it is recommended that NASA's Optical System Technology program include fundamental but highly focused research on systematic design and analysis methods, adaptive control, system identification, robust control, multiobjective optimal control, and control of high-dimensional systems.

Among the specific issues that need to be addressed is the interaction between the many control loops that will be operating simultaneously. As is the case in control structure interaction, this control-control interaction can degrade performance and bring about instability. Tools for coping with this problem are nonexistent. Therefore, the committee recommends that an effort be initiated to develop methods of suppressing optics control system interactions.

Table 13. System-Control Architecture Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Theory and Algorithms	Disconnected	Systematic Design and Analysis Theory for Multi-Loop Optics Control Systems	'96, '10	'93 - '10
Control System Interaction	Non-Existent	Optics Control System Loop Decoupling Techniques	'96	'93 - '96
Computation and Processing	Multiple, Independent Serial Processors	Massively Parallel Architectures and Algorithms Neural Network Prototype Controllers	'97, '10	'93 - '10
Modeling and Simulation	Special Purpose Prototypes, Idealized	Simulation, Design and Analysis Tool for Control Elements	'96, '04	'93 - '04
Optimal Design	Non-Existent	Multi-Loop Optics Control System Design Optimization Technique	'97, '10	'93 - '10

The very high dimensionality of typical optical system control problems (i.e., hundreds to many thousands of degrees of freedom) will overwhelm the capabilities of current computational resources. The design, analysis, and real-time implementation of such system will require massively parallel architectures, algorithms, and hardware. It is recommended that the Optical System Technology program aggressively pursue these areas, including the development of neural net based controllers.

To evaluate candidate designs, end-to-end system modelling, and simulation will be essential. Although the subject of integrated system modelling is covered extensively in the Optical Systems Integrated Modeling panel report, the Wavefront Sensing, Control, and Pointing panel feels it is appropriate to point out that specific developments are necessary to model and simulate the complex control elements within large optical systems. The current sate of the art consists of special purpose idealized models and codes. This panel recommends the development of general tools (e.g., like Matrix$_x$ or the Matlab Control System toolbox) for design, analysis, and simulation of optical system control elements.

Another area in which standard control system engineering practice falls short of meeting the needs of controlled optical systems is optimal design. The modern optimal control theory is well suited to traditional spacecraft guidance and navigation problems, but contains essentially no results of direct relevance to optical systems. Research in optimal design, leading to multi-loop optics control system design optimization techniques, is recommended. Specific problems in need of attention include simultaneous optics and control design optimization (e.g., optimal trade-off between optical sensitivities and control accuracies), minimum time figure and alignment initialization, and wavefront error minimizing figure and alignment maintenance.

SUMMARY

Many of the sensing and control technologies examined by the panel are just now emerging and maturing to the point where they are serious candidates for space missions in the next 5 to 10 years. A committed effort that leverages to the greatest extent possible the government work sponsored to date can allow the technology to be available in a timely way.

The complexity of the Astrotech 21 missions and the new sensing and control technologies needed will require a growing cadre of scientists and optical engineers versed in the new interdisciplinary technologies discussed here. Educational institutions should be encouraged to add sensing and controls courses, as related to optics, to their engineering curricula.

Finally, much of the sensing technology considered by this panel will be similar to the optical manufacturing and test metrology of the future. Additionally, the control system sensors developed under this technology program may (in some form) be substituted for the metrology sensors required during the fabrication process. Coupled with the computer controlled nature of the fabrication process, these sensors will support in-process testing of optics and will enable a reduction in the manufacturing and test time required.

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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.

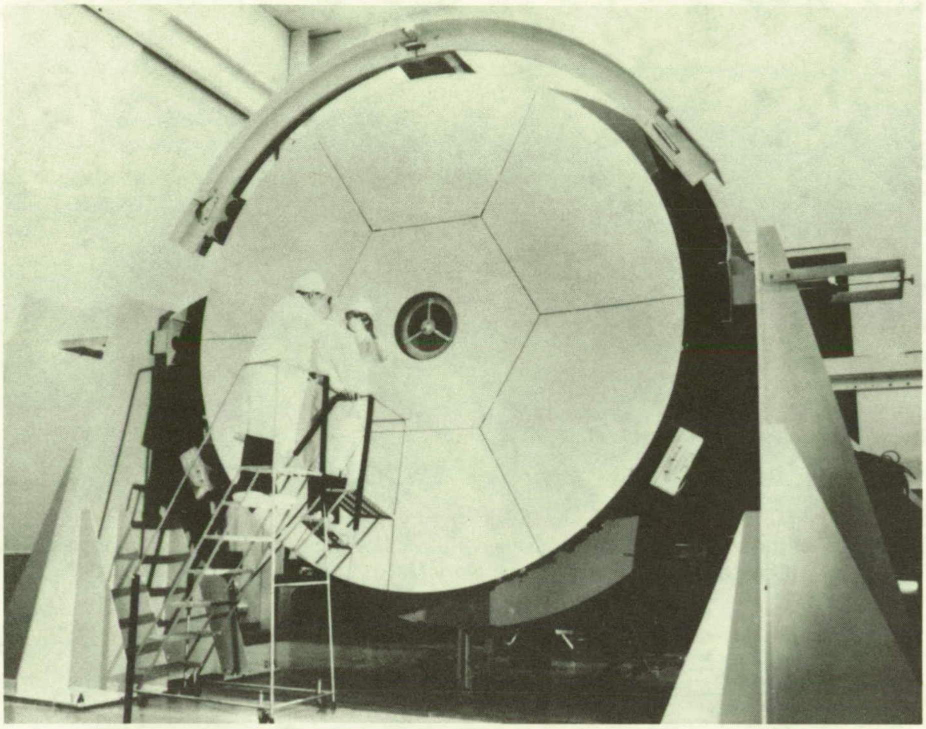


Figure 14. Large Adaptive Mirror Program (LAMP) – ITEK active segmented primary mirror (LAMP) representing a factor-of-10 reduction in weight over passive mirror technology. The active mirror can compensate for on-orbit environments to maintain optimum performance.

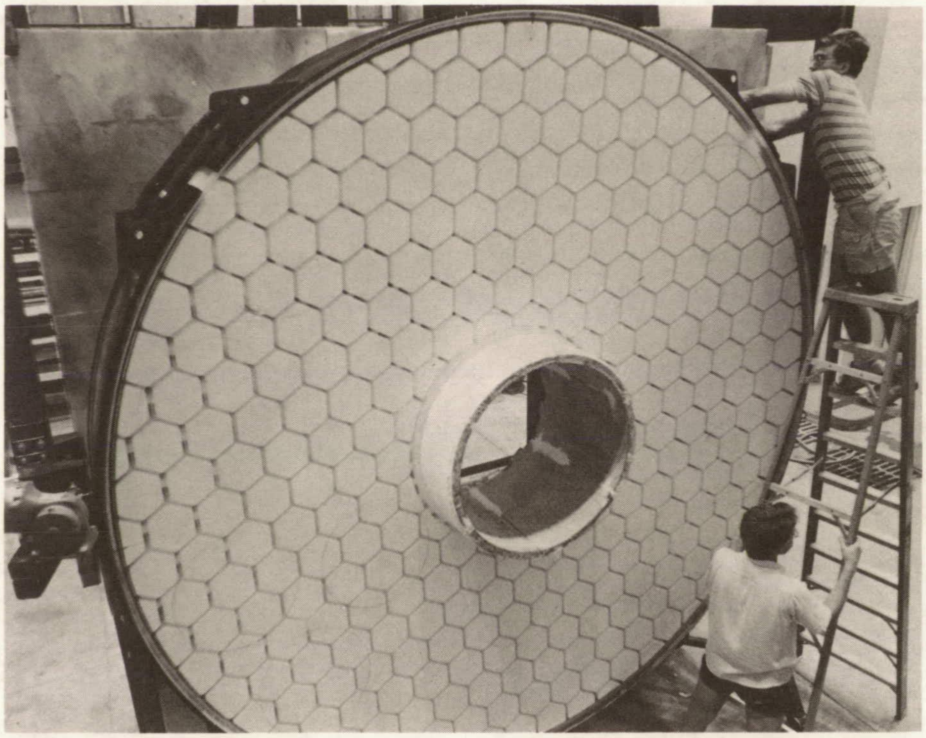


Figure 15. ARC 3.5 m Mirror – One of three 3.5-m honeycomb mirrors cast by Steward Observatory Mirror Laboratory. The fastest of these, f/1.5, is being figured at the laboratory with a stressed lap, and currently stands at 28-nm rms surface error. (Courtesy of Steward Observatory Mirror Laboratory.)

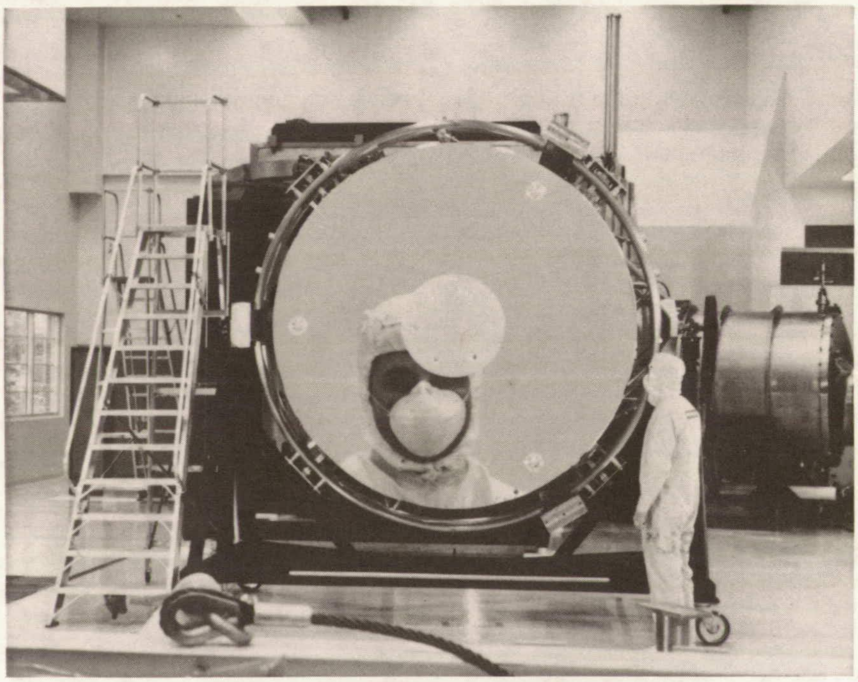


Figure 16. Hubble Primary Mirror

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 x 10^{-14}	–	5 x 10^{-16}

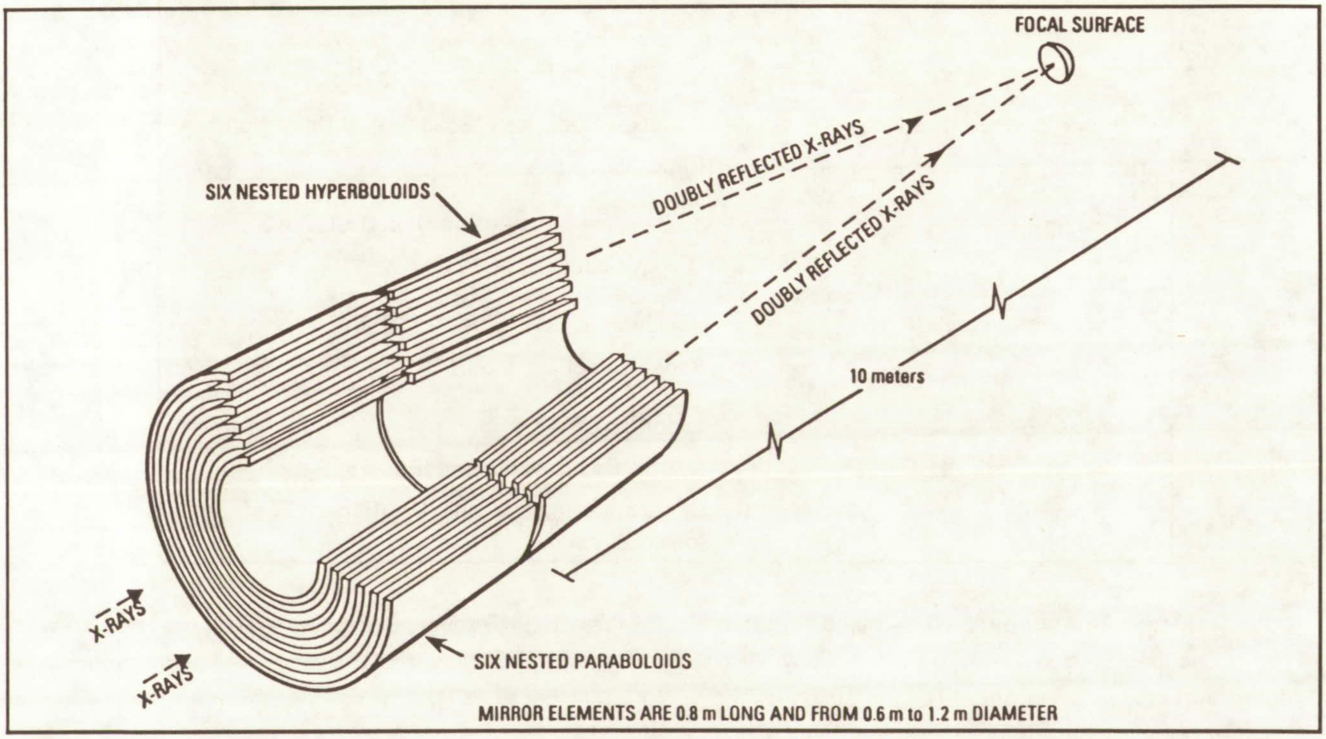


Figure 17. AXAF High Resolution Mirror Assembly (HRMA) – The HRMA consists of six nested paraboloids and six nested hyperboloids. The doubly reflected x-rays focus on a surface 10 m from the paraboloid-hyperboloid interface. Each of the mirror elements are 0.8 m long and range from 0.6 m to 1.2 m in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

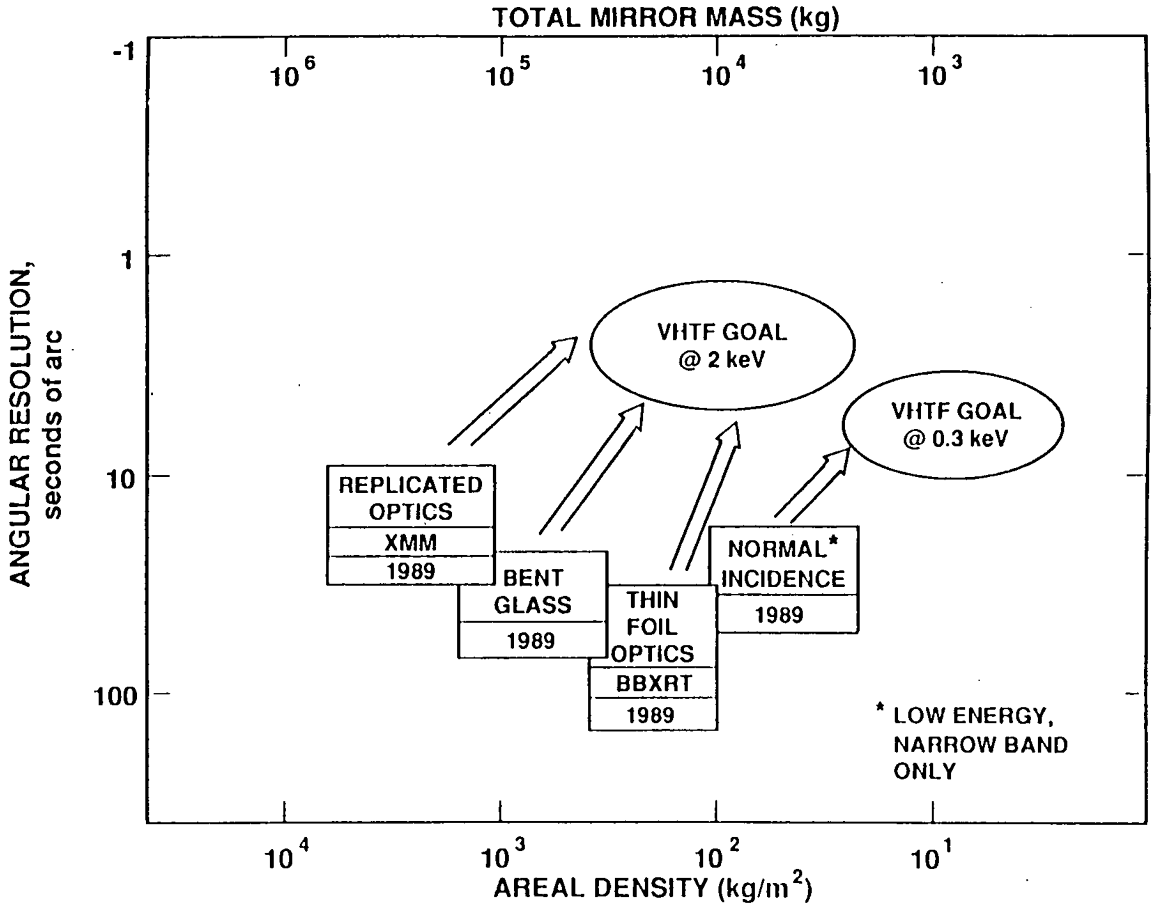


Figure 18. High Energy Requirements for Lightweight Mirror Technologies

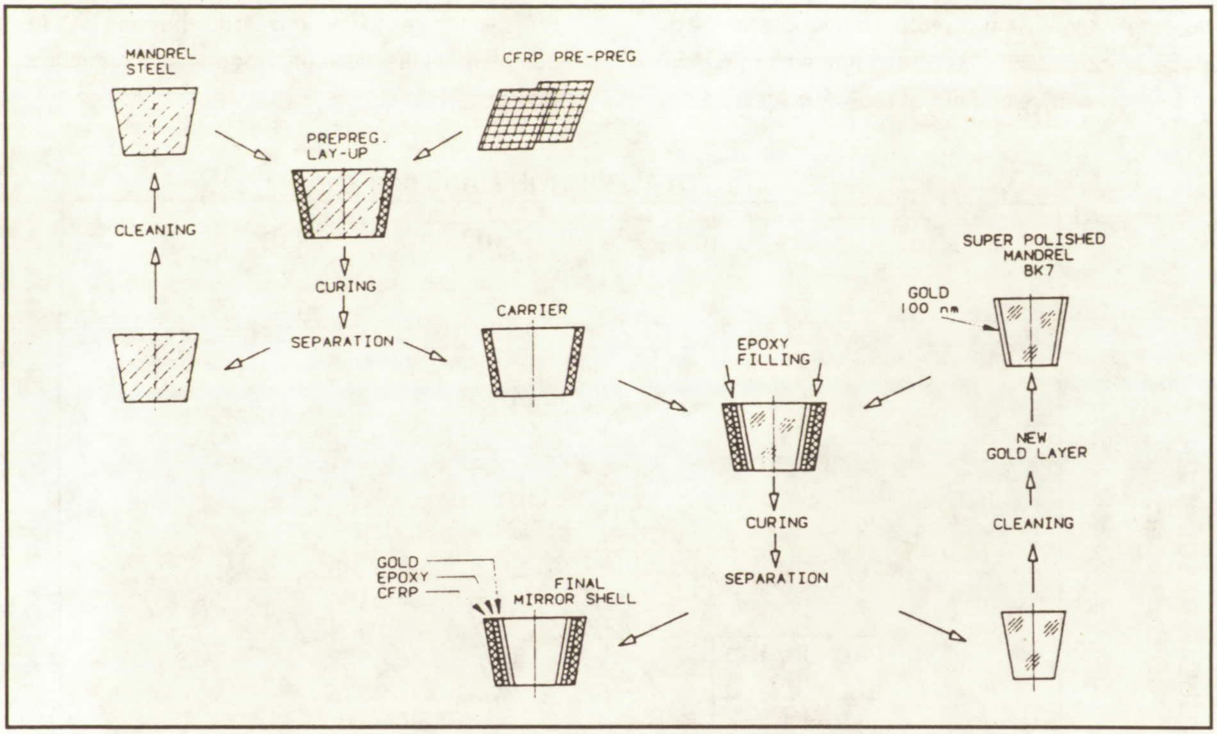


Figure 19. XMM Mirror Shell Process Diagram

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

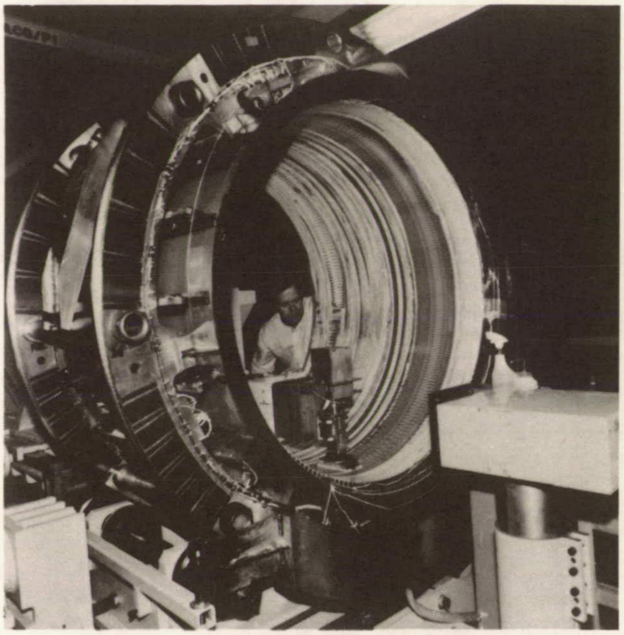


Figure 20. AXAF Parabola 1 (P1) – The P1 optic undergoes a grinding cycle on the Automated Cylindrical Grinder/Polisher (ACG/P) at Hughes Danbury Optical Systems, Inc. The manufacturing of the critical surface – the inside diameter of the cylindrical glass – is a lengthy process involving many grind/measurement 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.

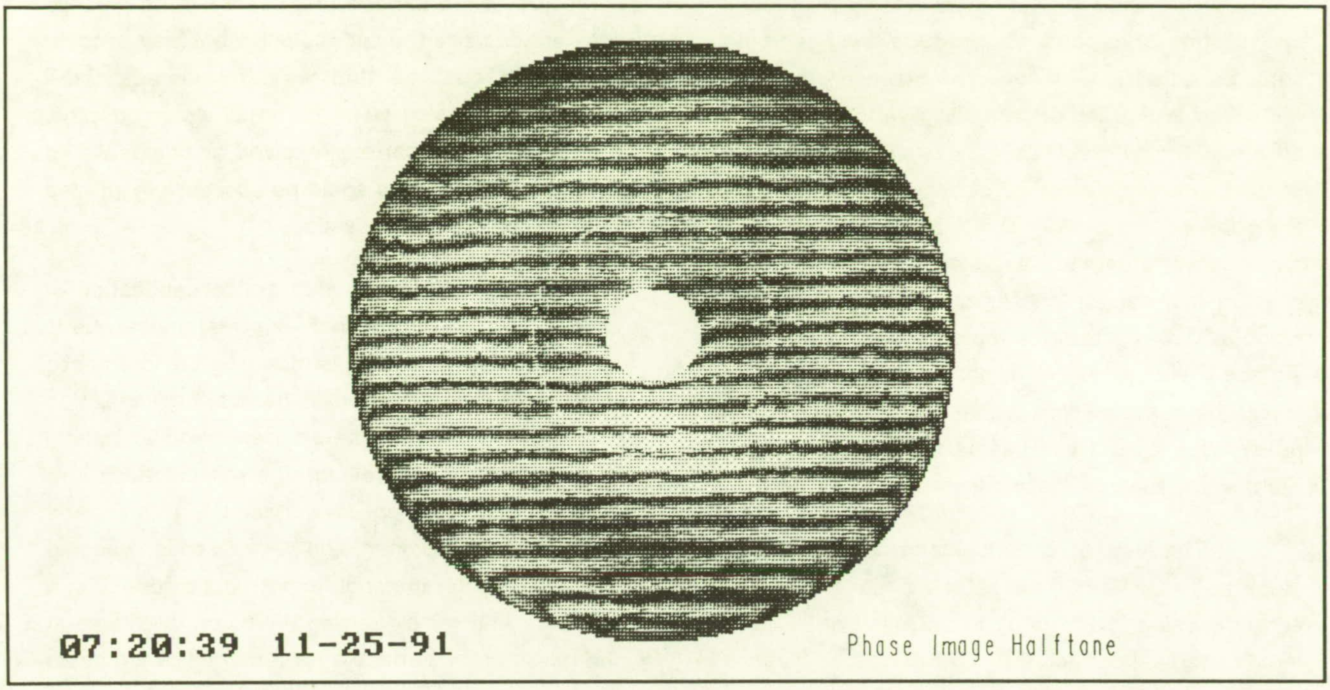


Figure 21. Test Interferogram of 1.8-m Mirror With Extremely Aspheric Figure – This is an in-process test interferogram at 633-nm wavelength of a 1.8-m f/1.0 asphere being polished by the stressed-lap method at the Steward Observatory Mirror Laboratory. The surface error is currently 18 nm rms. (Courtesy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

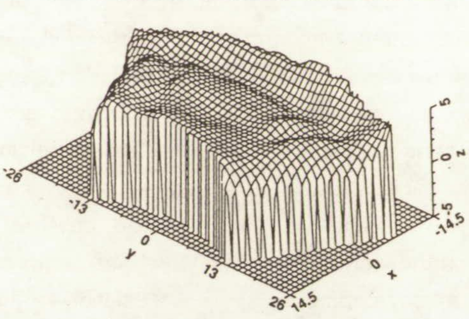
The ion figuring process offers significant advantages over current mechanical polishing processes, which ultimately allow for the final error correction of most optics to optical test limits in a few process iterations, in that:

- 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

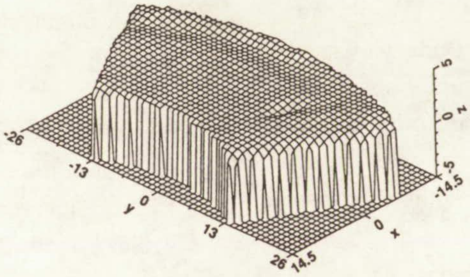
Optics with maximum dimensions of 2.5 m x 2.5 m x 0.6 m can be processed in the Kodak 2.5 m Ion Figuring System (IFS). This system is currently the only facility which has demonstrated a large optic processing capability. The IFS hardware comprises three basic subsystems: the vacuum chamber and pumping 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.

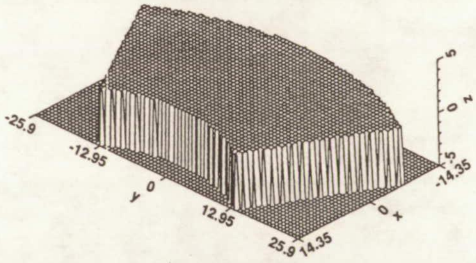
Several large, complex optical elements have been completed at Kodak during the past two years, demonstrating the full capability and utility of the ion figuring process. These include ion figuring a 1.3 m ULE™ off-axis, aspheric petal-shaped mirror and three W.M. Keck Observatory Telescope Zerodur™ 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.

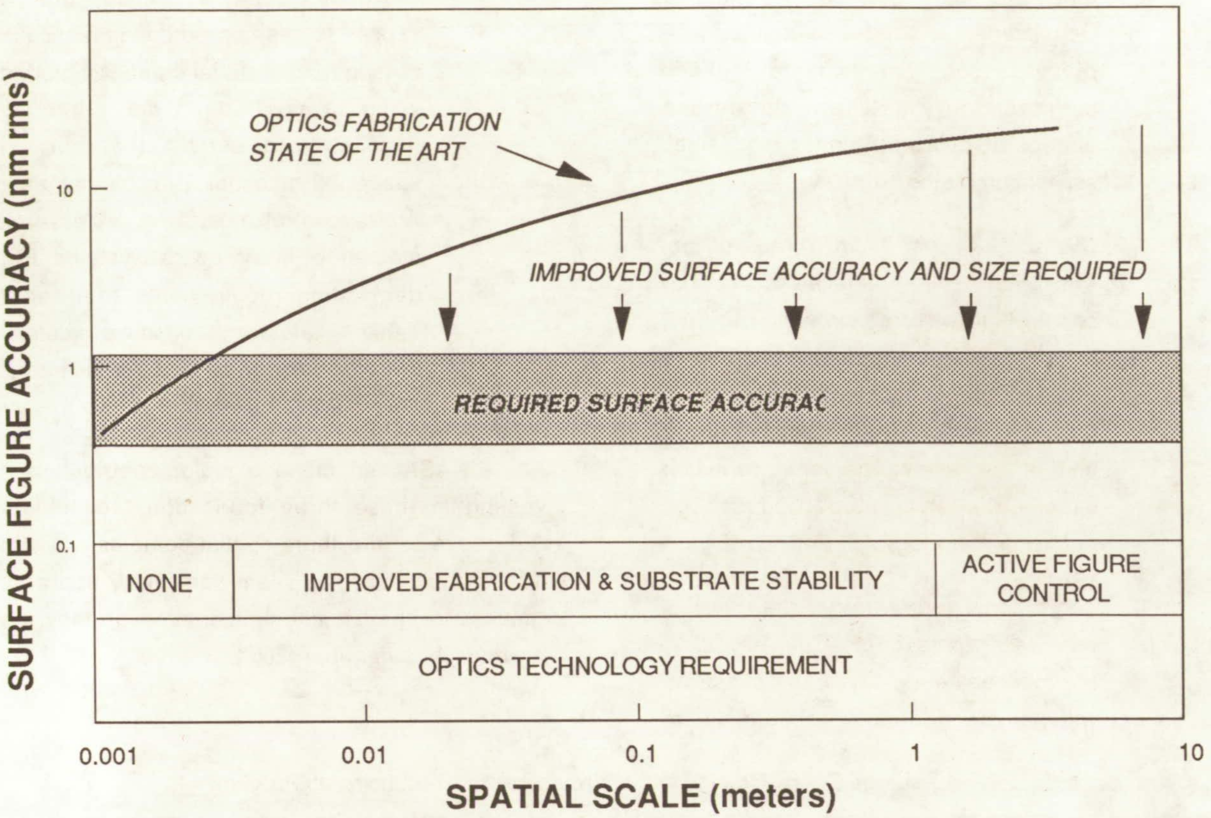


Figure 23. Technology for Surface Figuring to 1 nm rms

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.

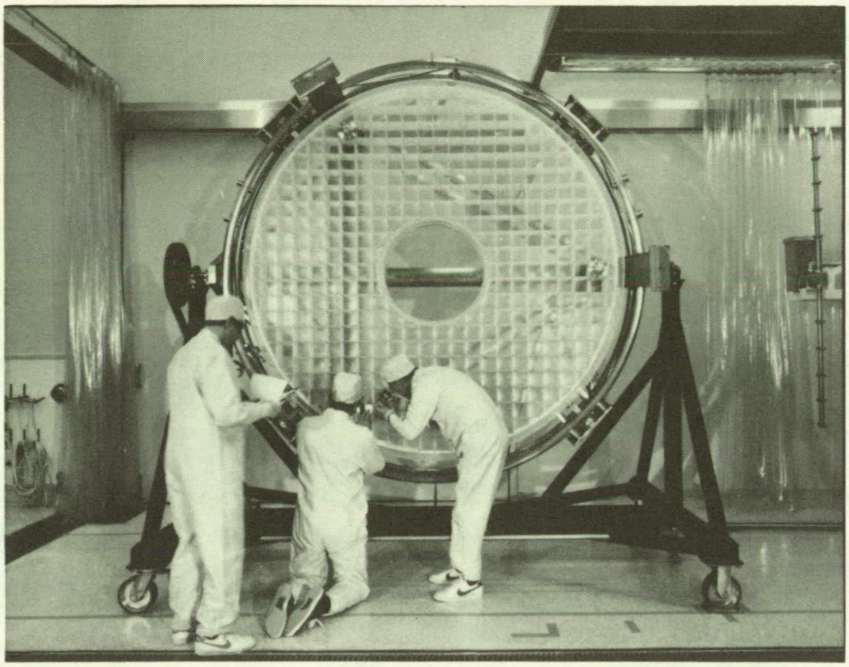


Figure 24. Lightweight 94 in. Primary Mirror – The final-polished 94 in. primary mirror is inspected prior to application of the reflective coating. The cellular hollow-cored structure of the primary mirror provides for maximum lightweighting. Solid face sheets cover the structure. During final shaping 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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Optical Systems Technology for Space Astrophysics in the 21st Century

SECTION IV (Cont'd)
WORKSHOP PANEL REPORT

3. MATERIALS AND STRUCTURES

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INTRODUCTION

Materials and structures technology covers a wide range of technical areas. Some of the most pertinent issues for the Astrotech 21 missions include dimensionally stable structural materials, advanced composites, dielectric coatings, optical metallic coatings for low scattered light applications, low scattered light surfaces, deployable and inflatable structures (including optical), support structures in 0-g and 1-g environments, cryogenic optics, optical blacks, contamination hardened surfaces, radiation hardened glasses and crystals, mono-metallic telescopes and instruments, and materials characterization. Some specific examples include low coefficients of thermal expansion (CTE) structures (0.01 ppm/K), lightweight thermally stable mirror materials, thermally stable optical assemblies, high reliability/accuracy (1 μm) deployable structures, and characterization of nanometer level behavior of materials/structures for interferometry concepts. Large filled-aperture concepts will require materials with CTEs of 10^{-9} at 80 K, anti-contamination coatings, deployable and erectable structures, composite materials with CTEs < 0.01 ppm/K and thermal hysteresis, 0.001 ppm/K. Gravitational detection systems such as LAGOS will require rigid/deployable structures, dimensionally stable components, lightweight materials with low conductivity, and high stability optics.

The Materials and Structures panel addressed these issues and the relevance of the Astrotech 21 mission requirements by dividing materials and structures technology into five categories. Table 23 summarizes these categories, the necessary development, and applicable mission/program development phasing. For each of these areas, technology assessments were made and development plans were defined.

The performance of materials and structures is an integral part of the success of spacecraft and instruments in meeting their mission goals. Performance demands can range from lightweight, stable, environmentally resistant materials to unique structural designs maximizing dynamic response, stability, or minimizing weight. Advancements are continually being needed in materials and structures to meet current and future mission requirements such as increased payload, improved optical properties, improved thermal control, cryogenic temperature operation, longer lifetime, and increased reliability.

There are some recent examples of the benefits of advanced materials and structural concepts. One such example is the Hubble Space Telescope (Figure 25), which used graphite/epoxy to achieve a more stable and lightweight truss structure than would have been achieved with conventional metallic materials. With graphite/epoxy composites, the structural design can be tailored to maximize the structural performance by taking advantage of the materials' unique properties.

Materials and structures will continue to play a major role in advanced optical systems such as telescopes, interferometers, and imaging spectrometers. These systems will require ultra-lightweight materials that must often operate at cryogenic temperatures. These materials must maintain their dimensional stability to high precision, despite being exposed to a space environment characterized by low temperatures, thermal gradients, vacuum, radiation, and atomic oxygen exposure (in Earth orbit).

Advanced composite materials for structural components and reflector substrates can greatly reduce the amount of thermal expansion and structural weight. Advances are being made in designing and processing graphite/epoxy composites for low cost, lightweight reflector panels (Figure 26) for large astronomical facilities such as LDR, as well as for a variety of optical benches and other elements of advanced optical systems. However, there remain many challenges in developing these materials to the point where they are ready for space applications. New materials could also revamp the approach to the structural design of composite parts.

Advanced coatings are essential to optimized systems performance are and minimized environmental effects. Coatings contribute in many ways including environmental and impact protection as well as radiation handling capabilities for optical performance. Understanding the operational environment for the Astrotech 21 missions is important in order to provide the best protective systems for each instrument.

Table 23. Required Materials and Structures Technologies for Astrophysics Missions : 1992-2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Vacuum Coatings	Develop the Techniques for Reliable (Survivable, Durable, Stable) Coatings for Mirrors, Filters, and Thermal Control	New High Performance Materials Microstructure Engineering Large Area Processes Advanced Deposition Technologies Improved Characterization Technologies	NGST LAGOS MOI SIRTF LDR AXAF	'02 '08 '97 '92-'94 '01 '90
Materials Science and Engineering	To Develop, Characterize, and Demonstrate Materials, Test Methods and Predictive Models for Astrophysics Missions	Dimensional Stability Measurements Dimensionally Stable Materials Cryogenic Materials Coatings Interfaces, Joints, Contact Surfaces Novel Materials	All	'95, '98, '00 '95, '98, '06 '99, '01, '98, '02 '98, '00 '98, '00 '98, '06
Environmental Protection	Test Materials and Structures In a Simulated Space Environment Develop Specifications for Flight Qualified Hardware Monitor and Maintain Optical Performance In Space	Contamination Control of Materials and Processes Cryogenic Testing Metrology Ground-Based Simulations Early Warning Contamination/Degradation Monitoring	All	'00, '05 '00, '05 '00, '05 '05, '10 '00, '05
Reflector Substrates	Develop Reflectors With Low Areal Density, High Surface Accuracy, Smoothness, Size, Shape, and Optical Stability at Desired Wavelengths and Operating Temperatures	Materials/Processes For Precision Mirror Replication Optically Stable Materials and Designs Large Area Segments and Monolithic Mirrors Active/Adaptive Optics Materials and Techniques for Efficient High Precision Figuring and Polishing Lightweight Materials for Large Mirrors	XST VHTF LTT MOI FFT NGST SIRTF' SMIM LDR OVLBI Interferometers	'95 '03 '95 '97 '04 '02 '94 '96 '01 '00 '05
Structures	Develop/Verify Structures and Mechanisms for Precision Erection, Alignment, and Control Large Scale Micro-Dynamics Structures Breadboard and 6 to 8 m 50 kg/m^2 Mirror Structural Model	Advanced Dynamics Modeling Noise Transmission and Dynamic Response Prediction Capability Dimensional Repeatability Prediction and Tests Highly Stable Structures Design and Verification Substrate Automatic Deployment and Alignment	NGST LTT LDR SMIM AIM	'02 '95 '01 "96 '97

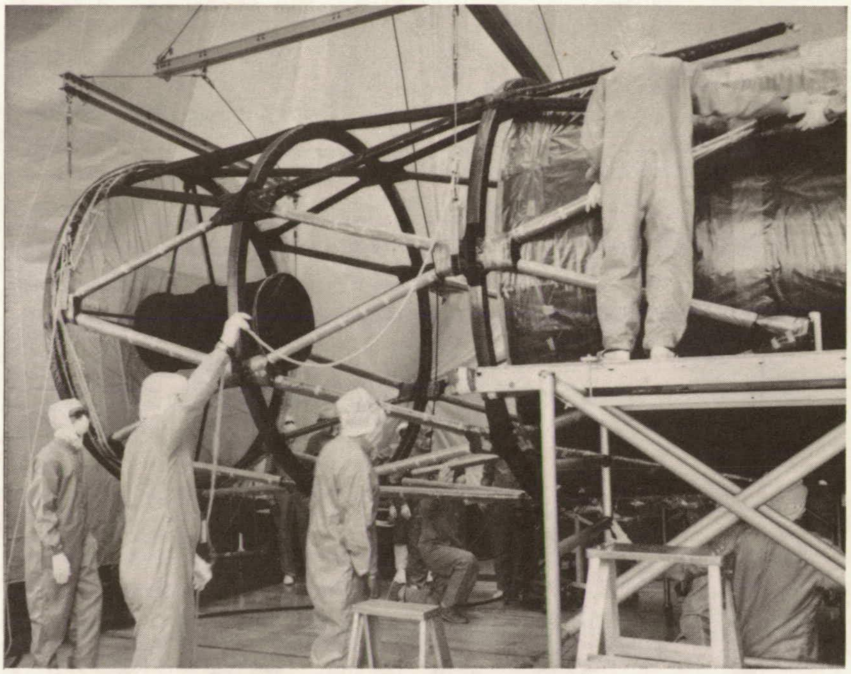


Figure 25. Hubble Metering and Focal Plane Truss Structures

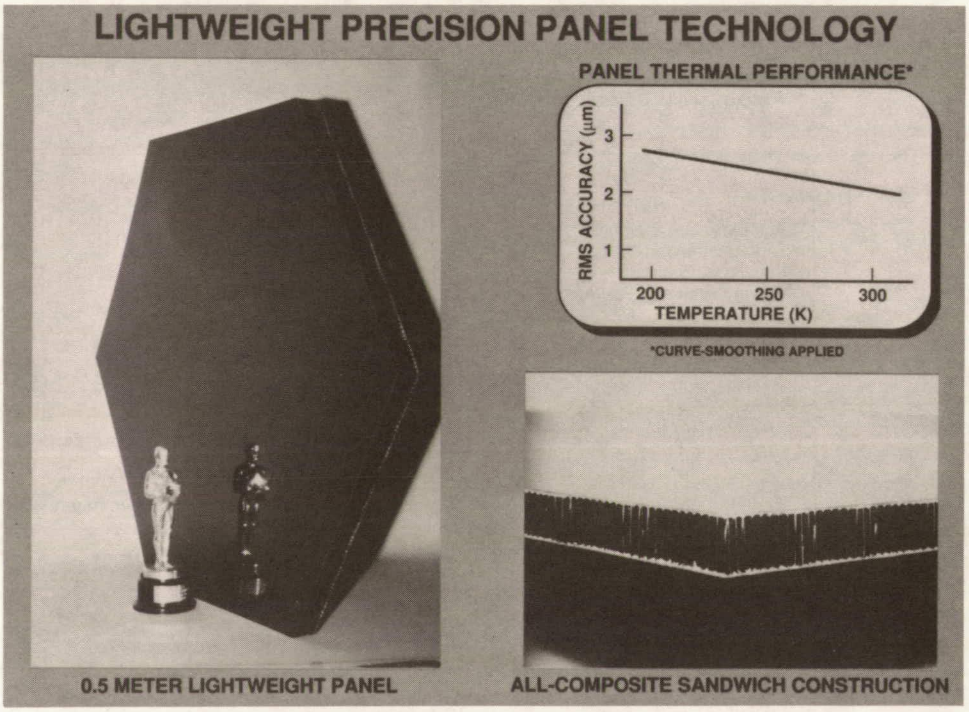


Figure 26. Composite Reflector Panels – Composite panels developed in NASA's Precision Segmented Reflector (PSR) Program. (Courtesy of Rick Helms.)

VACUUM COATINGS

A. Technology Assessment

Vacuum Coating is the preparation and placement of materials in thin layers. The optical and x-ray coatings necessary for the Astrotech 21 missions are characterized by performance exceeding the state of the art. Existing technology is rudimentary, application and material specific, based upon traditional techniques, and at scales less than required. Ongoing development efforts require a focused investment program along with support for new, promising techniques. Technology developments are required for fabrication of reliable coatings of all kinds (survivable, durable, stable in all relevant ways, especially with respect to temperature and chemicals) at the scale required for future missions.

B. Development Plan

The areas of technology development recommended are summarized in Table 24. The required developments for this item include new high performance materials, microstructure engineering, advanced deposition technologies, and improved characterization techniques. (Note that "Improved Characterization Techniques" has been deleted from the recommended program due to funding limitations identified after the workshop.)

New high performance materials include very thick multi-layer coatings that are built up from many thin coatings. Samples as thick as 0.25 mm in 100 mm square formats have been demonstrated in the laboratory. This program would concentrate on the development of analytic tools necessary to evaluate materials and process efficiency.

Coatings of different materials (stainless steel/zirconium in altering layers) can provide unusual properties. Fracture strengths of 700 ksi with very fine microstructure and moderate-to-low ductility can be made in the earlier deposition stages. Layers with moderate strength and moderate ductility can be deposited in later stages so that the final material is a tough "composite." (Figure 27) Super smooth substrates allow very thin, very smooth, shells for x-ray telescopes to be built. A second application is shields for micro-meteoroid impact protection. These are revolutionary concepts for very light materials with excellent and tailored properties.

Advanced deposition techniques include the improvement of methods such as ion beam, ion assisted, and ion cluster deposition. Part of the improvement will be to scale to large areas, and achieve uniformity and adhesion. The benefit of improved surface roughness from ion cluster deposition will be reflected in reduced cost (especially for pre-cleaning and pre-treatment).

Improved characterization will include using techniques such as Raman and x-ray spectroscopy for in situ diagnostics. The benefits of these improved diagnostics will include real time process diagnosis and control, and a better understanding of deposition processes.

MATERIALS SCIENCE AND ENGINEERING

A. Technology Assessment

The objective of the Materials Science and Engineering thrust is to develop, characterize and demonstrate materials, test methods, and predictive models. The five required technologies encompassed are: (1) dimensionally stable materials; (2) cryogenic materials; (3) thermal protection systems; (4) interfaces, joints, and contact surfaces; and (5) novel materials.

The dimensionally stable materials area includes the development of test methods, fundamental understanding of dimensional stability, and development of materials. In order to enhance a material's stability, accurate and meaningful three dimensional Coefficient of Thermal Expansion (CTE) measurements must be made over the applicable range of temperatures.

C-2

Table 24. Required Vacuum Coatings Technology for 1992-2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
High Performance Materials	Traditional, Simple Compounds and Metals	Develop Analytic Tools Over Material Ranges of Interest	'95, '00, '05, '10	'93 - '10
Microstructure Engineering	Rudimentary	Consistent, Tailored Thin-film Microstructures High Ductility Fracture Strength : > 700 ksi	'05, '10	'93 - '10
Local Area Processes	≈ 1 m	Coat 10 m Reflective Primary Mirror	'99, '05	'93 - '00
Advanced Deposition Techniques	Application Specific	Measurement of Thin-Film Properties at All Temperatures (including cryogenics)	'98, '00, '05	'93 - '10
Improved Characterization Technologies	Material Specific	High Optical Performance, Low Scatter, Durable Coatings Over Wide Spectral Range Resistance to Atomic Oxygen In Situ Diagnostics	'00, '10 '96	Deleted Due to Funding Profile Cap

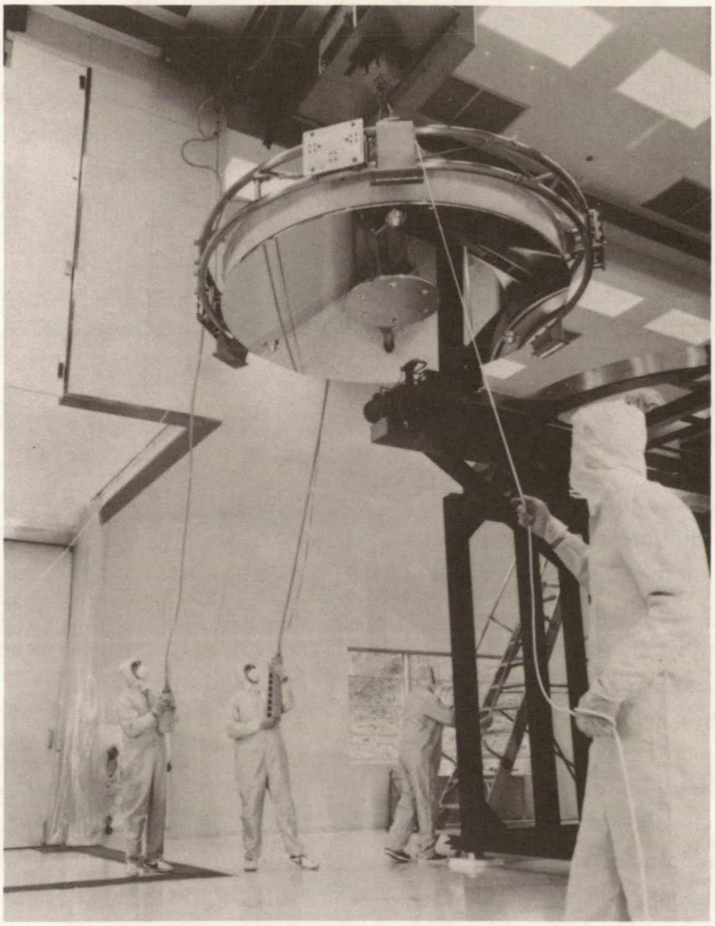


Figure 27. Hubble Primary Mirror – After being installed in a uniquely designed 14-ft diameter vacuum chamber, the primary mirror underwent a coating deposition process that took less than 1 minute. The mirror is coated with a reflective layer of pure aluminum 2.5 millionths of an inch thick. (Photo courtesy of Hughes Danbury Optical Systems.)

The more inherently stable we can develop materials, the less we need active controls on structures to meet mission goals. Stability includes both temporal and thermal. Today, we have the capability to measure CTE at the 0.01 ppm level in one direction. The best materials have a dimensional stability of 1 ppm.

Questions still exist as to materials performance at cryogenic temperatures. There is limited data at 2 to 4 K on materials and what data exists are for conventional metallic materials. The new advanced metals and composites are just now being fully evaluated at room and low (80–120 K) temperature much less at 2 to 4 K. Systems requiring operation at 2 to 4 K need both optical and structural materials to meet mission goals. Not only is a materials database needed for the design, but also such factors as insulation materials and joints are essential to the system performance.

Many of the missions require some form of thermal insulation or barrier. Improvements in these would enhance performance. Thermal blankets are typically used for insulation. Multilayer insulation films may replace some of the blanket usages today. In addition, instruments may require protection from orbital debris and micrometeorites. Protective systems such as blankets and films need further development.

The technical area of interfaces, joints, and contact surfaces encompasses many aspects of the system design and performance. Degradation of seals and elastomers is a significant issue. Compatibility of joints, coatings, thin films, reinforcements and matrix materials must be assessed for each operating environment.

The final technical area, called novel materials, provides for innovative, new developments to be included as potential materials for Astrotech 21 missions. These materials may be considered more high risk but because of their improvement potential they need to be supported. Smart materials are considered here; although they are early in their development stage they offer large payoffs in their ability to actively control structures and optical systems. Development of new materials for improvements in low density, high specific stiffness, high specific strength, and low temperature performance needs to be an ongoing effort to assure materials will meet the needs of the astrophysics future missions.

B. Development Plan

The measurement of material stability to one part per billion simultaneously in three dimensions is required, and is an enabling technology. The measurement equipment needs to evaluate materials in vacuum and cryogenic environments as well as standard room environments. Long term stability of the instrument must be guaranteed to allow slow changes in material properties to be measured. This equipment will be used to measure thermal stability, material hysteresis and thermal cycling, as well as true isotropy and homogeneity.

The dimensional stability of materials needs modeling and quantification of the physical and chemical mechanisms, particularly of composite materials and novel materials. Predictive models that accurately describe the changes of materials in a space environment over time are needed.

Cryogenic materials engineering is required to determine adequate structural materials, actuator technology, insulation materials, and low expansion/high expansion compatible joint materials. Materials that will provide mechanical damping at cryogenic temperature are also required.

Specific need dates have been identified for the five technology areas in materials science and engineering (Table 25)

Table 25. Required Materials Science and Engineering Technologies

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Dimensional Stability Measurements	1-D, at 1 ppm	Temporal Stability : 1 ppb, 3-D Thermal Stability , Hysteresis on thermal cycling : 1 ppb Isotropy and Homogeneity (Non-Destructive Measurements)	'93 - '94	'92 - '10
Dimensionally Stable Materials	CTE : 1 ppm/K, Temporal Unknown	Physical and Chemical Mechanisms Predictive Models Novel Materials/Technology CTE : < 0.01 ppm/K	'95 '98 '06	'92 - '08
Cryogenic Materials	Very Limited	Structural Materials Actuators Isolation Materials Low Expansion/High Expansion Material Joints Damping Materials	'99 '01 '98 '02 '02	'94 - '08
Coatings		Thermal Control Coatings Wavelength Selective Coatings Encapsulation/Barrier Atomic Oxygen	'98 '02 '02	'94 - '10
Interfaces, Joints, Contact Surfaces	Being Assessed	Coatings/Thin Film Interfaces, Reinforcement/Matrix Interfaces, Sliding Surfaces, Zero Gap Joints	'98 - '10	'94 - '10
Novel Materials		Smart Materials, Low Density, High Specific Strength, Stiffness, etc.	'98 - '06	Deleted Due to Funding Profile Cap

ENVIRONMENTAL PROTECTION

A. Technology Assessment

The Environmental Protection objective is to monitor and maintain performance in the presence of a hostile space environment and self-contamination from the spacecraft.

The required technologies for this thrust include controlling the contamination of (and from) materials and from fabrication processes. Material properties, such as outgassing, need to be better understood and well controlled. Fabrication processes may directly contaminate materials or make materials more susceptible to becoming contaminated.

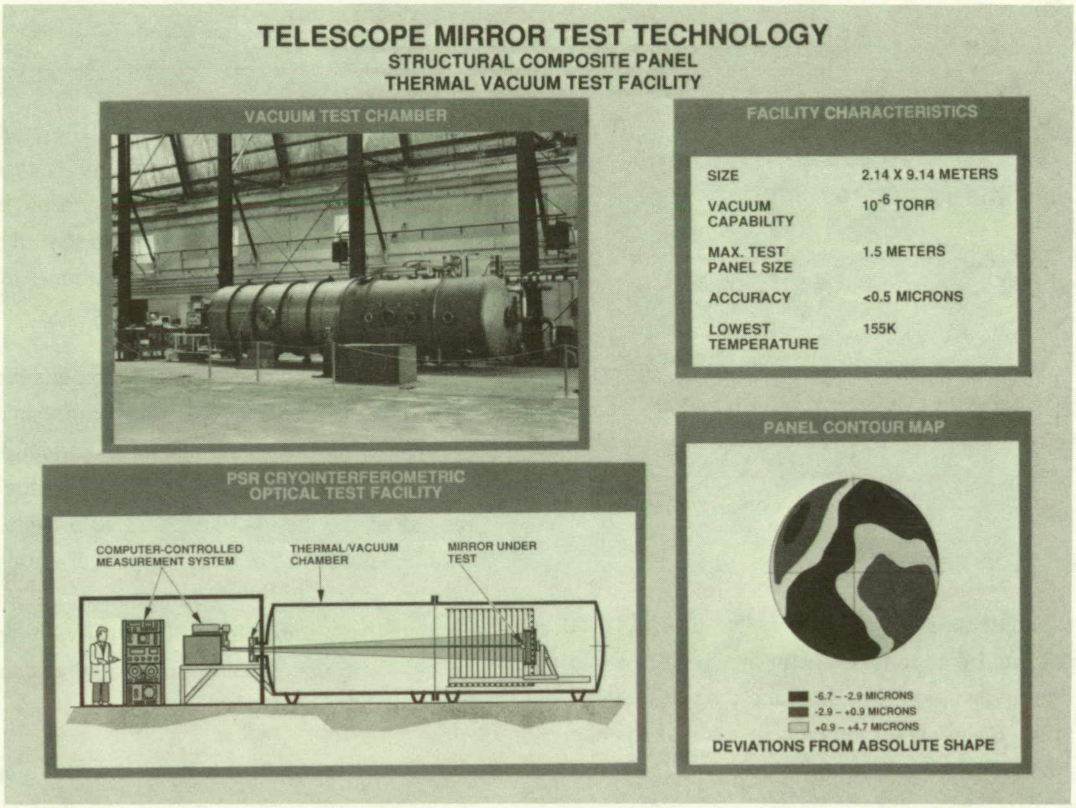
Cryogenic testing is needed to measure the effects of cryogenic cycling and cryogenic contamination. (For example, issues like "How does contamination grow?" and "How can it be removed at cryogenic temperatures?") Ground-based simulations of the space environment will provide greater insight into space contamination. Early warning of contamination coupled with degradation monitoring will be helpful in controlling contamination sources and effects in their early stages during the mission.

Technology is needed to protect exposed components from micro-meteroids, atomic oxygen, and natural space radiation. Alternative materials need to be identified. Valuable information was derived from the Long Duration Exposure Facility (LDEF). A variety of material samples placed on LDEF have been analyzed for degradation. Many of the composite samples had almost disintegrated from the atomic oxygen and radiation exposure. As new materials are developed and incorporated into instrument designs, information on materials degradation and protection must be available.

B. Development Plan

This objective has three subobjectives. First, to develop the materials to protect the hardware in a space environment. Second, to ensure that protection is adequate by testing materials and structures in a simulated space environment (Figure 28). Third, to develop protection specifications for flight qualified hardware. Metrology of contamination and environmental effects in space must also be developed.

To meet the overall objective of environmental protection, six specific tasks have been identified. The tasks and technology need dates are presented in Table 26.



SIZE	2.14 X 9.14 METERS
VACUUM CAPABILITY	10^{-6} TORR
MAX. TEST PANEL SIZE	1.5 METERS
ACCURACY	<0.5 MICRONS
LOWEST TEMPERATURE	155K

Figure 28. Thermal Vacuum Test Facility

Table 26. Environmental Protection Milestones for 1992-2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Contamination Control of Materials and Processes	Limited	Clean System Specification On-Board Contamination Removal	'97 '00	'92 - '03 '92 - '10
Cryogenic Testing	Limited	Experimental Test Facilities	'96	'92 - '99
Characterization In Space	Limited	Characterization Techniques Development	'05, '10	'92 - '10
Ground-Based Simulations of Space Environment	Limited	Design/Develop/Execute Ground-Based Experiments	'05, '10	'92 - '10
Early Warning Contamination/Degradation Monitoring	Very Limited	Design/Develop/Execute Space-Based Environmental Experiments	'05, '10	'92 - '10

REFLECTOR SUBSTRATES

A. Technology Assessment

Reflector substrates with required low area density, high surface accuracy and smoothness, size, shape, and optical stability at desired wavelengths and operating temperatures are needed to support astrophysics missions. Technology for reproducible, lightweight, optical quality substrates does not exist.

B. Development Plan

The required technologies for the reflector substrates can be summarized into five items. Table 27 lists those development items and their associated need dates. Several of the recommendations overlap with those of the Fabrication Panel. They are provided here as necessary developments identified by this panel from a materials and structures viewpoint.

The materials and processing for precision mirror replication will develop technology to provide substrates with < 5 Å rms microroughness with the appropriate optical figure. One particular milestone is a < 2 arcsec slope-error x-ray substrate in the year 2005. A second associated milestone is 10 Å rms figure replicate visible mirror by the year 2010.

The second development area is the materials and the designs for optically stable (both temporally and thermally) mirrors. The goal is, by the year 2004, to improve on the visible mirror performance of 70% encircled energy within 0.1 arcsec to demonstrate performance of >70% of encircled energy within 0.025 arcsec at the use temperature.

The third development area is substrates for active/adaptive optics. Current "smart" mirrors have many actuators with significant electrical power and weight requirements. The first milestone for this project will be, by the year 2008, to provide large stiff segments with one actuator per square meter. Then, by the year 2010, to demonstrate a mirror with actuators integrated into the mirror with significantly lower electrical requirements and a capability to operate at low temperatures.

The fourth area is the development of materials and techniques for reflector substrates, which are compatible with highly efficient fabrication techniques, to achieve the demanding accuracy tolerances. This will be a significant improvement on the many iterations required for the fabrication of current technology mirrors such as the Hubble Space Telescope primary mirror. (Technology development in this area was also identified by the Fabrication panel see Section IV, 2. Fabrication: Replicated Optics; Figuring Large Optics to 1 nm rms; Fabrication of a Lightweight, Cryogenic 4-m Mirror; and Innovative Techniques with Longer Range Potential.) By the year 2005, this project will demonstrate a high figure quality in the mid- and low-spatial frequencies and low microroughness on large areas with only a few iterations.

The fifth area is the development of lightweight mirror substrates that meet the optical figure and scattered light requirements for UV, visible, and x-ray missions. The goal is to demonstrate a 2-m diameter substrate with a 1-5 kg/m^2 areal density for x-ray, and a larger than 2-m mirror with areal density less than 20 kg/m^2 by the year 2002.

Table 27. Required Developments In Reflector Substrates for 1992–2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Materials and Processing for Precision Mirror Replication	Epoxy, Graphite/Epoxy, Electroforming, CVD	< 5 Å rms µ-roughness X-ray: < 2 arcsec Slope Error VIS: ≤ λ/500 rms (visible)	'00, '02	'93 - '10
Materials and Designs for Optically Stable Mirrors	70% Encircled Energy In 1 arcsec (visible)	Materials/Designs Achieving: ≥ 70% Encircled Energy In 0.025 arcsec (visible)	'00	'93 - '04
Large Area Segments and Monolithic Mirrors	0.1 – 2.5 m Depending on Material	X-ray: ≥ 2 m Lightweight, Identical Segment VIS: 6 – 8 m Monolith	'99, '05	'93 - '10
Active/Adaptive Optics	Many Actuators, Added-On, High Power, High Temp., Heavy	X-ray: Large, Stiff Segments, 1 Actuator/m^2 VIS: Actuators Integrated In Mirror, Low Power and Low Temp. Ops.	'02, '04	'93 - '05
Materials and Techniques for Efficient, High Precision Figuring/Polishing	Glass, Simple Figures, Many Iterations	High Quality Figure (Mid-Low Spatial Frequencies) Low µ-roughness on Large Scales With Small Number of Iterations	'98	'93 - '03
Lightweight Materials for Large Mirrors	5 –10 kg/m^2 : Graph./Epoxy, SiC 20 –200 kg/m^2 : Glass 10 – 20 kg/m^2 : Beryllium	X-ray: ≤ 2 m Dia.,1 -5 kg/m^2 UV/VIS: > 2 m Dia, < 20 kg/m^2	'02	Deleted Due to Funding Profile Cap

STRUCTURES

A. Technology Assessment

Optical positioning structures for the next century astrophysics missions will in general be larger, lighter, and more susceptible to jitter and vibration by at least an order of magnitude beyond current systems. They will be deployable, possibly augmented by remote teleoperator intervention, and need to be able to maintain the alignment between optical elements separated by tens of meters to fractional wavelength precision. (For example, single structure interferometers will require figure initialization and maintenance to better than 12 nm [visible] over 30 m baselines.) This latter requirement will be accomplished in conjunction with alignment sensing and control subsystems, at least up to their bandwidth limits. Understanding jitter and vibration beyond the bandpass of the control systems is critical to the success of this new generation of optical systems. The development of these advanced structures and the development of techniques to characterize and verify their performance in the laboratory (Figure 29) before committing them to a mission are the principal objectives of this thrust.

B. Development Plan

Before initiating these technology development programs, a comprehensive systems

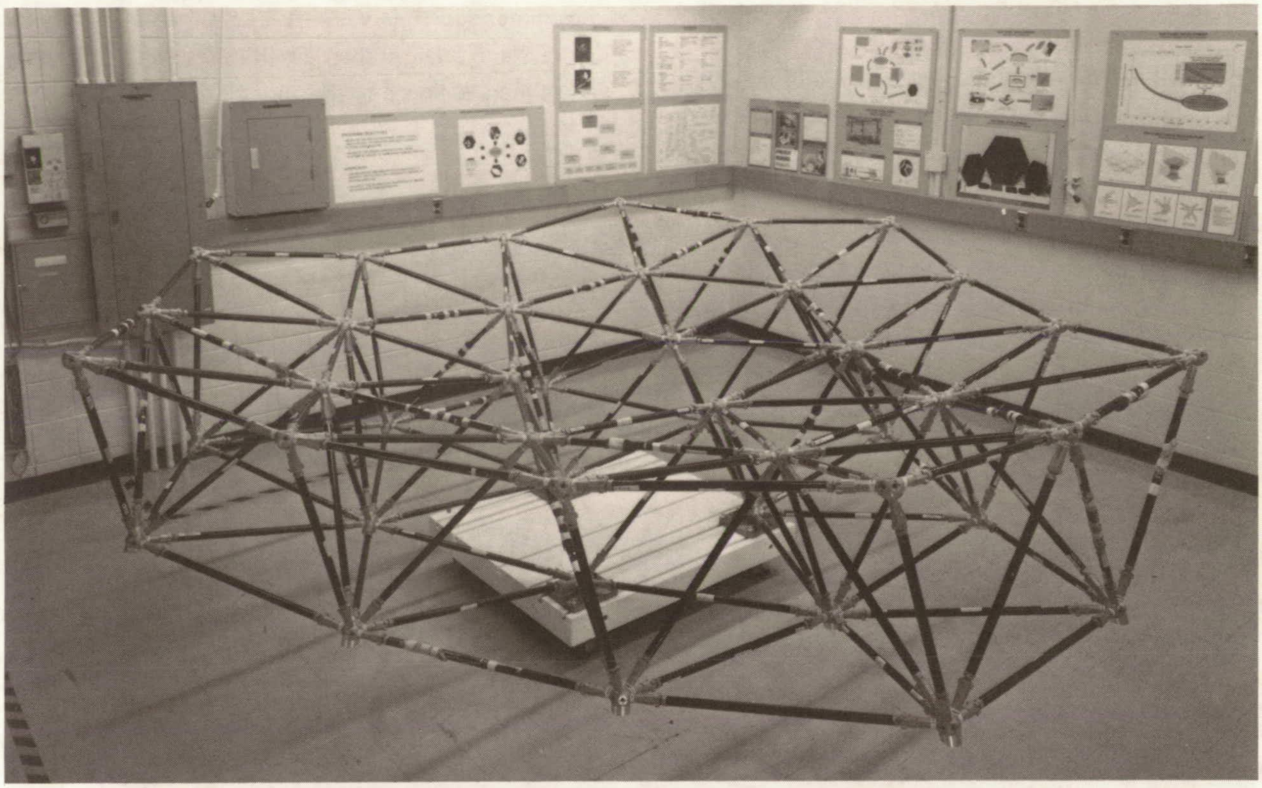


Figure 29. CSI Truss Structure

definition and requirements development activity must be undertaken to quantify what the precise goals should be. This would need to be mapped over what the next century mission requirements and science objectives are. In this activity, the synergism between structures, alignment sensing and control, performance analyses, and large scale system functional architectures would be established.

The first of the required technologies is the development of a quantitative understanding of the behavior of these systems in a (quasi) zero-g environment where self-weight preload is not available to linearize or at least monotonically bias the various hinges and pivot devices that are found in deployable systems.

A program of component level and small scale structural systems modeling and experimental work needs to be carried out in ambient conditions and in vacuum to eliminate the effects of air damping on measured material properties applicable to operation in the vacuum of space. Similarly structures could be off-loaded by floating them on a low pressure near-static air film to note any differences due to the elimination of self-weight preload. As one plateau of understanding is achieved, the size and complexity of the structures can be increased and the ability to analytically scale performance can be tested in the laboratory.

Coupled with this is research into how micro-noise dynamic disturbances are transmitted in these lightweight, pivot joint dominated structures. This is the second area where technology development is needed. The ability to model these structures and to demonstrate correlation with tests at the extremely low strain levels and concomitant low damping in the presence of cabling, thermal control blankets, and other real-world complications is essential.

The third technology development area encompasses the effect of cryogenic operating temperatures on the microdynamic and expansivity characteristics of these large structures, where response amplitudes measured in fractions of microns are important. Of particular concern are mechanical pivots where frictional changes between ambient and cryogenic operation can influence the end fixity of structural members and alter the overall dynamics and the influence of cabling and other polymers whose stiffness varies with temperature. Testing and modeling these structural systems in as large a scale as time and resources permit are recommended to gain as much real-world experience as possible and to disclose problems that might otherwise go undetected in smaller and less challenging experiments.

Lastly, and related to cryogenic operation of segmented mirror optical systems, is the need to develop and verify mirror substrates whose basic shape stability, i.e., radius of curvature over temperature is adequate to achieve ($\Delta R/R$) precisions of only several parts per million. Here trades between substrate thermomechanical stability and active shape control, as opposed to position control only, need to be explored. As cascaded control systems become more complex, the need to accurately and reliably define the 'plant' characteristics becomes increasingly important. The developments and need dates for structures are summarized in Table 28.

Table 28. Required Developments In Structures for 1992–2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Dynamics Modeling	Limited Experience Based Upon HST	Realistic/Accurate Modeling of Practical Structures Verification at m-strain Levels In a 0-g Environment	'98 Components '01 System Level	'92 - '01
Mechanical Noise Prediction	HST	Accurate Prediction of Mechanical Noise Transmission and Dynamic Response in a 0-g Environment	'02	'92 - '06
Deployment/Erection Dimensional Repeatability (Room Temp.)	Technology is in Infancy	Prediction and Test Verification of Dimensional Repeatability to Optical Tolerances	'97 Components '99 System Level	'92 - '10
Deployment/Erection Dimensional Repeatability (Cooled Structures)	Technology is in Infancy	Dimensional Changes and Repeatability of Ensemble Structures With Temperature : 293 K to 100 K, ± 10 K Around 100 K	'98 Small Scale '02 Full Systems	'92 - '06
Structural Materials for Substrates	150 kg/m^2 With External Bending Control	25 – 35 kg/m^2 Substrates, 2 – 4 m in Diameter $\Delta r/r$ Stability : 3 ppm Over All Environments	'00	'92 - '06
Substrate Automatic Deployment and Alignment	None	Deploy/Erection of Two-Segment Mirror to Within Alignment Sensor Capture Range	'02	'92 - '98
Systems Engineering	N/A	Analyze Mission and System Requirements and Define Tech. Dev. Required, Coord. w/ Optics, Controls, etc.	'94	'92 - '94

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SECTION IV (Cont'd)
WORKSHOP PANEL REPORT:

4. OPTICAL TESTING

James Wyant, WYKO Corporation, Chair

Eric Hochberg, Jet Propulsion Laboratory, California Institute of Technology, Co-Chair

Optical Testing Panel Participants

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Gary Hunt	Marshall Space Flight Center
Pete Mason	Jet Propulsion Laboratory, California Institute of Technology
James McGuire	Jet Propulsion Laboratory, California Institute of Technology
Aden Meinel	Jet Propulsion Laboratory, California Institute of Technology
Mike Morris	University of Rochester
Larry Scherr	Aerojet Corporation
Eldred Tubbs	Jet Propulsion Laboratory, California Institute of Technology
Tom Wolfe	Eastman Kodak Company

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INTRODUCTION

Optical testing is one of the most vital elements in the process of preparing an optical instrument for launch. Without well understood, well controlled, and well documented test procedures, current and future mission goals will be jeopardized. We should keep in mind that the *reason* we test is to provide an opportunity to catch errors, oversights, and problems *on the ground*, where solutions are possible and difficulties can be rectified. Consequently, it is necessary to create *tractable* test procedures that truly provide a measure of the performance of *all* optical elements and systems under conditions which are close to those expected in space. Where testing is not feasible, accurate experiments are required in order to perfect models that can exactly predict the optical performance. As we stretch the boundaries of technology to perform more complex space and planetary investigations, we must expand the technology required to test the optical components and systems which we send into space. As we expand the observational wavelength ranges, so must we expand our range of optical sources and detectors. As we increase resolution and sensitivity, our understanding of optical surfaces to accommodate more stringent figure and scatter requirements must expand. Only with research and development in these areas can we hope to achieve success in the ever increasing demands made on optical testing by the highly sophisticated missions anticipated over the next two decades.

Testing is not a static art. Developments over the last decade, such as digitized figure measurements, have improved test capabilities enormously. However, continued development in this area is essential. The technological progress required for testing optical components and systems for future observational instruments depends heavily on the wavelength at which the experiment will be conducted, the scale of the instrument, and the overall scientific objective of the mission. In some cases, improvements are imperative across the entire frequency range. For example, improvements are required in the resolution, speed, and accuracy of measuring large-aperture aspheric mirror surface figures in a gravity-free, space-like environment. This is necessary for virtually all of the Astrotech 21 missions.

Some specific wavelength ranges, however, will require a considerable amount of additional effort. For example, in the x-ray region many technological barriers exist. We need to better understand how to test the shape and tolerances of grazing-incidence x-ray optics; improve x-ray sources, detectors, and collimators; extend measurements of surface roughness to near atomic dimensions; and determine the effect of subsurface damage on the off-axis mirror scatter. In addition, at these wavelengths, advances in polarization-based metrology, spectropolarimeters, and imaging polarimeters are necessary to reduce polarization aberrations. X-ray material properties, such as refractive index and reflectivity, are not currently available, thus compounding the problem of testing. Fundamental measurements such as these will have to be made before optical testing can be accomplished.

Different technological needs drive the innovations necessary in optical testing in other wavelength regions. For example, in the far infrared region where telescopes, such as SIRTF, are expected to operate for many years at LHe temperatures, much work is required to understand the effect of temperature on the optical components and the overall system performance. How does the mirror figure or off-axis scatter change with temperature, and how do we measure these accurately at <10 K? How do we calibrate these changes and how do we measure and predict the effect of contamination on these super-polished mirror surfaces? The technology is available to answer some of these questions, but cryogenic material data, high vacuum, cryogenic test equipment facilities and a better understanding of both operating and testing optical systems at these temperatures are critical to the success of infrared missions. Such a facility for technology development in the x-ray, but not the infrared, region has already been built at the NASA Marshall Space Flight Center for testing optics on the AXAF program. NASA should not delay in providing equipment and facilities, which are needed *now*, for testing in the infrared spectral region. It takes a long time to set up cryogenic equipment which can be counted on to test optics successfully at these temperatures.

These and other topics were the primary concerns expressed by the Optical Testing panel. Results and recommendations arising from discussions that occurred during the workshop are presented below and in Table 29. Where appropriate, the pertinent recommendations of other groups are also included (e.g., Fabrication, Wavefront Sensing).

Optical parameters were condensed into six areas:

1. Surface Figure
2. Surface Roughness
3. Alignment
4. Image Quality
5. Radiometric Quantities
6. Stray Light

In many cases the panel felt that the optical testing requirements of the mission set could be approximately met with existing technology or extensions of existing methods. However, many of these missions are likely to push existing capabilities to the point where practicality and reliability of the results will be questionable. The modifications and extensions of existing technologies will greatly increase the difficulty of testing, increase the testing time, and introduce additional uncertainties into the test data. We need to simplify, speedup and improve the accuracy of existing test methods as the scale and complexity of space optical systems increases.

The performance of complete optical systems must be ensured with optical validation testing of components, subassemblies and, when practical, complete assemblies. This includes measurement of both component performance (surface figure of the individual segments in a segmented primary for example) as well as the quality of the "assembled" wavefront arriving at the science detector. The panel also felt that full-up system optical performance can be ensured by means of testing of active/adaptive optical systems whose demonstration will serve to ensure that all "on-orbit" disturbances to the optical train can be accounted for and corrected. In this regard, optical testing work closely dovetails with the work being done in wavefront sensing, control and pointing, and optical fabrication.

Table 29. Recommended Optical Testing Technologies for Astrophysics Missions : 1992-2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Surface Figure	Measure the Surface Figure Parameters Including rms, p-v, Absolute ROC of Large-Aperture Aspheric Surfaces With High Spatial Resolution and Speed	Aspheric Measurements Test of Large Convex Secondaries Gravity Compensation Testing Cryogenic Measurements Sources and Detectors X-Ray Mirror Testing	AIM NGST (FFT) II LDR SMMI SIRTF AXAF XST, SMIM HXIF	'97 '02 '04 '01 '05 '92 '90 '95, '96 '99
Surface Roughness	Measure Surface Roughness Parameters including rms, p-v and Power Spectrum	Stitching Software Sub-Surface Damage Measurement Sampling Statistics on Large Curved Surfaces	NGST AIM II	'02 '97 '04
Alignment	Assembly and Alignment of Optical Systems, Ground-Based, Lunar Surface and Deployable	System Assembly Techniques Figure Initialization Star Simulators Alignment Software Laser Gauges	AIM NGST (FFT) II LDR SMMI AXAF XST, SMIM	'97 '02 '04 '01 '05 '90 95, '96
Image Quality	Measure the Overall System Performance by Monitoring the Image Quality (e.g., Encircled Energy)	Modeling Sources and Detectors System Wavefront Measurements	AIM NGST (FFT) II LDR SMMI SIRTF AXAF XST, SMIM HXIF	'97 '02 '04 '01 '05 '92 '90 "95, '96 '99
Radiometric Quantities	Measure Radiometric Quantities, such as Transmission Reflectivity, Absorption, Radiance, Irradiance, Vignetting, and Polarization	Reflectivity Measurements Metrology Data Base Calibration	AIM NGST (FFT) II' SMILS SIRTF XST, SMIM HXIF	'97 '02 '04 '01 '92 '95, '96 '99
Stray Light	Stray Light Measurements, Predictions, and Monitoring to Satisfy Mission Requirements	Stray Light Control BRDF Stray Light Testing Signatures Sources and Detectors Scatter Measurements Calibration	All	'95

SURFACE FIGURE

A. Technology Assessment

Surface figure measurement is fundamental to the characterization of the individual reflective optical components that make up a system. The Astrotech 21 mission set requires ground-based measurements of large aperture surfaces (e.g., Figure 30) to determine parameters such as the absolute radius of curvature and the rms and peak-to-valley surface figure errors. This data is required at high spatial resolution and at high speed. A large fraction of the measured surfaces will be aspheric. A requirement also exists for improved accuracy (into the 1 nm range).

The most common method of testing optical surfaces and wavefronts is interferometry. Interferometric surface figure testing is done by constructing interferometers that include the surface to be tested. Figure 31 illustrates an infrared, phase-measuring interferometer of the Twyman-Green type, one of the most common interferometric configurations. Infrared interferometry can be useful for figure evaluation during the early stages of fabrication before polishing, and for rough testing of aspheric surfaces. Interferograms are recorded and analyzed to determine the surface shape.

When surface errors are large compared to the reference surface (in terms of the interferometric metrology wavelength) the resulting fringe patterns can become exceedingly complex and difficult to accurately convert into surface topography (Figure 32). Additionally, multiple interferograms are typically required so as to unambiguously discriminate between "hills and valleys."

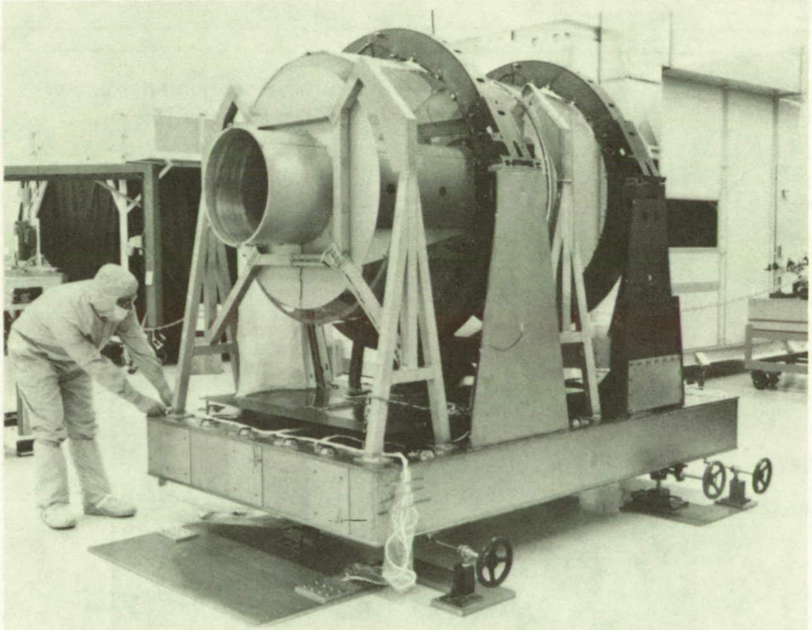


Figure 30. AXAF Optics Test – In June 1991, Kodak technicians and engineers successfully mounted the largest (48 in. diameter) of two special grazing incidence optics for AXAF. The optics are intended initially for use in a ground-based demonstration of the ability of the optics to precisely focus x-ray energy. This x-ray test was successfully conducted in September 1991 at a unique NASA x-ray test facility located at MSFC. A significant challenge addressed and overcome by Kodak was the development and implementation of a strain-free mirror mount, rugged enough to safely support the 500-lb fragile optic throughout the ground handling and transportation environment. To accomplish this, the mirror was bonded to 12 Invar tangential flexures that stabilize the mirror in all degrees of freedom while providing the radial compliance needed to minimize thermal and structural loads. (Courtesy of Eastman Kodak Company.)

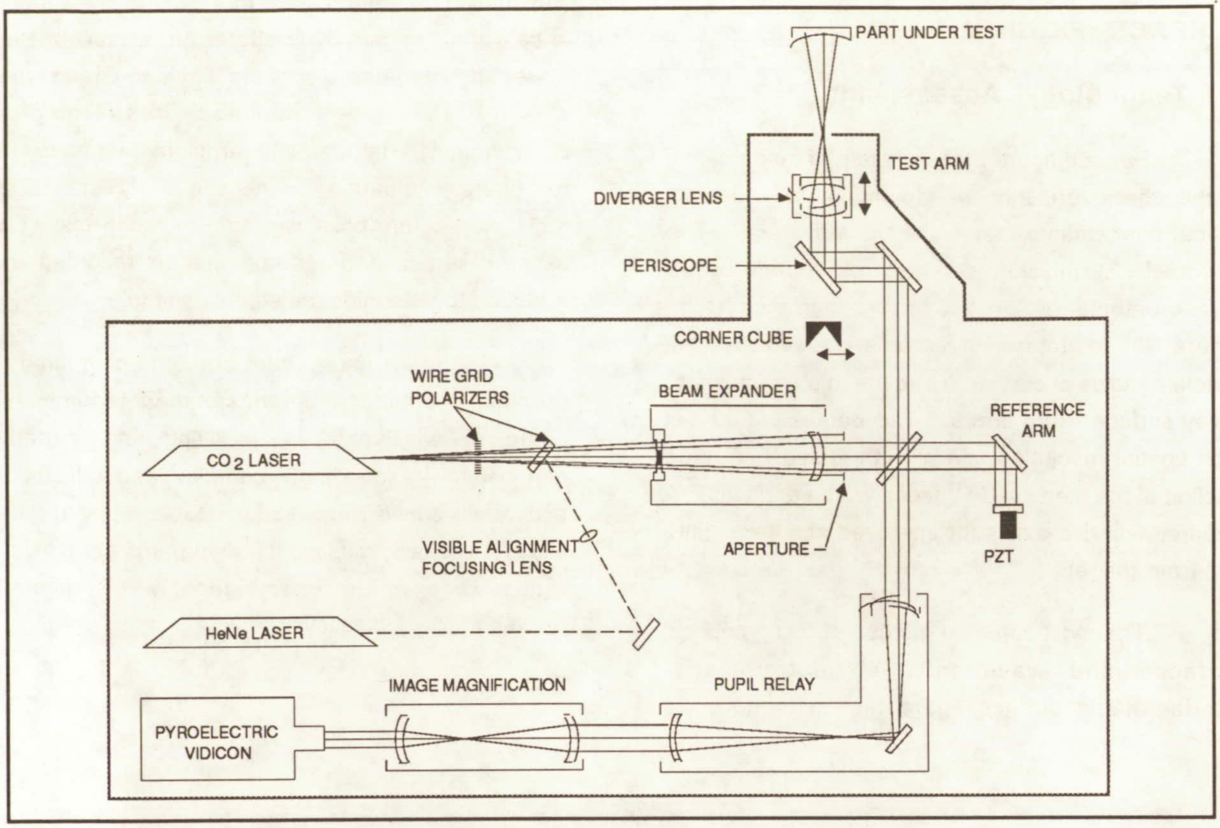


Figure 31. Twyman-Green Infrared Phase-Measuring Interferometer (Courtesy of Breault Research Organization, Inc.)

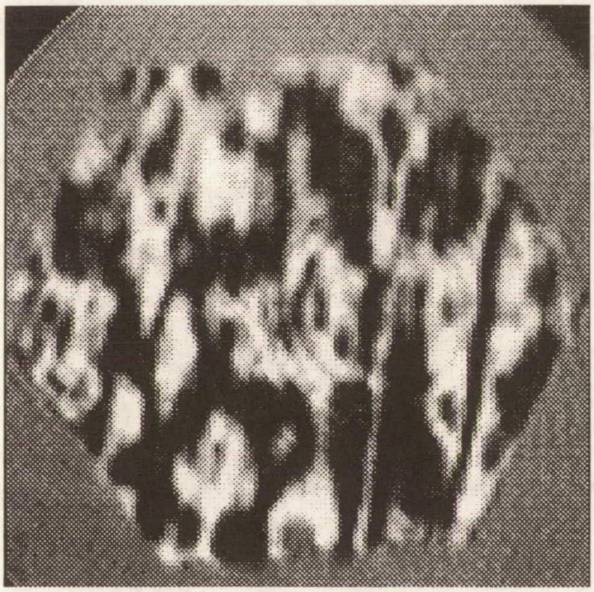


Figure 32. Null Interferogram – Showing 10.6 µm 'null' interferogram of a large composite mirror. Note complexity of fringes. (Courtesy of Jet Propulsion Laboratory/California Institute of Technology.)

These multiple interferograms are usually acquired serially rather than in parallel resulting in increasingly extreme demands on the stability of the test setup — particularly as the dimensional scale of the test set-up increases. High speed measurement will also become increasingly important when it comes to meeting cryogenic test requirements in which even this relatively short metrology "snapshot" can result in significant heat loading on the test article.

Vibration may or may not be a problem depending upon a number of factors including : (1) the test methodology (mechanical, ray or wave-based); (2) the dimensional scale of the optics under test; (3) frequency and amplitude of the vibration; (4) the wavelength of test and/or the desired resolution and accuracy; (5) the intrinsic quality of the surface or wavefront; and (6) sampling rate requirements. If vibration causes the surface or wavefront to be unstable over the course of the measurement, the measurement may be compromised. For example, when certain interferometric techniques are employed, the measurement acquisition time must be made short for the fringe contrast degradation to be made acceptably small. When phase-shifting techniques are used (as are typically required when the surface errors cannot be unambiguously resolved in a single interferogram), then wavefronts must be kept stable over the entire phase-shifting cycle. [Note high speed or instantaneous phase shifting interferometric techniques have been recently developed (see Refs. 1, 2, and 3) in response to requirements for vibration immunity and/or high measurement bandwidth.] Common-path and shearing interferometric techniques as well as a number of ray-based optical tests founded on geometrical optics principles [e.g., slope or curvature sensing (see Refs. 4 and 5) or PSF inversion] may be intrinsically more robust with respect to vibration insofar as they allow the effects of vibration to be "averaged out" with sufficient integration time. Essentially, a variety of wave- and ray-based vibration-tolerant metrologies have successfully made possible the testing of large optical elements and systems in conventional, non-vibration-isolated environments. At this point in time, it appears fairly clear that vibration is not likely to be a major technology hurdle for future optical testing.

A limited capability to test aspheric surfaces currently is available. Most tests require a null optic (refractive, reflective or diffractive; see Offner null lens example in Figure 33) to compensate for the asphericity of the surface and to reduce the number of fringes in the interferogram. In addition to being hard to design and fabricate, the performance of the nulls is also difficult to validate, and errors in the nulls or their alignment translate into apparent errors in the surface under test. Some aspherics can be tested in null configurations against flats or spheres, but these tests are often impractical due to the size requirements placed on these auxiliary optics. The current approach to testing aspherics must be reconsidered as surfaces to be tested become larger and more aspheric.

Testing convex surfaces has always been a challenge simply from a practical perspective — typically, the required reference surface (Hindle sphere) must be substantially larger than the surface under test. Figure 34 schematically shows a Hindle test of a convex hyperboloid. For secondaries larger than 1 m, this approach is clearly impractical; a reference surface does not exist and would be impractical to fabricate. The current approach is to test subapertures of the surface and stitch or assemble these subaperture results together to obtain the full surface. While this approach is used, it is inconvenient and unreliable. New technology to allow for the testing of large convex surfaces is needed. This technology will impact the missions with primaries larger than 4 m (AIM, NGST, FFT, LDR, and LSMM).

The shape and tolerances of grazing-incidence x-ray optics present unique problems in their testing. The limited technology that exists for this application relies primarily on measuring one-dimensional longitudinal surface profiles of the mirrors. New technology is clearly needed for the x-ray missions. Representative of the state of the art in x-ray test facilities is the x-ray calibration facility at

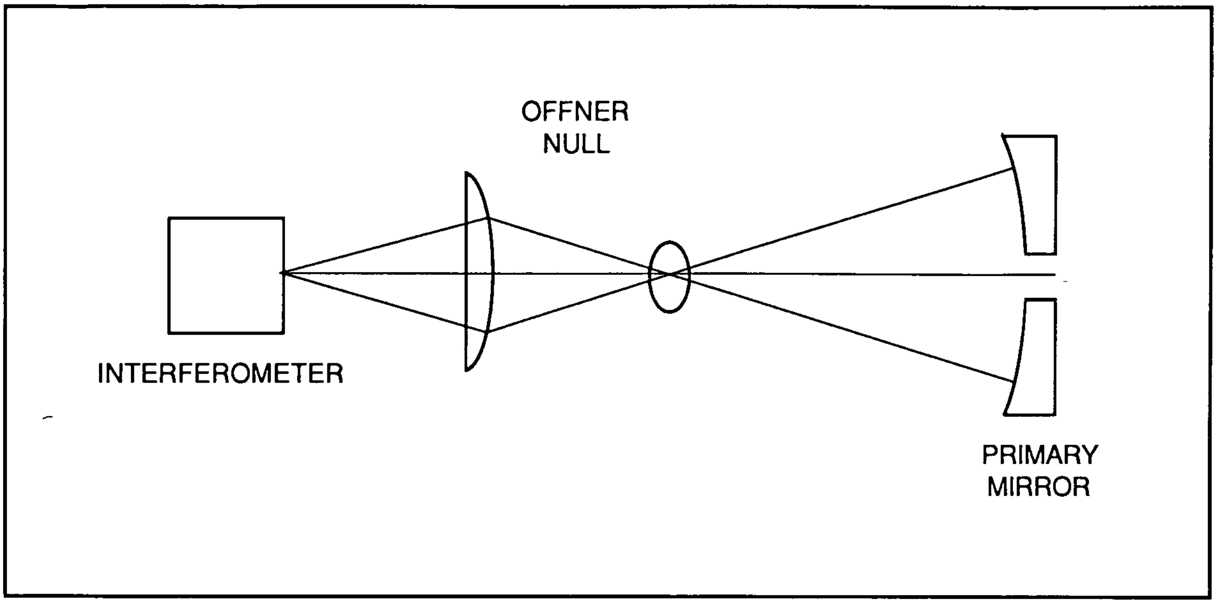


Figure 33. Offner Null Lens

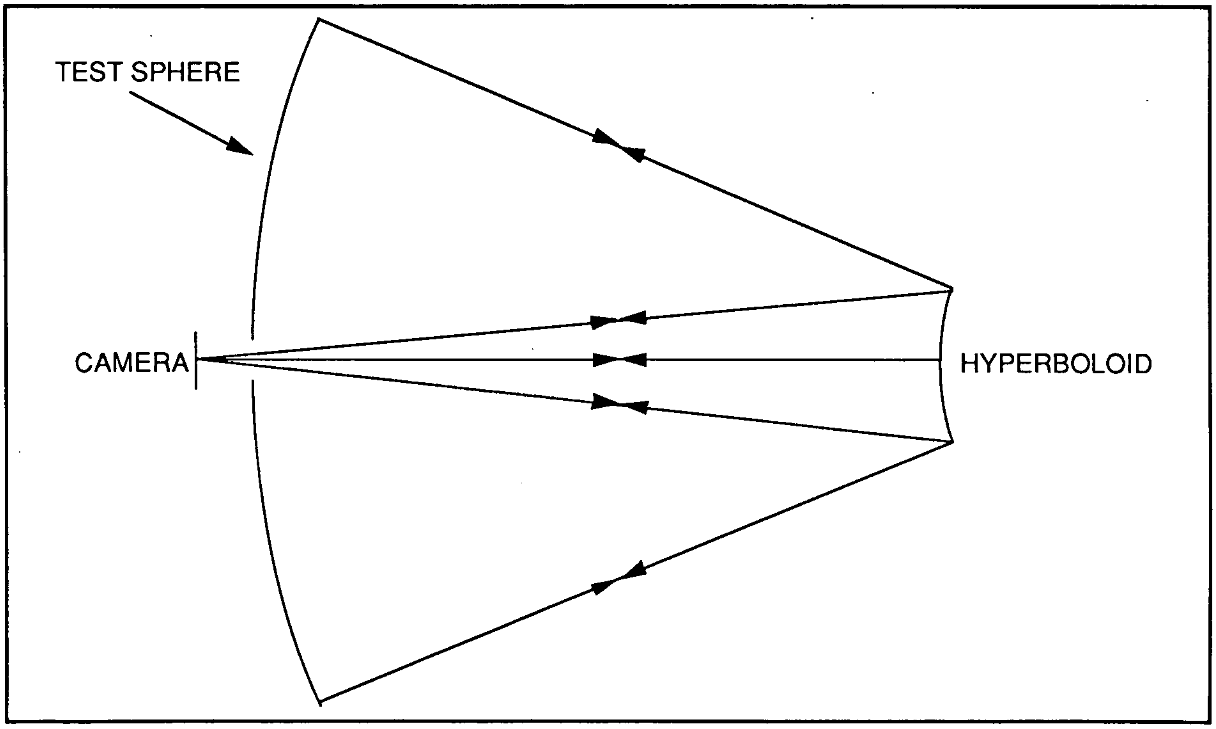


Figure 34. Hindle Test for Convex Hyperboloid

MSFC (This is the test facility that was used to verify the AXAF P1/H1 mirror performance).

The MSFC X-ray Calibration Facility (XRCF) provides a 57.5 in. dia, near-parallel beam of x-rays for ground test and calibration of x-ray telescope optics and experiments. The XRCF comprises vacuum systems, clean rooms, x-ray generator and monitor systems, data acquisition and control systems, test hardware handling systems, and associated support hardware. The XRCF vacuum envelope consists of a 24-ft-wide by 60-ft-long Instrument Chamber (IC) connected to the east side end of a 3- to 5-ft-diameter by 1700-ft-long Guide Tube. The west end of the Guide Tube is joined to Alignment and Source Chambers, which provide interfaces for the XRCF Alignment Telescope, Alignment Laser, and x-ray generator assembly. To maintain the cleanliness levels required for optical testing, all vacuum systems are rough-pumped with dry mechanical or cryogenically trapped mechanical pumping systems. High vacuum pumping (to the 10^{-7} torr pressure range) is accomplished using cryogenic and turbomolecular pumping systems.

The X-ray Generator Assembly (XGA) is a multifocus type bremsstrahlung source of selectable energies filtered for spectral purity. The XGA provides x-ray energies over the range from 0.2 to 8.1 keV at flux levels from 0.1 to 1000 photons/(sec • cm^2) at the instrument chamber. Calibrated x-ray monitors measure the x-ray flux to within 10% accuracy. Optical baffles are located along the length of the guide tube to prevent scattered radiation from reaching the entrance aperture of the hardware under test. To track dimensional drift in the XRCF, a motion detection system is available. The motion detection system can be used to measure relative motion of the test optics, focal plane instruments, and the x-ray generator support structure to within 0.2 μm. Access to the IC is gained through a 5900-ft^2 class-10,000 clean room. A 2300-ft^2 class-10,000 clean room is used as a receiving area for the IC clean room. Entry into the IC is provided via a 24-ft-diameter removable dome. Test hardware is staged into the IC clean room and mounted on movable test benches using a 20-ton bridge crane. The test benches supporting the test hardware are rolled into the IC using a rail system with Thompson bearings and offloaded onto the rail system support piers. To isolate the optical hardware under test from externally induced vibration, the support piers are isolated from the IC wall using complaint vacuum bellows and are mounted to a 5-ft-thick seismic pad. A 48-in. entry port is located on the IC 24-ft removable dome to provide for personnel access and to transport small hardware into the IC. In a typical test, the x-ray optical test hardware is mounted in the west end of the IC on the facility optical axis. The x-ray detector hardware is located near the east end of the IC at the focus of the x-ray optics. The alignment laser and telescope are used to precisely align the test hardware to the facility optical axis. The facility is evacuated, the x-ray generator is activated, and a known x-ray environment is provided to test the X-ray performance of test hardware.

The MSFC XRCF is unique in that it provides an optically clean, dimensionally and thermally stable, high vacuum test chamber with a well collimated x-ray beam, clean rooms, and other previously mentioned capabilities into the largest facility of its type in the world. It was originally constructed in 1990–1991 to measure the x-ray optical performance of the Advanced X-ray Astrophysics Facility (AXAF) Verification Engineering Test Article No. 1 (VETA-1) optics. Modifications are currently in design to enhance the capabilities of the XRCF. These modifications include upgrading the IC clean room to better than a class 1000, adding additional high vacuum pumping to accommodate the increased gas loads imposed by large test hardware, and upgrading the IC thermal control system to provide for a spatially uniform and temporally stable thermal environment over the temperature range from -60°F to +160°F. Modifications are also planned that would extend the energy range and increase the spectral purity of the x-ray generator assembly. After modification, the XRCF will be used for ground testing of the AXAF High Resolution Mirror Assembly (HRMA) and Science Instruments (SIs).

For many systems, it is desirable or necessary to test the surface or component at the wavelength it will be used (for example, transmissive components). The important parameters for sources include uniformity, stability, and coherence while important detector parameters are number of pixels, response time, uniformity, and responsivity. For tests in the visible and the near-IR, there are ample sources and detectors. This same situation does not exist at other wavelengths especially from the mid-IR out to the submillimeter. Improved x-ray sources and collimators are also needed. While it is unlikely that testing alone can justify the development of new source and detector technology, NASA should encourage this development and modify and learn to use this technology as it becomes available.

It is critically important to measure, at least at the component level, the surface figure of optical elements that will be operating at cold temperatures. (This need was also highlighted by the optical fabrication group.) Optics for the submillimeter telescope missions call for figure quality at temperatures between 100 K and 200 K and may include significant thermal spatial gradients over the aperture. The LHe-cooled SIRTF primary must have a good surface figure when actively cooled to <10 K. Surface figure must be measured, inferred, or predicted with high confidence at these temperatures. Test limitations are primarily in large cryogenic test facilities which present design challenges in vibration control, isolation, insensitivity, and invasiveness for the test metrology. The present state of the art for 632.8 nm systems (Rome Air Development Center, New York) is video rate (15 ms figure measurements), 128^2 pixels spatial resolution integrated with a 2.0 m class LN_2 cryogenics chamber. A schematic of a phase-shifting interferometric workstation (generic) is shown in Figure 35. Improvements in spatial resolution are being realized primarily with higher pixel density detectors.

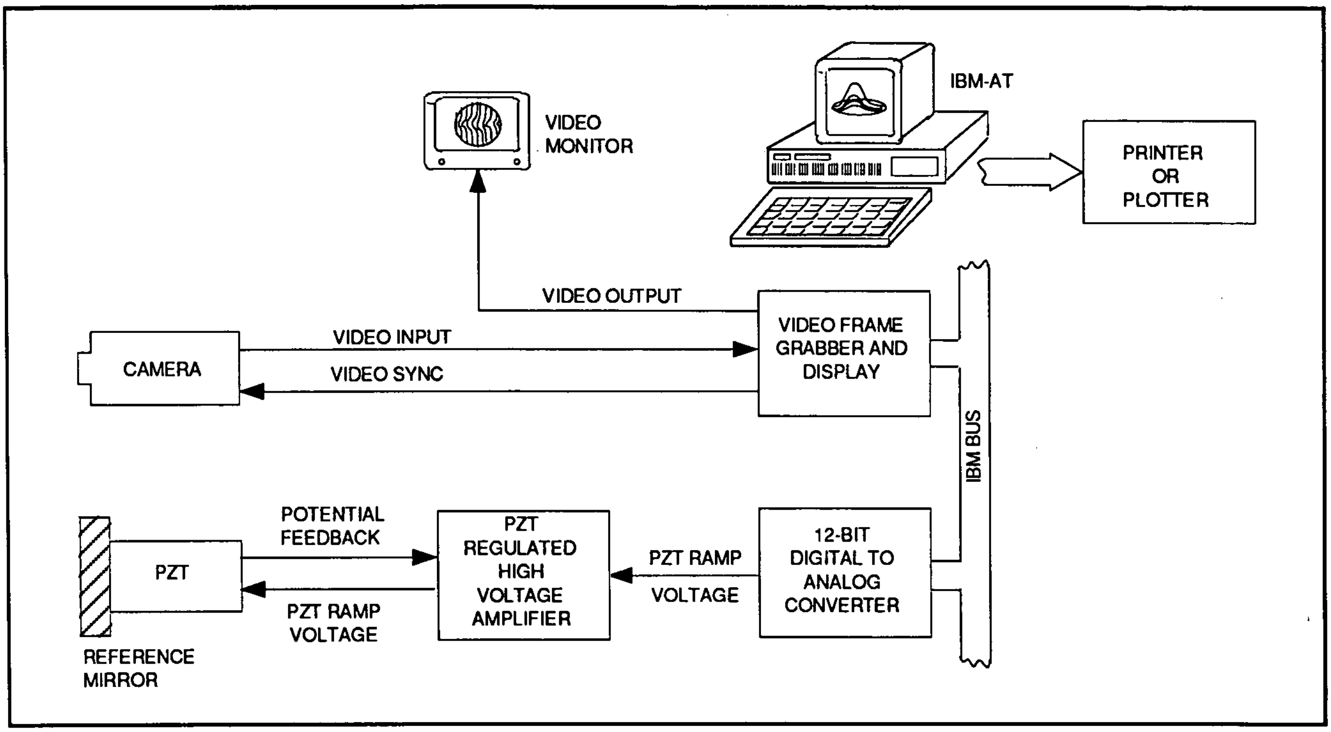


Figure 35. Phase-Shifting Interferometric Workstation. (Courtesy of Breault Research Organization, Inc.)

B. Development Plan

New interferometric technology must be developed that will allow for the detection and interpretation of more complicated fringe patterns to reduce the requirements placed on existing detectors and null optics. In addition, improved calibration procedures are needed to push the accuracy of these tests towards the 1 nm level from their current level of about 10–21 nm. These improvements in aspheric testing will undoubtedly require the interaction of ray tracing software with the interferometric software. Most of the missions in the mission set we are considering will be able to make use of this technology.

The panel recommends that technology be developed in five specific areas: aspheric surface testing, testing of large convex secondaries, cryogenic measurements, sources and detectors for optical measurements, and the testing of grazing-incidence x-ray mirrors. (Need for development in these areas has also been highlighted by the optical fabrication panel.) Table 30 summarizes the Surface Figure technology area.

Table 30. Surface Figure Technology Development Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Aspheric Measurements	Hubble, Keck	1 nm Accuracy on f/1 surfaces	'97, '02, '04,	'92 -'04
Large Convex Secondaries	Keck	1 m Aperture	'97, '02, '04, '01, '05	'92 -'04
Cryogenic Measurements	SIRTF 0.5 m @ 10 K	Measurements at LN $_2$, LHe 1.0 m @ 2 K	'95, '02, '92	'92 -'03
Source and Detectors	VIS + Near IR	Mid IR to Submm and UV Resolution ; > 1000 ^{2} Pixels X-ray Sources, : > 8.1 keV X-ray Flux Monitors : Better Than 10%	'90, '95, '99, '01	'92 -'02
X-Ray Mirrors	Limited	Improved Capability Test Facilities Large Beam Diameter : > 60"	'90, '95, '99, '03	'92 -'04

SURFACE ROUGHNESS

A. Technology Assessment

Technology developments in surface roughness measurements to measure parameters including root-mean-square (rms), peak to valley (p-v), and power spectrum at µm to centimeter spatial periods are needed for the majority of the missions for wavelengths shorter than the mid IR.

Optical profilers are commercially available for angstrom height measurements for spatial periods ranging from approximately one-half µm to several centimeters for flat and spherical surfaces. Cylindrical or general aspheric surfaces can be measured for spatial periods of a few mm. Small spatial period measurements can be stitched together to obtain larger period information. Additional software and hardware developments are required to properly align the subapertures without artificially introducing surface errors.

Only a limited area of large surfaces can be measured for surface roughness. The roughness statistics of flat surfaces do not vary much over the surface area, so only a few spots on the surface need to be measured. The BRDF on the other hand might vary more significantly and should be measured in more locations. This is not true for aspheric surfaces where the surface statistics can vary considerably over the surface. Additional analytical work is required to determine the sampling requirements for large optical surfaces. Stitching software needs further development for mid spatial frequencies and to bridge the gap between low spatial frequency figure errors and high spatial frequency surface roughness.

B. Development Plan

Optical profilers for cylindrical and general aspheric surfaces need to be developed. The technology associated with accurately moving profilers over large surfaces, while maintaining absolute position knowledge of the measurement, is essential in developing full surface roughness models. Software that will take sectional measurements, and develop a full surface roughness profile and analysis needs to be developed.

The spatial frequency of roughness measurements needs to be extended to near atomic dimensions to support technology development of new fabrication techniques for the ultraviolet and x-rays, and to the large spatial frequency data required to close the gap between high frequency figure errors and surface roughness.

Finally, technology requiring development in measurement tools that will allow the relation of subsurface damage measurement to final achievable surface roughness. This technology area is undeveloped.

Table 31 summarizes the recommended development program for three surface roughness technologies.

Table 31. Surface Roughness Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Stitching Software	Non-Existent	Software Development Integrating Figure and Roughness Testing	'95, '97, '02, '04	'93 - '04
Subsurface Damage	Limited, Mostly Destructive Techniques	Non Destructive Techniques Instrumentation Statistical Data	'95, '97, '02, '04	'93 - '04
Sampling Statistics	Cumbersome	Statistics on Large Surfaces	'95, '97, '02, '04	'93 - '04

ALIGNMENT

A. Technology Assessment

Alignment technology is perhaps the most primitive of all of the optical testing technologies. The basic alignment methods used for most large optical systems rely on surveying technology developed in the last century, augmented with HeNe pencil alignment beams and microprocessor readouts. The procedures used to align complex, multimillion-dollar optical systems are essentially ad hoc, with little or no model verification of the procedure before or during alignment.

The panel considered four technologies necessary to improve alignment and optical system assembly capability to meet the requirements imposed by the Astrotech 21 mission set. These technologies are:

1. Partially Assembled System Alignment
2. Segmented Optics Initialization
3. Laser Gauges
4. Marriage of Optical and Mechanical Software

B. Development Plan

Table 32 summarizes the recommended development program in alignment technology. The following paragraphs address the individual elements of the program.

Partially Assembled System Alignment is required in process in the assembly and test of optical systems containing large numbers of components. The technology is undeveloped, except for a few special case techniques. The development plans call for the modeling and design of partially assembled systems, with the test fixtures and mounts built into the overall system concept (Figure 36). Hardware and software developments will be required to capture and analyze the complex fringe patterns resulting from tests of partially assembled systems.

Segmented Optics Initialization is required for phasing large segmented optical systems. Some current development efforts are under way for submillimeter telescopes, but these are slow and cumbersome. Additional work in segment control is being pioneered by the Keck Observatory. Additional efforts are needed for high speed systems that converge rapidly in the presence of thermally induced distortions of mirrors and structures. The technology effort will be to simulate the various algorithms, the operating software and the mirrors, including distortions, diffraction, and high and low frequency spatial errors to demonstrate the ability to initialize a system.

Laser Gauges are used to measure dimensional changes of panels and structures. The current positional resolution is about 1.0 nm. The technology development plans call for improving this resolution by a factor of 10 to 0.1 nm. This resolution is required for submillimeter antennas and for space interferometers.

Optical and Mechanical Software interactions are fairly limited. Some of the more sophisticated codes can read interferograms and NASTRAN-generated surface perturbations and use them to deform the optical surfaces. (Since the spatial resolution of structural analysis codes is not high, this is rarely a completely thorough calculation.) The technology development plan requires the interactions to be fast, and accessible to users trained in both disciplines. This activity is addressed in more detail in the next panel report, 5. Optical Systems Integrated Modeling.

Table 32. Alignment Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
System Assembly	Initial Evaluation	Alignment Techniques for Partially Assembled Systems	'97, '02, '04, '01, '05	'93 - '04
Figure Initialization	Cooperative Point Sources	Initialization and Phasing of Segmented Optics, in ALL Degrees of Freedom	'01, '02 , '04, '05	'93 - '04
Star Simulators	DoD	Star Simulators for System Testing	'97, '01, '02 , '04, '05	'93 - '04
Software	Few Disciples, Limited Data	Marriage of Optical and Mechanical Software Including Gravity, Mounts, and Thermal	'01, '02 , '04, '05	'93 - '04
Laser Gauges	Good, Improvement Needed	Accuracy : ≤ 1 nm	'01, '02 , '04, '05	'93 - '04

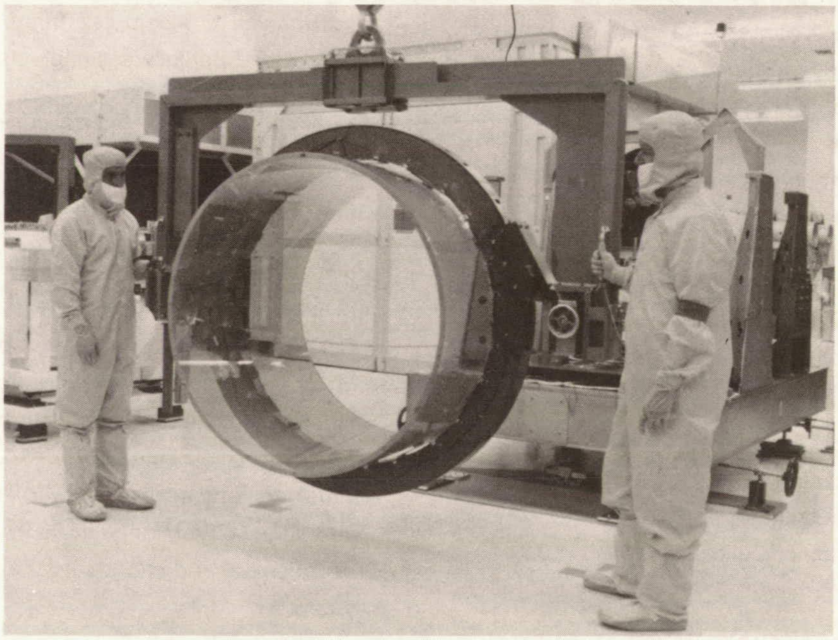


Figure 36. Verification Engineering Test Article (VETA) In Final Assembly – Technicians complete final wiring of the VETA prior to shipment to MSFC in early August 1992. The VETA (shown here without its thermal enclosure) used the largest pair of AXAF grazing incidence optics to successfully demonstrate the ability of the optics to form precise x-ray images. A significant challenge addressed and overcome was the development of a precise mirror alignment control subsystem. Alignment was achieved by supporting the secondary mirror on an ensemble of six submicron resolution actuators (not shown in this shipping configuration) arranged to provide 6 degree-of-freedom alignment control to 0.1 arcsec accuracy. (Courtesy of Eastman Kodak Company.)

IMAGE QUALITY

A. Technology Assessment

All systems, except for light buckets, need measurements of overall image quality. Image quality metrics include: encircled energy, Strehl ratio, the optical transfer function, and quality of the transmitted wavefront. The required measurements depends upon mission science requirements. For some missions it is only necessary to measure the image quality at a single field point, while for other missions many measurements over the field of view and for different wavelengths are required. More attention will need to be paid to polarization properties of system elements as well.

B. Development Plan

An important component of any overall system performance measurement is the light source used for the measurement. In many instances a high quality collimated source is required. Collimated sources with the requisite wavefront flatness and radiometric uniformity must be available for many different wavelengths. (Developments are especially needed in the UV.) Also, both point and area array detectors are required for the measurements. There is little problem with detectors for the visible and near infrared, but technology development is needed for other wavelengths.

The optical systems required for some missions are so large it will probably not be feasible to measure the wavefront across the entire aperture and therefore subaperture measurements will be required. In these cases improved stitching software is required to go from the sub-aperture wavefront to the full-aperture system wavefront.

Required technology includes improved diffraction analysis and modeling. Vector diffraction analysis is required for missions using segmented optics, and Fresnel diffraction capability is required for some of the longer wavelength systems. By improving diffraction analysis capability, it will be possible to reduce the number of measurements required for different field angles and wavelengths. The effects of noise sources and misalignments can be reduced. Table 33 summarizes three Image Quality technology areas.

Table 33. Image Quality Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Modeling	Limited	Advanced Diffraction Analysis and Modeling Software	'97, '01, '02, '04,	'93 - '04
Sources and Detectors	VIS and Near IR	UV, Mid IR to Submm : Sources Point and Area Array Detectors	'90, '95, '99, '01, '02	'93 - '04
System Wavefront	Hubble, Keck	Full Aperture System Wavefront (Via Stitching)	'97, '01, '02, '04, '05	'93 - '04

RADIOMETRIC QUANTITIES

A. Technology Assessment

Polarization is important in systems that: measure total intensity (radiometers and spectrometers), measure polarization (polarimeters), are based upon interferometric principles (interferometers, phased arrays), or use grazing incidence optics.

The goal of spectrometers and radiometers is to make accurate intensity measurements independent of incident polarization state. Because of the polarization properties of the optics, they are biased by the incident polarization. Currently accuracies of 5% and 1% are realistic for grating based spectrometers and radiometers, respectively. To design more accurate spectrometers and radiometers, improved software analysis tools are required, chiefly a closer coupling between existing thin film, diffraction grating, and optical design software. Software for polarization analysis of binary optics is currently not available, but will be required if binary optics are used for any of systems discussed in this section. Analysis software for stress birefringence may be required for some instruments.

Polarimeters can be used to studying solar magnetic fields, solar flares, and quasars. Planned radiometers, interferometers and x-ray optics would benefit from advances in polarization based metrology, such as polarization BRDF which measure polarization dependent scatter, spectropolarimeters which measure wavelength dependent polarization, and imaging polarimeters. Polarization BRDF is a simple extension of standard BRDF measurements with a polarimeter instead of source and detector. Spectropolarimeters exist in the IR and visible but are calibrated to only 5%. Imaging polarimeters exist in IR and visible but lack accuracy. Polarimetric accuracy is limited by modulators in the IR, UV, and x-ray and lack of completely characterized (i.e., full Mueller matrix) polarization standards in all wavelengths bands.

Polarimetric accuracy is also limited by polarization changes by optics prior to the polarization modulators. Design of improved polarimeters requires new software models for birefringent and optically active materials in addition to the software requirements mentioned above.

In interferometers, interference can occur only between wavefronts with the same state of polarization. In this sense, polarization mismatch leads to a loss in fringe visibility and signal-to-noise. Design and fabrication of improved interferometers for both the science missions and metrology depend on the improved polarization design software and polarization metrology tools discussed above.

The optics for grazing incidence, x-ray, and FUV instruments will have larger polarization aberrations resulting from operation at larger angles of incidence. The polarization aberrations from some single mirrors (e.g., AXAF) and mirror systems have been, or will be, large enough to produce observable polarization-dependent point spread functions and surface interferograms. This image degradation is in addition to degradation in radiometric and spectrometric performance. (Polarization aberrations may, of course, degrade image quality in any optical system, but will probably be negligible in all but the most sensitive such as the NGST). Design and analysis of improved x-ray optics depends on improved polarization design software and characterization of x-ray materials. Characterization of x-ray materials will require new techniques and devices to measure the complex refractive index.

B. Development Plan

There are two major technology developments that are required. The first is to develop the material data bases that allow proper designs to be built, tested and validated. Significant tests are required of the complex refractive index and reflectivity, particularly of ultraviolet and x-ray materials. This is a fairly low level continuing technology study area. There is no empirical polarization property data base available to system designers. The necessary test of materials must be made and documented in a usable catalog.

The second technology development is to increase the accuracy and capability of the measurement instruments. An order of magnitude improvement is needed in absolute radiometric calibration, polarization, and radiometric quantities.

Table 34 summarizes four technologies for Radiometric Quantities.

Table 34. Radiometric Quantities Enabling Technologies Program

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Reflectivity Measurements	Visible and Near IR only	Reflectivity Measurements (complex n) at UV and X-Ray Wavelengths	'97, '01, '02, '04,	'93 - '04
Metrology	10%	Polarization Metrology, Analysis of Components and Full Systems; 1%	'95, '97, '01, '02, '04,	'93 - '04
Database	Limited	Polarization Database	'95, '97, '02, '04	'93 - '04
Calibration	10% absolute accuracy	Development of Absolute Radiometric Calibration Techniques; 0% absolute accuracy	'97, '01, '02, '04,	'93 - '04

STRAY LIGHT MEASUREMENT

A. Technology Assessment

Many of the Astrotech 21 missions will require very good stray light suppression. Several of the missions will have a bright source (star) near a dim object (planet). The dim object is often the critical object to be observed. In order to minimize stray light, there needs to be a good design; the design needs to have clean, low scatter optics, and the baffles need to be highly absorbing. An incorrect choice of any of these parameters can make a dramatic difference in system performance (Figure 37). Technology is required that will:

(1) Correlate fabrication procedures with BRDF in order to identify processes that lead to lower scatter surfaces, low rms roughnesses, and particle-free surfaces. (Figure 38 illustrates the effect of polishing time on the BRDF of an optical surface.)

(2) Cleaning of surfaces to restore the original low scatter characteristics.

(3) Measured data to aid in the selection of materials for design and fabrication.

(4) Simplified system-level stray light tests.

(5) Polarization sensitive BRDF data.

(6) Near angle scatter measurements.

(7) Long life, stable, Lambertian reference calibration samples at UV and IR wavelengths.

(8) Next-generation stray light analysis software with more extensive BRDF databases and polarization analysis capability.

To achieve some of the above data or measurements, there is an immediate need for higher-power sources and more sensitive detectors especially in the UV and far IR wavebands.

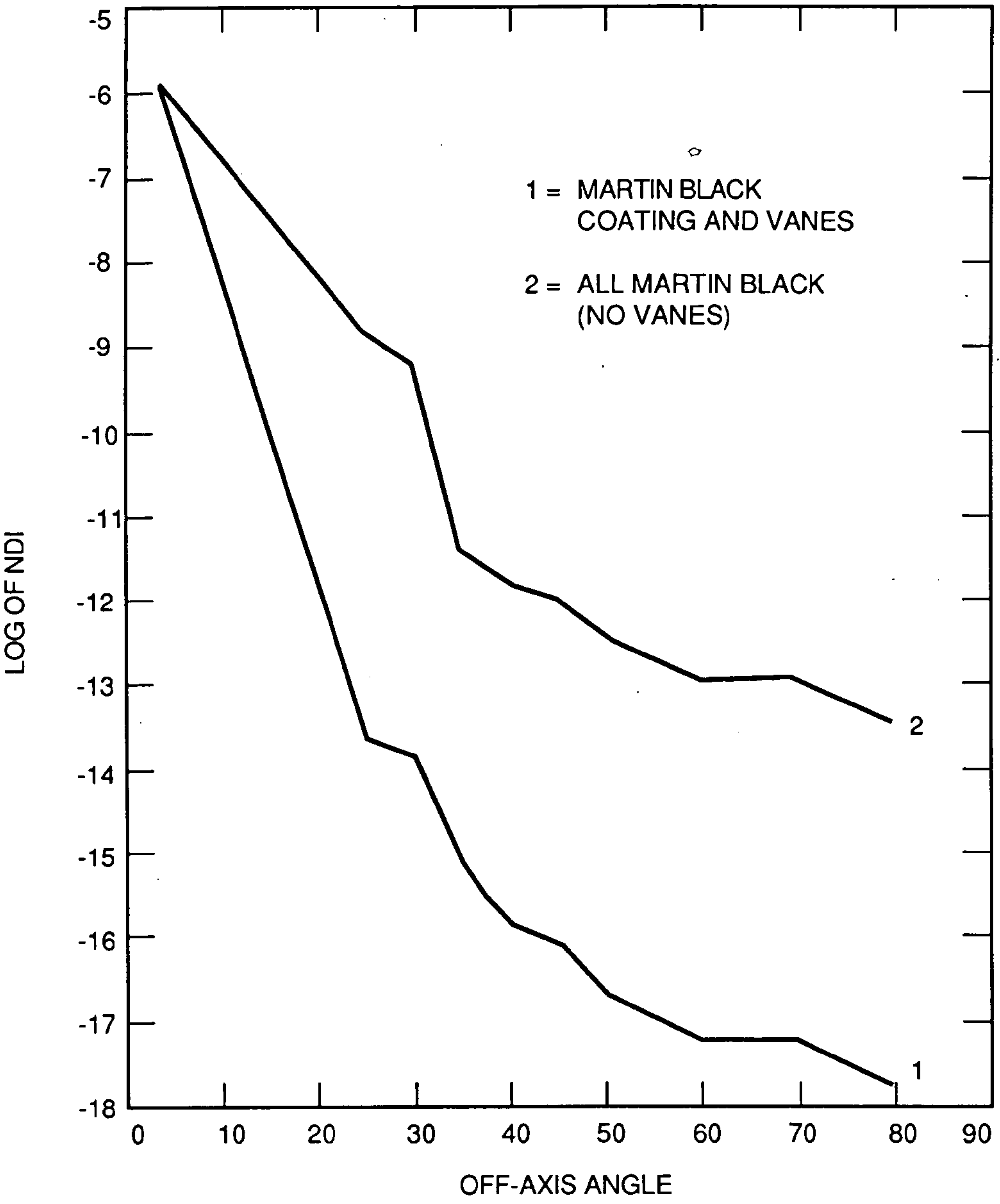


Figure 37. APART Analysis of SPACELAB 2 Telescope – The Normalized Detector Irradiance (NDI = detector irradiance/input irradiance) for a telescope with and without vane structure. (Breault Research report for the Smithsonian Institute, Cambridge, Massachusetts, "Analysis of the Small Helium-Cooled Infrared Telescope for Space Lab 2," 1977.)

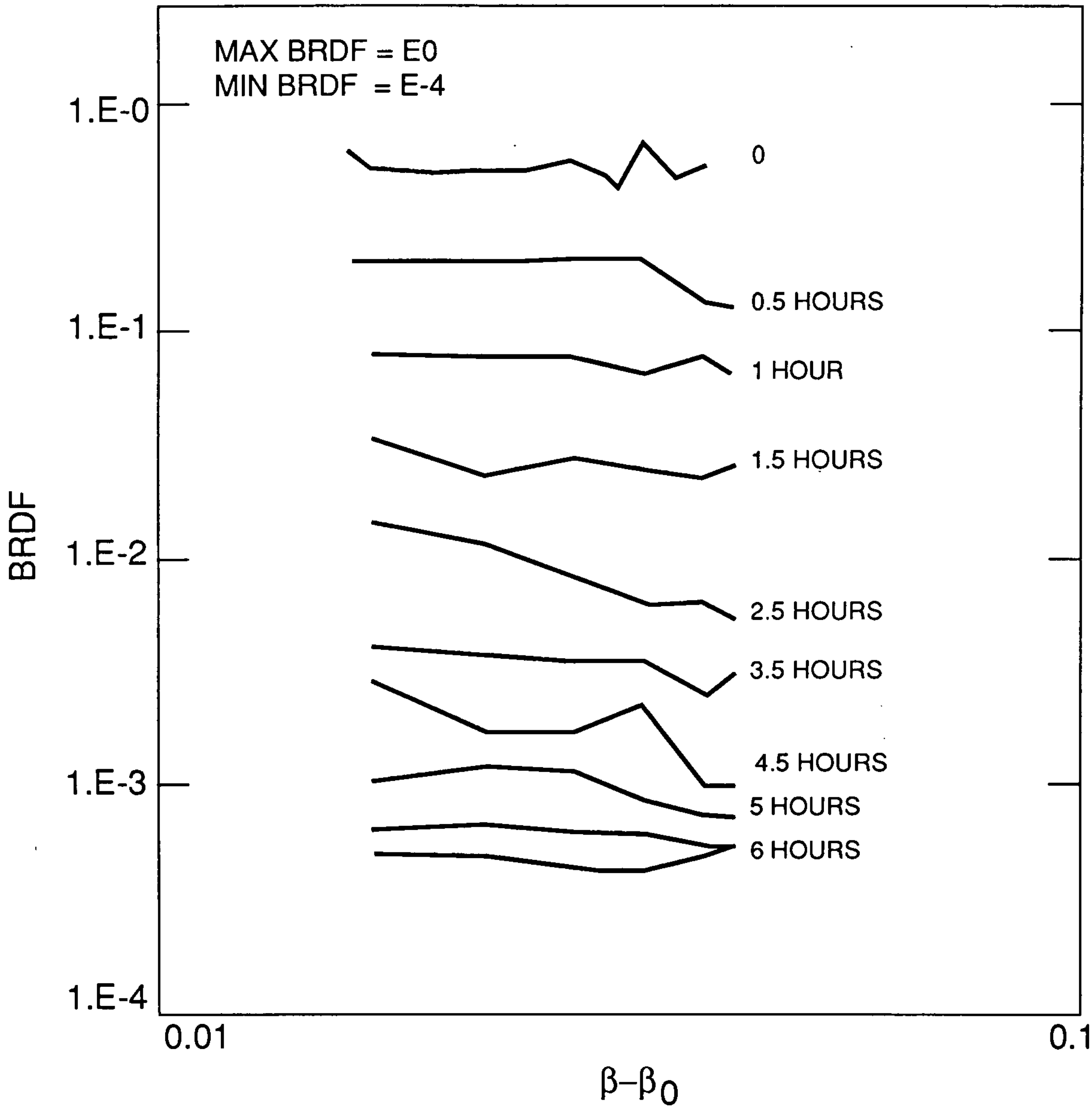


Figure 38. BRDF as a Function of Polishing Time in Hours. (Courtesy of Breault Research Organization, Inc.)

B. Development Plan

Taking the above issues one by one; lower scatter surfaces sometimes require lower surface roughnesses, but not always. A lower rms roughness will not help if the dominant scatter mechanism is due to particulate scatter or subsurface damage. For small (<15 cm in diameter) parts rms roughnesses <1 angstrom have been achieved. There is not much call for improvement here. There is room for improvement on the very large surfaces that are being considered. Particulate scatter will probably dominate unless the mirrors are periodically cleaned. This is especially true for the near IR wavebands. The Air Force's Rome Air Development Center, under Captain Deidre Dykeman, is in the flight verification stage of cleaning space-based optics. Hopefully this will be accomplished by 1993. It holds the promise of decreasing the stray light background noise on systems like SIRTF by a factor of 100. Space-based cleaning promises a great return on investment for long-life systems.

BRDF data below wavelengths of 0.4 µm s and above 20 µm s is almost nonexistent. BRDF data of black absorbing coatings in general shows a strong angle of incidence dependence (Figure 39 (a), (b), and (c)); additionally, black coatings in the 2 µm to 6 µm band show strong wavelength dependence. Wavelength sensitive BRDF measurements are needed in this wavelength region. NASA should fund the enhancement of existing facilities and the fabrication of vacuum UV BRDF instruments. Then data should be accumulated on mirrors, filters, lenses, and black coatings so that stray light analyses in the future will have realistic BRDF data to work with. This should not require a very expensive investment but it is needed now and is crucial.

Existing BRDF instruments (or scatterometers, an example of which is shown in Figure 40) can be modified to determine the polarization signature of mirrors, lenses, and coatings. The Mueller Matrices can be measured for the various materials. The results can be used in the scatter analysis and also in determining the radiometric characteristics of the sensors.

Currently most BRDF instruments use the "reference" method to calibrate their BRDF data. The mathematical justification for this approach is:

$$\Phi_{DET_{REF}} = \Phi_L \, BRDF_{REF} \, \Omega_{DET} \cos\theta$$

$$\Phi_{DET_{MIR}} = \Phi_L \, BRDF_{MIR} \, \Omega_{DET} \cos\theta$$

$$BRDF_{MIR} = \frac{\Phi_{DET_{MIR}}}{\Phi_{DET_{REF}}} \; BRDF_{REF}$$

Only in the visible spectrum is there a reliable and calibrated Lambertian reference material. NASA should fund the development and characterization of Lambertian reference materials for the UV, IR, and Far IR wavelength regions.

Each of the sensors should develop a plan to measure the system's stray light characteristics. Those systems that will only be assembled in space will need to be tested in parts, i.e., a full segment at a time if nothing else. The full range of off-axis angles will NOT need to be evaluated. A series of measurements near the FOV data will help significantly in verifying the expected performance in space. They verify that the most critical elements, the mirrors and other surfaces seen by the detector, are scattering in compliance with the analysis.

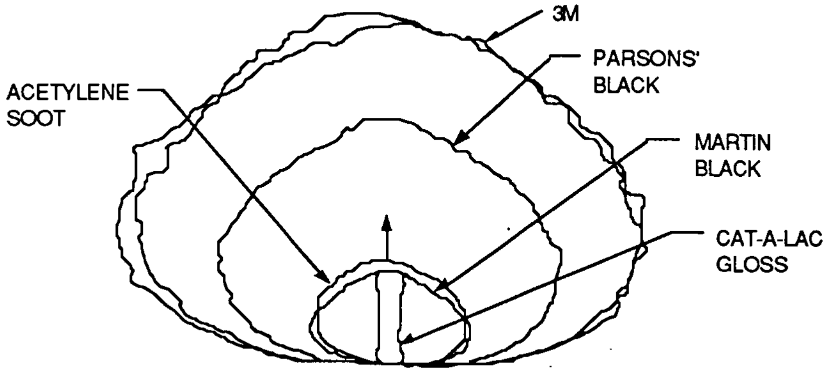
Very near angle scatter measurements are an important part of many of the missions. None of the existing BRDF instruments measure high quality, low scatter surfaces at angles less the about 0.5 deg. New methods are probably needed to evaluate the BRDF at angles much less than 0.5 deg. Techniques need to be developed that prevent scattered light from a bright "point-like" stellar sources from reaching the detector, be it the detector of the BRDF instrument or the science sensor.

(The optical fabrication group highlighted the need for developments in the areas of mid- and high spatial frequency figure measurements; also measurement of subsurface damage.)

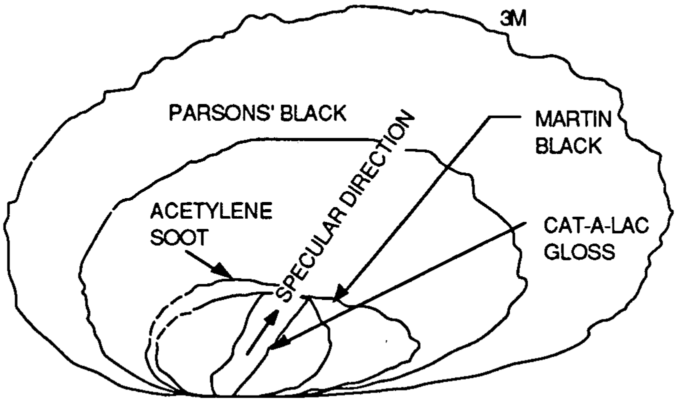
Table 35 summarizes the seven technologies for stray light measurement areas.

Table 35. Stray Light Measurement Enabling Technologies Program

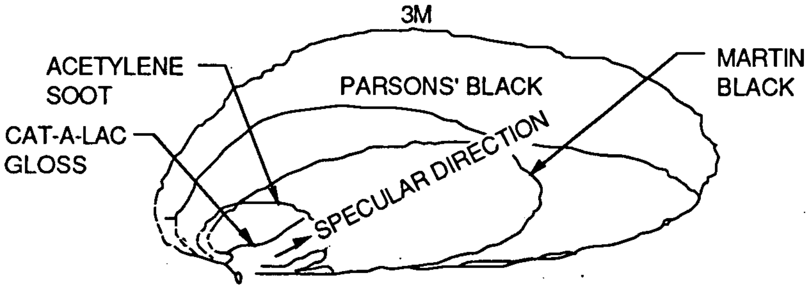
TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Stray Light Control	Non-Existent	Onboard Stray Light Control System	'95	Support RADC Research
BRDF	Limited	$\lambda < 0.4$ m $2 < \lambda < 6$ mm $\lambda > 20$ mm	ASAP	'93 - '97
Stray Light Testing	Limited, IRAS	System Level Test	'95	'93 - '97
Signatures	Lacking Hardware	Hardware for Polarization Signature Measurements of Scatter/Muller	'95	'93 - '94
Sources and Detectors	VIS and Near IR	More Powerful UV and Far IR Lasers and Detectors to Make BRDF and System Measurements	95	'95 - '99
Scatter Measurements	Visible and Some IR Bands	UV and Far IR Capabilities Very Near Angle Scatter Measurement Capability of < 0.5°	ASAP	'94 - '95
Calibration	Limited	Lambertian Reference Materials : UV, IR, Far IR	'95	'93 - '95



(a) NEAR NORMAL ANGLE OF INCIDENCE POLAR PLOT



(b) NEAR 30° ANGLE OF INCIDENCE POLAR PLOT



(c) NEAR 60° ANGLE OF INCIDENCE POLAR PLOT

Figure 39. Angle of Incidence Dependence for Black Absorbers.
(Robert Breault, Suppression of Scattered Light, Ph.D. Dissertation, University of Arizona, 1979.)

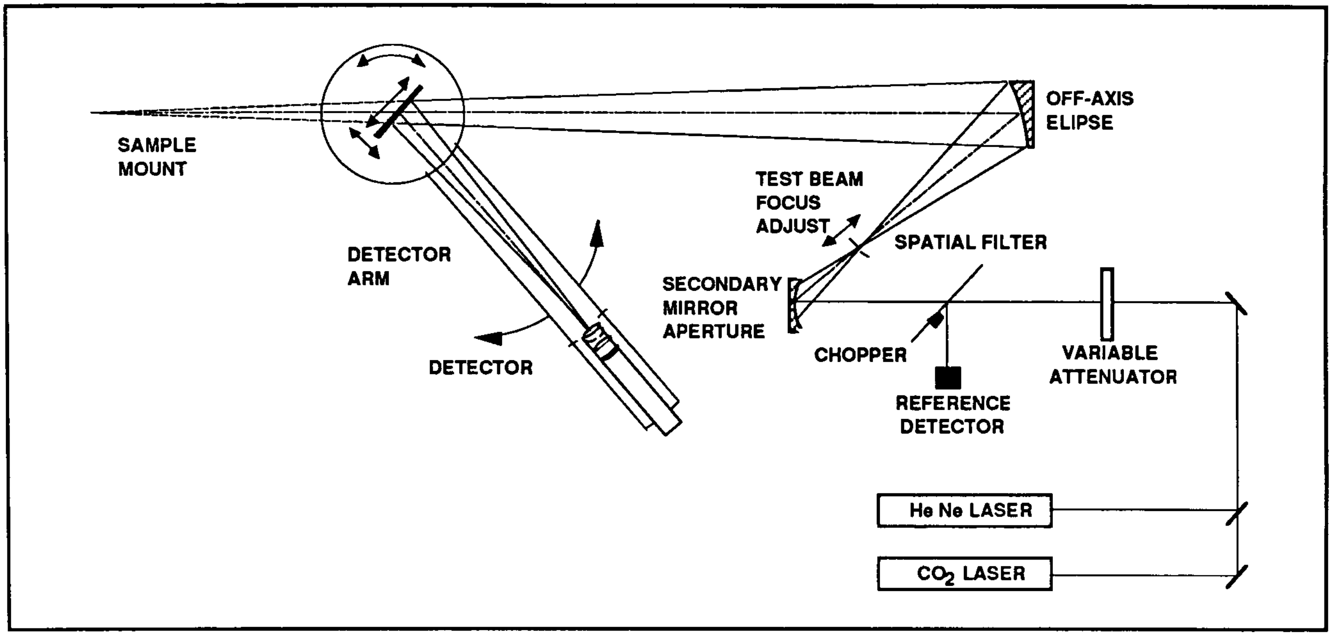


Figure 40. Scatterometer Schematic Diagram. (Courtesy of Breault Research Organization, Inc.)

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SECTION IV (Cont'd)
WORKSHOP PANEL REPORT:

5. OPTICAL SYSTEMS INTEGRATED MODELING

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INTRODUCTION

An integrated modeling capability that provides the tools by which entire optical systems and instruments can be simulated and optimized is a key technology development, applicable to all mission classes, especially astrophysics. Many of the future missions require optical systems that are physically much larger than anything flown before and yet must retain the characteristic sub-micron diffraction limited wavefront accuracy of their smaller precursors. It is no longer feasible to follow the path of "cut and test" development; the sheer scale of these systems precludes many of the older techniques that rely upon ground evaluation of full size engineering units. The ability to accurately model (by computer) and optimize the entire flight system's integrated structural, thermal, and dynamic characteristics is essential.

Two distinct integrated modeling capabilities are required. These are an *initial design capability* and a *detailed design and optimization system*. The content of an initial design package is shown in Figure 41. It would be a modular, workstation based code which allows preliminary integrated system analysis and trade studies to be carried out quickly by a single engineer or a small design team. A simple concept for a detailed design and optimization system is shown in Figure 42. This is a linkage or interface architecture that allows efficient interchange of information between existing large specialized optical, control, thermal, and structural design codes. The computing environment would be a network of large mainframe machines and its users would be project level design teams. More advanced concepts for detailed design systems would support interaction between modules and automated optimization of the entire system.

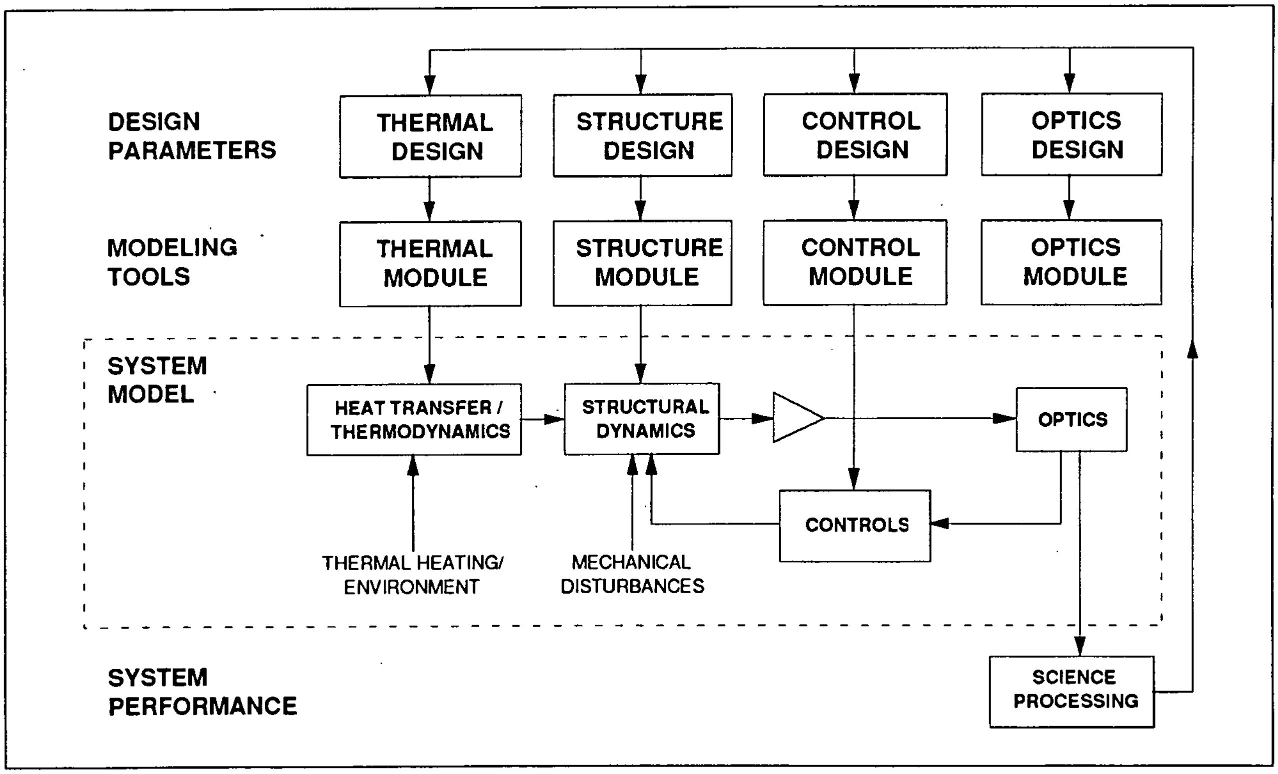

Figure 41. Integrated Modeling – Concept for an initial design capability that allows preliminary integrated system design and analysis. Implementation as a modular workstation-based code would allow a single engineer or a small design team to carry out system design and optimization.

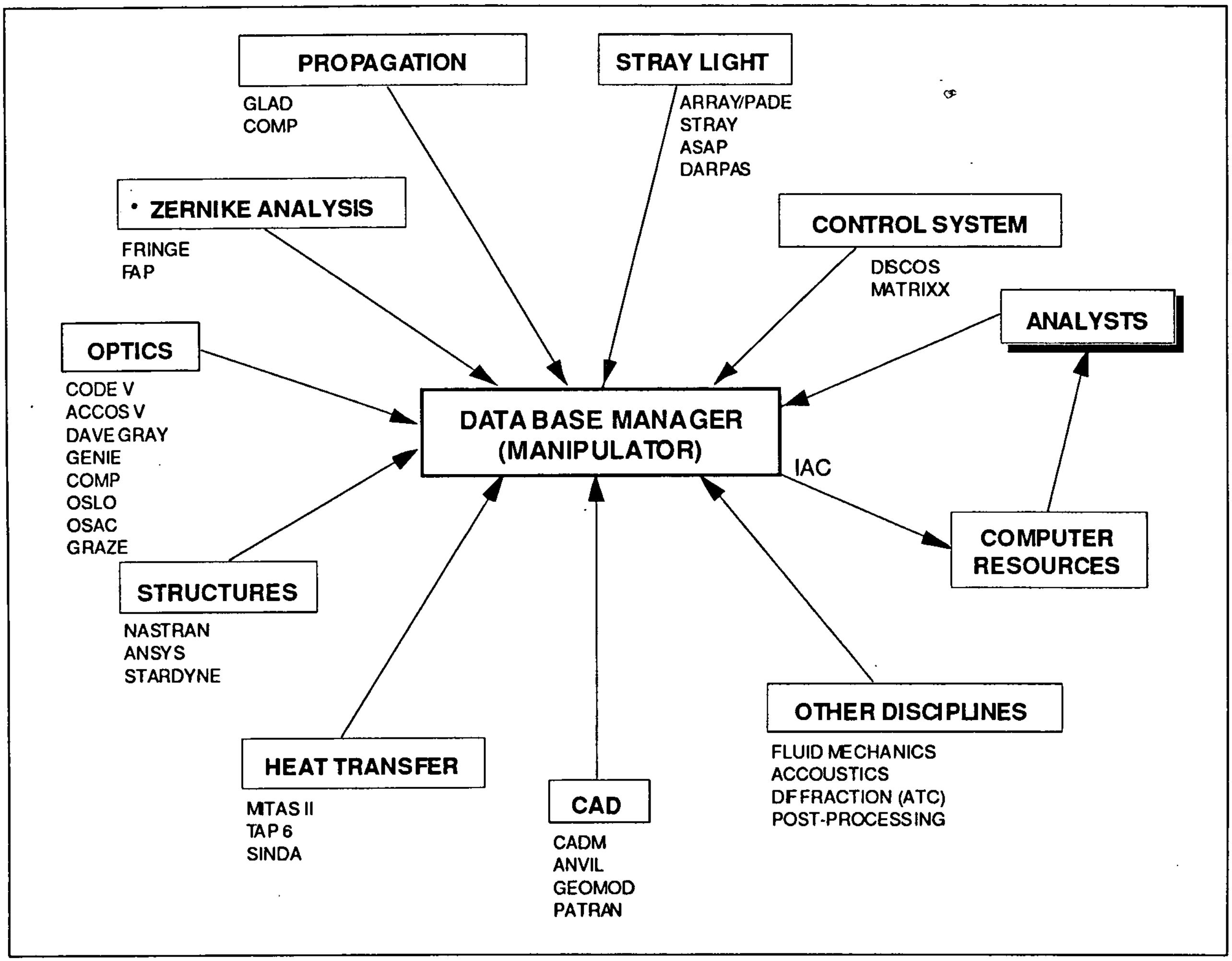

Figure 42. Integrated System Modeling (ISM) Concept

Since it will be difficult, perhaps impossible, to fully test future large space optical systems on the ground, the system designers and integrators will rely heavily on model predictions without the benefit of direct corroborating data. Confidence in the accuracy of the models must be high and this can only be achieved through validation against small scale experiments and existing flight performance data. Validation is a critical part of the integrated modeling effort.

In order to focus the NASA component of the integrated modeling technology effort, the panel adopted the set of guiding principles that are summarized in Table 36. Table 37 summarizes the recommendations of the panel with respect to technology development in modeling.

Table 36. Principles for Directed Technology Development in Integrated Modeling

1	NASA should undertake the development of an integrated modeling capability that supports initial design.
2	NASA should not attempt to develop its own universal detailed design and optimization system. Instead, NASA should support the development of an "industry standard" language for interpackage communication that includes networking and documentation. The goal is to achieve maximum leverage from the substantial investment and experience that can be obtained from existing specialized design software.
3	Ongoing validation of the accuracy of component and system level performance predictions is critical.
4	NASA should also obtain leverage from the strong modeling expertise that exists in academic and industrial laboratories.

Table 37. Recommended Integrated Modeling Technologies for Astrophysics Missions : 1992-2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Integrated Package for Initial Design	Software Tool that Allows Preliminary Design, Characterization, and Optimization of Optical Systems.	IMOS Software Package	All	'92 - '08
Interface Development for Detailed Optimization	Develop and Maintain an End to End Simulation Capability, Integrating Optical, Structural Control, and Environmental Design and Analysis Develop the Simulation Capabilities Covering Both Preliminary Design and Detailed Analysis	Cross Discipline Software Coupling Software Interface Standards Module Development and Validation Development of Package Interconnections Image Chain Analysis	All	'92 - '08
Validation	Validation to the Appropriate Detail of the Components and End to End Accuracy of the Integrated Packages Via Specific Laboratory Experiments	Simulation Software Propagation Software Database Development Integrated Software Tool(s)	All	'92 - '08
Modeling Research	Research Into the Basic Techniques for Optical System Modeling	Scattered Light Scalar and Vector Diffraction Image Processing and Inversion Test Data Integration Cryogenic Heat Transfer Micro Mechanics Image Reconstruction	All	'92 - '08

INTEGRATED PACKAGE FOR INITIAL DESIGN

A. Technology Assessment

Space optical systems of the future will not have large monolithic circular optical elements. Future telescopes will have actively controlled, segmented, hexagonal apertures with ultra fast focal ratios. The optical elements of future telescopes, interferometers, and optical arrays will be precisely positioned by optical metrology systems rather than by heavy mechanical linkages. The traditional techniques for understanding and comparing the performance of initial optical system designs, techniques that are only extensions of Rayleigh's original work, cannot adequately describe the performance of these complex, non-circular, alignment sensitive systems. Accessible software tools are needed that allow initial designs to be characterized and compared quickly and inexpensively. The characterization must include the system's response to dynamic and thermal perturbations as well as static performance. In addition, these tools must be capable of providing the science instrument designers with an early and reasonably accurate understanding of the expected imaging and radiometric performance of the system.

Workstation based software tools for initial end-to-end design of complex optical systems are not available. The JPL Integrated Modeling of Optical Systems (IMOS) Project is attempting to fill this need, but the work is preliminary. Broad accessibility will require the use of common hardware and operating environments. Maintenance support and the existence of an active user group is also required. The system should be consistent with the standard software interfaces developed for detailed design so that the initial design can easily (transparently) be used as the starting point for the detailed design process.

B. Development Plan

The proposed development plan is to complete, document, and maintain the IMOS package and encourage its wide distribution and use. The software architecture is highly modular, which encourages individual discipline modules from a wide variety of sources. A single institution with vested interest in the results, sophisticated software testing capability and configuration control discipline, should have the responsibility for the integration, validation, documentation, maintenance, and publication of the package. If the initial release of the package is widely accepted, commercialization of this activity may be possible. In any implementation, it must be closely linked to the ongoing validation program and it must be responsive to the user group.

INTERFACE DEVELOPMENT FOR DETAILED OPTIMIZATION

A. Technology Assessment

Existing software is available to carry out major portions of the modeling effort, but these software components are generally separate dedicated packages that address the geometrical design, physical optics analysis, structural analysis, and thermal effects separately. Since future missions will be dominated by the size and complexity of the optics, these separate areas must be tied together to permit system level evaluation of future design concepts.

Software packages (e.g., NASTRAN, ANSYS, SINDA, TRASYS, CODE V, GLAD, COMP, MATLAB, MATRIXX, EASY V, LINPACK, etc.) have been developed within several discrete technical disciplines for the separate analysis of the optical, structural, material, thermal, dynamic, science data analysis and control aspects of telescopes, spacecraft, and missions. Integration of existing software and the development of advanced codes are required to enable end-to-end simulation of system performance. A good start at producing software of this type has been taken under the U.S. Air Force funded Integrated System Modeling (ISM) effort and the ISM Lab tool. This effort is targeted at developing highly detailed subsystem designs whereas a design tool that allows rapid system design and analysis within the context of global system performance is needed. Unfortunately, the Air Force has withdrawn their support of this program and further development will cease with the delivery of the final report to the Phillips Laboratories (contract monitor) in January 1992. Nevertheless, the ISM might be an excellent jumping off point in the development of an end-to-end modeling capability.

B. Development Plan

A summary of the tasks associated with this development area is presented in Table 38. Specific need dates and development time frames for this technology program are identified. The goal of this effort is to develop and maintain an end-to-end simulation capability that integrates optical, structural, control, and environmental design and analysis. This technology addresses the development of both the loosely linked detailed analysis capability and the tightly integrated initial design capability. The individual tasks that comprise this program follow.

The first development, *Cross Discipline Software,* is the development of a common "front end" for integrating cross discipline initial design software. For example, this would include the tight linking of optical software to NASTRAN node generators through compilation using a common output language.

In addition to front end software, *Coupling Software* is necessary such that a preliminary level of design optimization can be carried out. This effort would provide for the design and development of software that would allow first order integrated optimization with the coupled design packages.

Concurrent with the other tasks, *Interface Standards* establishes a NASA wide board with industry and academic participation to develop interface standards for the various software simulation modules. The modules to be developed would be integrated into the detailed analysis package produced under this program.

Module Development and Validation are essential. This item includes creation and validation of each of the individual software packages that describe the components on an optical system. Validation against experimental data is critical. For example, thermal and mechanical stress tests would be carried out on a number of different lightweight mirror concepts, and the accuracy of prediction of response verified.

The last item implemented is the *Image Chain Analysis* effort. This is a full throughput image chain analysis (system verification) that includes all of the system and surface perturbations predicted by the various structural and environmental program modules. Taken as whole, this development program will provide the capabilities necessary for next century astrophysics missions.

Table 38. Required Interface Developments for Detailed Optimization

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Cross Discipline Software	Some Development Ongoing, But Very Limited ISM	"Front-End" Software to Integrate Cross Discipline Packages For Application to Initial Design	'97 Prelim '01 Update	'93 - '06
Coupling Software	Integrated Optimization Currently Not Possible	Develop Coupling Software	'98 Prelim '02 Update	'93 - '06
Interface Standards	ISM (Canceled by AF) Represents De Facto Standard	Develop Interface Standards for Existing and New Software Technology	'95 Prelim '97 Update	'93 - '06
Module Development and Validation	Incomplete	Create and Validate Program Modules Against Experimental Data	'98 Prelim '02 Update	'93 - '06
Image Chain Analysis	No General Purpose Capabilities Available	Develop Generic Capability by Adaptive Optics Modeling Example, i.e., Wavefront Sensing and Active Optics	'97 Prelim '02 Update	'93 - '06

VALIDATION

A. Technology Assessment

All modeling software that will be developed *must be validated as part of* the development effort. Software that cannot produce experimentally corroborated answers is useless. Since most of the advanced modeling capabilities required are very limited to non-existent, validation with experimental demonstrations or hardware has not occurred. In addition, the current materials and components database is inadequate and needs expansion. This is particularly important with respect to material micro properties.

B. Development Plan

Table 39 summarizes the development milestones necessary to meet the needs of the mission set. The individual tasks follow.

The validation of *Simulation Software* item is a comparison of new and existing software models against hardware data that is derived from tests and or actual mission operations. The accuracies of the simulations are evaluated and the respective models improved.

Validation of *Propagation Software* is also necessary. This effort validates the propagation software by comparing actual test data against the predicted propagation of wavefronts through sample systems, including polarization, diffraction and scattering effects. Laboratory systems would provide the data necessary for validation of the software predictions.

The establishment of a *Materials and Components Database* is essential. This effort establishes and maintains a materials and components database that has been verified by structural analysis. This database would contain qualified materials to be used for structural or optical components of systems. New materials and environmental conditions would be included in the database to eliminate the uncertainties presently existing in handbook data.

The final validation item, *Integrated Software Tools*, builds upon the experience gained with ground-based systems for extension to space-based systems of the future. Simulation software would be used to predict the effect of environment or dynamics upon the output of selected ground-based systems, and verified against observations. Once validated on ground-based systems, extension of the simulation capability to space-based systems could proceed.

Table 39. Required Developments In Validation

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Simulation Software	Very Limited	Validation of Simulation Software Against CSI or Equivalent Experimental Hardware	'98 Prelim '03 Update	'93 - '06
Propagation Software	Limited to GLAD and COMP	Validation of Propagation Software With Experimental Demos	'00 Prelim '04 Update	'93 - '06
Materials and Components Database	Inadequate	Establish and Maintain a Materials Database (Especially in Micro Properties)	'98 Prelim '02 Update	'93 - '06
Integrated Software Tools	Limited	Validate Simulation Capability of the Integrated Software Package With Ground Based Telescope Observations (e.g., Adaptive Optics)	'97 Prelim '00 Update	'93 - '01

MODELING RESEARCH

A. Technology Assessment

Research into the basic physics and analysis of the techniques needed to carry out optical modeling is required. Codes needed here have been developed in the past on an individual basis to solve specific problems/applications. As more problems have been solved, more software has been developed. Unfortunately, this method does not provide for the incorporation of these codes into a user friendly tool that can be used for subsequent application to other concepts. Polarization codes such as PMAP have been developed at the University of Arizona and the University of Alabama, Huntsville, under NASA sponsorship. Scalar diffraction codes that exist (GLAD V, formerly OASIS) have been very application specific with no existing integrated packages. COMP started within the DoD and has developed with Air Force funding at the University of Arizona and the Jet Propulsion Laboratory/California Institute of Technology. While most concepts covering optical propagation are well founded, there are some critical areas that need basic investigation for incorporation into an integrated modeling process. Examples within the discipline of optics are: (1) scattered light, (2) scalar and vector diffraction modeling for the optimization of submillimeter and far infrared imaging telescopes and for modeling of instruments, (3) image formation and reconstruction from synthesized large apertures (fringe patterns), (4) integration of subsystem models, (5) thermal background noise modeling for optimization of infrared imaging telescopes, (6) nonlinear micromechanics, and (7) radiometric fidelity. It is important that NASA support this development as the length of time required to develop these codes negates the incentive within private industry to commit internal funding.

B. Development Plan

This research would produce a series of algorithms to be used in integrated optical modeling codes. Table 40 summarizes the techniques required with the individual tasks explained below.

Diffraction Modeling will provide for the development of a full vector analysis approach to diffraction imagery that can be used in polarization sensitive systems in all wavelength regions. The initial research would focus on the submillimeter regime. As the development program matures, extensions to shorter wavelength regimes would be implemented.

The *Scattered Light* research effort will extend the knowledge of scattered light generation, thermal emission, and polarization. This would be accomplished through a series of measurements at various wavelengths on calibrated sample surfaces. The resulting data would be used to improve surface scattering theory and direct advanced modeling algorithm development.

Image Processing and Inversion research would build upon current algorithms and provide basic research for the extension of radio astronomy techniques to image processing and wavefront inversion at optical frequencies. It would also support the automation of wavefront reconstruction, phase retrieval, and optical prescription evaluation. Additionally, advanced research would be conducted on synthesized array imaging and image reconstruction. These program elements are necessary for full exploitation of current and novel techniques in future astrophysics systems.

Test Data Integration research would provide a methodology for integrating subsystem test data within the overall system model for design verification.

The *Cryogenic Heat Transfer* research would refine the modeling of cryogenic heat transfer to permit high quality (accuracy) modeling of cooled optical components as well as detector focal planes. This effort would initially concentrate on the submillimeter and IR systems (liquid helium temperature heat transfer), with later extension to warmer systems.

The *Micro Mechanics* research activity involves a set of hardware and software experiments necessary for the modeling of nonlinear micromechanics in candidate materials. This effort would provide important information regarding the ability of materials to survive stresses, as well as to determine the long-term stability of candidate optical structures.

Table 40. Required Developments In Modeling Research

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Diffraction Modeling	EM/Polarization Not Used	Develop and Incorporate Advanced Scalar and Vector Diffraction Codes	'96 Prelim "00 Update	'93 - '02
Scattered Light	Sparse Database	Accepted Measurement Procedures Experimentally Verified Code	'95 Prelim '98 Update	'93 - '01
Image Processing and Inversion	Limited Experience	Automation of Retrieval and Wavefront Reconstruction Codes Application of Radio Astronomy Codes Synthesized Array Imaging and Reconstruction Research	'96 Prelim "00 Update	'93 - '01
Test Data Integration	Non Correlated Techniques	Design Verification	'97 Prelim "00 Update	'93 - '06
Cryogenic Heat Transfer	Very Limited	Develop Advanced Codes for Predicting/Simulating Cryogenic Heat Transfer	'97 Prelim "00 Update	'93 - '03
Micro Mechanics	Limited	Research and Development of Modeling Codes for Predictions of Micro Mechanics of Structural Features	'99 Prelim '04 Update	'93 - '06

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SECTION IV (Cont'd)
WORKSHOP PANEL REPORT:

6. ADVANCED OPTICAL INSTRUMENTS TECHNOLOGY

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Kurt Weiler	United States Naval Observatory
Bruce Woodgate	NASA Goddard Space Flight Center

INTRODUCTION

The science objectives for proposed NASA missions for the next decades push the state of the art in sensitivity and spatial resolution over a wide range of wavelengths, including the x-ray to the submillimeter. While some of the proposed missions are larger and more sensitive versions of familiar concepts, such as the next generation space telescope, others use concepts, common on the Earth, but new to space, such as optical interferometry, in order to provide spatial resolutions impossible with other concepts. However, despite their architecture, the performance of all of the proposed missions depends critically on the back-end instruments that process the collected energy to produce scientifically interesting outputs.

Much of the science possible with these proposed missions requires not only their high spatial resolution, but also high spectral resolution on the back-end instrument. Thus, one of the challenges in the area of advanced optical instruments is the development of higher resolution and higher sensitivity spectrometers. The wavelength range includes the infrared to the x-ray. The challenges are acute at the extremes of the range, including the UV, and especially the x-ray, where significant progress has been made, but further advances are required for future NASA x-ray missions. Tunable filters, another means of providing spectral resolution, may also play an important role in future missions.

Some of the proposed missions have as their goal observations that require the accommodation of enormous dynamic ranges in their fields of view. One particular observation is the detection of a faint planet near a bright star. Proposed techniques that require development include coronagraphs, which use occulting masks and Lyot stops, and interferometric methods, which use interference nulls to suppress light from the bright source. Another area of great interest is the development of beam combination techniques for optical interferometers. Particularly challenging are high spectral resolution cryogenic combiners for multiple beam interferometers, such as the proposed lunar optical interferometer.

Finally, there are several technologies whose development would enable or enhance a number of advanced optical instruments. These include materials and components for the far infrared region for missions such as SIRTF and LDR; coatings for the extreme ultraviolet, for missions such as fuse; coatings for the x-ray region, for reflective spectrometers; and low dispersion, wide wavelength range optical fibers for application to spectrometers and spatial filters.

The Advanced Optical Instruments Technology panel was chartered with defining technology development plans that would best improve optical instrument performance for future astrophysics missions. At this workshop the optical instrument was defined as the set of optical components that reimage the light from the telescope onto the detectors to provide information about the spatial, spectral, and polarization properties of the light. This definition was used to distinguish the optical instrument technology issues from those associated with the telescope, which were covered by a separate panel.

The panel identified several areas for optical component technology development: diffraction gratings, tunable filters, interferometric beam combiners, optical materials, and fiber optics. The panel also determined that stray light suppression instruments, such as coronagraphs and nulling interferometers, were in need of general development to support future astrophysics needs. In the sections following, the specific technology areas within these general headings are detailed.

Table 41 summarizes the recommended technologies for Advanced Optical Instruments.

Table 41. Recommended Advanced Optical Instruments Technologies for Astrophysics Missions : 1992-2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Diffraction Gratings	Increased Diffraction Efficiency for Increased Signal From Same Sized Aperture Instrument Reduced Stray Light for Large Dynamic Range of Latest CCD Technology and Photon Counting Arrays Produce Holographic Gratings With Good Diffraction Efficiencies for Both Conventional and Aberration Corrected Gratings Develop Gratings for X-Ray Telescope Missions With Increased Diffraction Efficiency	UV Echelles : Low Scatter, High Diffraction Efficiency Aspheric Gratings : Variable Blaze Blazed Holographic Gratings : High Diffraction Efficiency X-Ray Gratings : Multilayer Coatings, Order Sorting Coatings, High Frequency Transmission Gratings	FUSE, HST II, HST III, NGST AXAF II, VHTF, XMM, FUSE	'92, '95, '97, '02 '92,'95 '02
Tunable Filters	Develop Narrow-Band Tunable Filter for Detecting Velocity Distribution of Extended Emission Line Objects for UV, VIS and IR	AOTFs Fabry-Perot : UV Mirrors Birefringent Filters : Achromatic Waveplates for UV and IR	HST III, NGST	'97, '02
Interferometric Beam Combiners	Enable High Angular Resolution Imaging Concepts and Optical Interferometry Missions	Pupil Plane Beam Combiner Image Plane Beam Combiners	AIM, Imaging Interf., Filled Arm Fizeau	'97, '04
Optical Components	Develop Far Infrared (FIR) Materials and Components Develop Simplified Achromatic Cameras and Correctors Develop High UV Transmission Curved Windows Develop High FUV and EUV Reflectivity Mirrors and Gratings Develop Large-Format, Soft X-Ray Windows for X-Ray Detectors	FIR Materials Binary Optics UV Windows EUV High Reflection Coating Beryllium Vapor Deposition Windows, Diamond Vapor Deposition Windows, Tungsten or Silicon Strongbacks	SMIM, SIRTF, LDR, FUSE, HST III, NGST AXAF II, VHTF, XMM	'96, ' 98, '01 "92, '97, '02 '95, '02
Stray Light Suppression/High Dynamic Range	Develop Techniques and Components for Diffracted and Scattered Light Suppression	Coronagraph and/or Nulling Interferometer Woods Filters	NGST, Imaging Interf., AIM, LDR NGST, Imaging Interf.	'97, '01, '02, '04 '02, '04
Technologies With High Potential	Efficient UV and IR Transmission Interferometer Connection	UV - IR Wide Bandwidth Fibers Multi-Object Spectrograph Visible, Low Dispersion Single Mode Fibers Non-Linear Optics Phase Conjugation	HST II, HST III, NGST Imaging Interferometer	'95, '97, '02 '06

DIFFRACTION GRATINGS

A. Technology Assessment

There are a number of technology development areas for diffraction gratings but a general concern of the panel needs to be brought forward. This was the need for consistent funding for the grating production industry to flourish. The grating industry in the United States is very small, consisting of two or three companies that do not have the resources required to fund the technology developments identified here. External funding is required to support grating development within the United States. Indeed, Hitachi Incorporated (Japan) now leads the field in producing variable line spaced gratings with the lowest scatter.

Quality diffraction gratings will be required by all future astrophysics telescope projects, including HST upgrades, FUSE, NGST, and SIRTF. Producing better quality gratings with lower scatter and higher efficiency will benefit all of these missions. This is an area were technology development funding is extremely important, and in its projected plan the panel allocated it the highest funding level. The following paragraphs address the state of the various grating types in need of development.

UV Echelles - The major needs for ultraviolet echelle gratings are to improve diffraction efficiency and to decrease scattered light. The diffraction efficiency directly affects the transmittance of the optical system, which in turn determines the signal to noise ratio. The scattered light needs to be decreased to take advantage of the large dynamic range of the latest CCD technology and photon counting arrays. Without improving the scattered light, weak spectral lines are not detected because they are obscured by the cross talk from the bright spectral lines. UV Echelles will be used in the second and third generation instruments for HST and also for NGST. If full advantage is to be taken of the performance of the detectors that are now available, then UV echelle performance will need to be improved.

Aspheric Gratings - Steep aspheric gratings are needed for improvements in performance of UV spectrometers. Substituting aspheric gratings for plane gratings enables the number of components in the spectrometer system to be reduced, which is of particular importance in the far UV where each mirror reflection causes a considerable loss of light. The component reduction is possible because aspheric gratings can focus as well as disperse the light. This eliminates the need for separate collimator and camera systems that are required when plane gratings are used. High efficiency aspheric gratings with variable blaze angles are currently not available. The availability of these high diffraction efficiency gratings would result in a considerable improvement in the spectrometer performance for second and third generation instruments for HST, FUSE, and NGST.

Holographic Blazed Gratings - Holographic gratings have the advantages of focusing as well as dispersing the light, so no other components are needed in the spectrometer system. This leads to increased transmittance, because the reflection and obscuration losses in the collimator and camera used in conventional systems are eliminated. Holographic gratings also have low scattered light, an order of magnitude below conventional gratings. Holographic gratings with good diffraction efficiencies will find application in a number of astrophysics programs and will lead to improvements in the spectrometer performance for second and third generation instruments for HST, FUSE, and NGST.

X-Ray Gratings - One of the major goals of the next generation x-ray astronomy missions is high resolution spectroscopy of a large number of sources. High resolution spectroscopy of emission lines will allow us to determine the temperature, velocity, density, ionization state, and elemental abundances of the gas in x-ray emitting sources. Such measurements will resolve many outstanding questions concerning the nature of the astrophysical sources, raise many more new questions, and, in general, deepen our understanding. While outstanding advances have been made in nondispersive detectors, the resolving power of such devices is unlikely to exceed a few hundred at energies below 1 keV. High resolution spectroscopy at energies near and below 1 keV will require the use of dispersive elements. The timely development of x-ray gratings for dispersive spectroscopy is crucial to the success of the next generation of NASA x-ray astronomy missions.

X-Ray Transmission Gratings - A transmission grating consists of a periodic array of non-transmissive bars separated by gaps. X-rays passing through the gaps constructively interfere if they are diffracted so that the path length difference of rays passing through adjacent gaps is a multiple of the x-ray wavelength. The resolving power of a grating is constant in wavelength; therefore, the resolution improves at lower energies. The resolving power of a grating is determined by the line spacing (the spacing between centers of adjacent bars), the order of the diffraction (the number of multiples of the wavelength in the path length difference), and the angular resolution of the system including errors due to the telescope, spacecraft pointing, detector resolution, and aberrations. To obtain very high resolution, it is necessary to have very small line spacing and good system angular resolution.

To a first approximation, the thickness of the grating should be sufficient to stop the x-rays at the energy of interest. The theoretical maximum efficiency for a thick bar grating in first order is 20%. The maximum occurs when the bar width is exactly half the line spacing. However, the efficiency of the grating over a selected energy band can be increased by choosing a grating thickness such that the phase of the x-rays passing through the material is shifted so that the x-rays transmitted through the material add constructively to the diffraction pattern. This effect has been demonstrated to double the efficiency of a grating over a selected band.

The current state of the art in transmission gratings is given by the gratings currently being prepared for the AXAF. Two transmission gratings have been selected, one optimized for low energy and the other for higher energies. The low energy grating is being constructed at the Laboratory for Space Research in Utrecht, the Netherlands. The grating is designed to cover the energy band from 0.1 to 4 keV. It is an array of facets, each roughly 50 mm square. The facets are produced by replication from a master. The master was made using an interferometric technique. Replication is carried out by contact printing the master onto a photo-resist substrate, developing the photo-resist, and then electrodepositing the metal grating. The gratings are 0.6 mm thick gold, have a line density of 1024 lines/mm, and have a bar-to-period ratio of 0.5. The grating facets are placed to approximate the shape of a Rowland toroid to reduce the aberrations that arise when a grating is used in a focusing system. The spectrometer system operates in first order and has a wavelength resolution of 0.05 Å, giving a resolving power which is about 2000 near 0.1 keV falling to 100 at a 2 keV. The efficiency of the grating is expected to be close to 10% for energies below 1 keV. Constructive interference of x-rays transmitted through the bars increases the efficiency to about 20% near 2 keV. The high energy grating covers an energy band from 0.5 to 9 keV. The grating, being constructed at The Massachusetts Institute of Technology (MIT), is an array of facets, similar to the low energy grating. There are approximately 480 facets, each 2.5 cm square. The facets form a Rowland torus to reduce aberrations. The grating is actually a hybrid of two different types of facets optimized for medium and high energies. The two types of facets are oriented at slightly different angles to separate the spectra. Because of the strong dependence of x-ray reflection efficiency on grazing angle, the outer mirrors of an x-ray telescope provide most of the effective area at lower energies, while the inner mirrors provide the effective area at higher energies. Therefore, an approximate selection of energy range can be made by considering a subset of the nested mirrors. The outer three mirrors provide 70% of the effective area of the telescope for energies below 3 keV. The facets covering the outer mirrors of the AXAF telescope are optimized for energies near 1 keV. They are 0.5 mm thick silver mounted on 0.5 mm thick polyimide for mechanical support. The line spacing is 0.6 mm. The inner three mirrors of the telescope provide all of the effective area above 4 keV. The gratings covering the inner mirrors are optimized for this high (4 to 9 keV) energy range. The gratings are 1.0 mm thick gold supported by

1.0 mm thick polyimide. The line spacing is 0.2 mm. Both types of facets were fabricated at MIT using x-ray lithography.

X-Ray Reflection Gratings - Reflection gratings employ the interference of x-rays reflected from an array of grooves. Because of the low reflectivities characteristic of the x-ray region, this type of grating has not enjoyed the popularity of transmission gratings. Reflection gratings have not yet been flown on an x-ray astronomy payload. However, recent development of the conical diffraction mode and improvements in grating manufacture promise to make reflection grating a vital part of the next generation of x-ray spectroscopy missions. In addition, the use of multilayer diffraction gratings promises to make possible near normal incidence spectrometers for soft x-rays. Reflection gratings can be oriented so that the x-rays are incident perpendicular to the grooves ('in-plane' mount) or so that the x-rays are incident parallel to the grooves ('off-plane' mount). Use of the off-plane mount has been suggested as a way to vastly increase the efficiency of x-ray reflection gratings. In the off-plane mount, the polar angle (the angle about an axis parallel to the groves) of the incident and reflected rays is the same. Diffraction causes the azimuthal angles of the reflected rays to vary, producing a cone of light (conical diffraction). For use with x-rays the angle of incidence onto the grating can be made very small, so the high reflectivities available at grazing incidence can be exploited. In-plane mount gratings encounter an efficiency versus resolution trade-off when used at grazing incidence because of shadowing of each groove surface by the preceding ridge. However, the in-plane mount has the advantage that for a given groove spacing its resolution is significantly higher because the projected line spacing (perpendicular to the line of incidence) is much smaller. X-ray reflection gratings are currently manufactured using mechanical ruling or holographic lithography. In mechanical ruling, a diamond stylus scratches lines into a thin layer of metal. The shape of the groove is determined by the stylus. The accuracy of the line spacing is determined by the controlling machine. The extension of mechanical ruling to variable line spaced grating is relatively straight forward. Holographic techniques are used to produce an interference pattern on a photoresist. After developing the photoresist, the surface is etched. The accuracy of the pattern produced in this way exceeds that possible with mechanical ruling. Both of the techniques offer promise for the future and both should be developed. At present, there are no manufacturers of low scatter variable line spaced gratings in the U.S.

Order Sorter Coatings - Currently, order sorting filters have to be used in front of the detectors for spectrometers to eliminate spectral contamination from higher orders. These filters have the disadvantage of reducing the light transmission and causing aberrations, which have to be compensated. The filters could be eliminated if the reflective coatings on the grating performed order sorting, by having a short wavelength cutoff. This would lead to spectrometers with better transmission and spectral resolution to be used for HST (second and third generation) and NGST.

B. Technology Development Plan

Table 42 summarizes five technologies that the panel recommended.

UV Echelles - The diffraction efficiency of echelle gratings is mainly controlled by the groove profile shape, which should ideally be triangular with a flat reflecting facet. This is hard to achieve in practice, and varying angles of the groove facets and distorted groove profiles lead to lower diffraction efficiencies. Research into grating ruling technology is needed to improve the groove profile shapes. The scattered light is controlled by the variations in the groove spacing and also the surface roughness of the grooves. For ruled gratings the scattered light tends to be dominated by the errors the ruling engine makes in spacing the grooves. Technology development is needed to make ruling engines with better control on the groove spacing. Once the groove spacing has

Table 42. Required Developments In Gratings Technology

TECHNOLOGY	CURRENT TECHNOLOGY	REQUIREMENTS	NEED DATES	TECH. DEV. TIME FRAME
UV Echelles	Scattered Light : 10^{-5}	Lower Scattered Light : 10^{-7}	'95, '97, '02	'93 - '04
Aspheric Gratings	No Ruling Engines for Multiple Blaze Gratings	Ruling Engine With Variable Blaze for Steep Aspheres	'96, '04	'93 - '04
Holographic Gratings	Peak Diffraction Efficiency of 33% With Sinusoidal Profile	Blazing Techniques For Peak Diffraction Efficiency of 80% Low Frequency Variable Spaced Ruling : 30 – 60 grooves/nm	'96, '97, '04	'93 - '04
X-Ray Gratings	Transmission Gratings : Line Spacing : 5000 lines/mm at 1 .0 mm Thick	Low Scatter Transmissive Gratings Line Spacing : 2x10^4 Lines/mm	'95, '97, '05	'93 - '04
Coatings	Broadband Metallic Coatings	Coatings With Short Wavelength Cutoff for Order Selection	'95, '02	'93 - '04

been better controlled, the surface roughness will need to be decreased to further reduce the scattered light. Ion etching is a promising way of doing this, but it needs further development to become a production technique.

Aspheric Gratings - Ruling steep aspheres is a problem because the ruling diamond has to move up and down while still ruling straight grooves that are very precisely spaced. The blaze angle of the grating also needs to be changed across the grating surface to maintain reasonable diffraction efficiency. To do this, the angle of the diamond needs to be changed as the grooves are ruled. No ruling engine at present has this capability. This effort should concentrate on the technologies necessary to produce ruling engines that can rule steep aspheres while varying the blaze angle on the grating.

Holographic Blazed Gratings - The main area of improvement for holographic gratings is their diffraction efficiency, which only reaches a peak of 33% due to their sinusoidal groove profiles. Improving their diffraction efficiency will lead to spectrometer systems with reduced scattered light and increased transmission. There have been attempts to improve the diffraction efficiencies, and peaks of 60% have been obtained for gratings with high ruling frequencies where the groove profile has been ion etched to give a distorted triangle. Research is needed to find a general way of making holographic gratings with higher diffraction efficiencies.

X-Ray Gratings - Two types of gratings are required: transmission and reflection.

X-Ray Transmission Gratings - To achieve the high resolutions (R ~ 3000 to 10,000) desired for the next generation of x-ray astronomy missions, it will be necessary to obtain increased line densities. Since the thickness of the gratings is fixed by the requirement that they stop x-rays (or optimally cause them to interfere constructively), increased line density means increased aspect ratio of the bars (and gaps). The present state of the art is 5000 lines/mm with 1.0 mm thick gratings, giving a resolving power that is about 2000 near 0.1 keV falling to 100 at 2 keV. This can probably be increased by a factor of 2 or 4. This research is probably best done at universities or NASA centers. The main technological development necessary for the payloads in the Astrotech 21 mission set, will be the development of inexpensive methods for fabricating large areas of gratings. A transmission grating must cover the entire aperture of the telescope. The main spectroscopic x-ray mission in the set is the Very High Throughput Facility. The effective area of the telescopes for this satellite is given as 30 m^2. The gratings for such a telescope will need a similar surface area. The two methods used to produce the AXAF gratings are, at present, the most promising. Research on replication techniques should emphasize their extension to higher line densities and improved uniformity of grating thickness. Research on x-ray lithography should emphasize techniques for the mass production of gratings. If x-ray lithography comes into widespread use in the semiconductor industry, then much of that technology will be transferrable to grating manufacture.

X-Ray Reflection Gratings - Advances in grating manufacture are necessary to obtain high line densities, improved groove figures, and variable line spaced gratings. High line densities are necessary to achieve the high resolutions called for in future missions, particularly the Very High Throughput Facility. Improved groove figure is crucial to obtain high efficiencies. Variable line spacing will be important to achieve high resolution when the gratings are placed behind the telescope. As discussed above for transmission gratings, to minimize the aberrations due to the focusing geometry, the grating surface forms a Rowland torus. For reflection gratings, the groove spacing along the grating must vary slightly to compensate for the converging beams. Variable line spacing adds another level of complexity to grating manufacture. Both mechanical ruling and holographic lithography offer promise for the future and both should be developed.

Order Sorter Coatings - The principal item is the development of a coating design where the short wavelength cutoff could be selected. This program also includes the development of techniques for application of the coating to the grating.

TUNABLE FILTERS

A. Technology Assessment

Tunable filters encompass Acousto-Optic Tunable Filters (AOTF), Piezoelectric tuned Fabry-Perot Filters, and Birefringent Filters. These filters need further development for detecting the velocity distribution of extended emission line objects by looking at the spectral shifts of their emission lines in the ultraviolet, visible, and near IR.

Development of these tunable filters would make them available as candidates for NGST and HST.

AOTFs have already been developed for the visible and IR over the wavelength range 250 nm to 5 μm. When used in an imaging mode for astrophysics, it would be an advantage to eliminate their side lobes, which are about 5 percent of the central peak. These give the appearance of false images.

Fabry-Perot Etalons have been developed and are very effective for the visible region. They would have greater application if their use could be extended into the ultraviolet region (Figure 43).

Birefringent Filters require achromatic waveplates for their operation. These waveplates are currently available for the wavelength range 400 nm to 1700 nm. Development is needed to extend the use of these high-efficiency broadband filters into the infrared and ultraviolet regions.

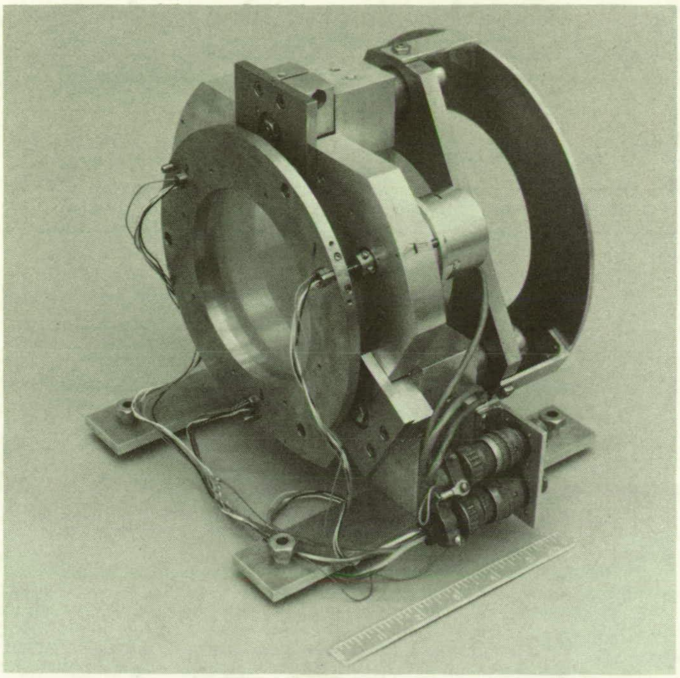

Figure 43. Fabry-Perot Etalon – 10 cm diameter, 10 cm separation scanning Fabry-Perot Etalon for 100 µm wavelength using gold-coated nickel mesh. (Courtesy of Herbert M. Pickett.)

B. Technology Development Plan

Table 43 summarizes three technology developments: AOTF, Fabry-Perot Etalons, and birefringent filters.

AOTF - Technology development is needed to adjust the acoustic wave profile so that the system would be apodized to eliminate the side lobes. Development is also needed to produce adjustable bandwidth AOTFs by adjusting the acoustic wave profile. To develop AOTFs for ultraviolet region below 250 nm and for the infrared region beyond 5 microns, new materials will need to be researched and developed. For the far infrared, there is also a question of power consumption since the power needed goes approximately as the wavelength squared.

Fabry-Perot Etalons - The development program to extend Fabry-Perot Etalons to the UV region hinges upon the availability of UV mirrors. This effort would concentrate on the development and manufacture of highly reflective mirrors for the ultraviolet and their integration into the filter. Figure 44 illustrates a state-of-the-art Fabry-Perot etalon fabricated for the far-IR.

Birefringent Filters - Extension of birefringent filters into the infrared and ultraviolet requires a development program in achromatic waveplates. This program would concentrate on developing achromatic waveplates for the 1700 Å to 4000 Å region.

Table 43. Required Developments In Tunable Filter Technology

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
AOTFs	VIS and IR Units Demonstrated in Laboratory	Develop a UV and Far IR AOTFs Eliminate Sidelobes	'97, '04	'93 - '04
Fabry-Perot	Visible Region	UV Region Fabry Perot	'97, '04	'93 - '04
Birefringent Filters	Small Angle and Low Throughput, Visible	Achromatic Waveplates and Polarizers 1700 Å < λ < 4000 Å	'97, '04	'93 - '04

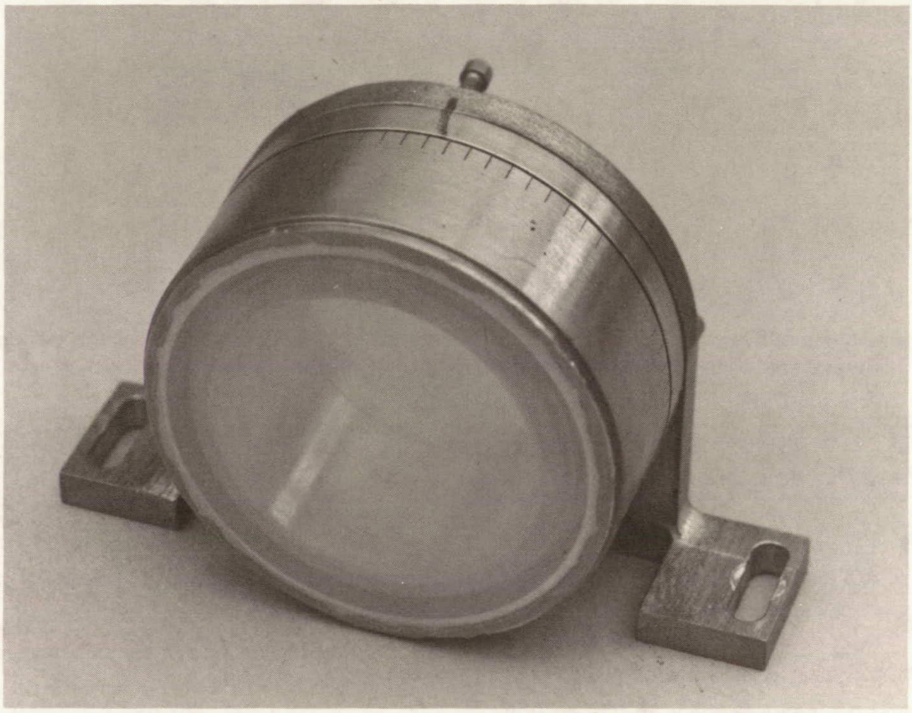

Figure 44. Cryogenic Fabry-Perot Etalon for Far R – A 3-cm diameter fixed separation Fabry-Perot that can be cooled to 4 K. The design uses free-standing metal meshes that can be repeatedly cooled with reproducible spacing of 1 part in 10^6. (Courtesy of Herbert M. Pickett.)

INTERFEROMETRIC BEAM COMBINERS

A. Technology Assessment

High angular resolution imaging at the milliarcsecond level and below requires the use of optical interferometers. Two missions are currently planned, the Astrometric Interferometry Mission and the Lunar Imaging Interferometer. These interferometers will require the development of beam combiners to join the light from the separate telescopes in a coherent manner.

While the light paths at the focus of a conventional telescope automatically combine to form an image, in an interferometer, such automatic combination cannot be assumed when combining the light from separate telescopes. Successful interference requires the beam combiner to perform several functions. The beam combiner's optical output will be detected by single pixel or focal plane arrays. The optical output must contain information that will enable the interferometer control computer to align and phase itself. In addition the beam combiner must lend itself to optical path monitoring with laser interferometers, when used in astrometric interferometers. Tilt and phase error signals must be derivable from combiner output. Beam combination will also need to be compatible with low resolution spectroscopy, consistent with the aperture dilution of the interferometer.

Several approaches to building beam combiners exist. Wavefronts can be combined at a pupil plane or an image plane. In addition combiners may be designed to accommodate two or more input beams. Combiners in the IR must also minimize the thermal background seen by the detectors. In this case, the beam combiner should be considered as part of the cryogenic optics in front of the detector. Currently beam combiners have been built to combine the light from two telescopes. The next stage is to develop beam combiners for combining the light from three or more telescopes onto the detector. Using three or more telescopes is important for self-calibration using the closure phase. For the beam splitter, it introduces the additional problem of maintaining the polarization orientation to ensure good interference. Cryogenic beam combiners also need to be developed for infrared interferometers.

B. Technology Development Plan

This program will focus on the development of various pupil and image plane techniques along with optical fiber research for the design and development of beam combiners that combine three or more sources. Additionally, designs will be developed for cryogenic applications (IR). The *Pupil Plane* effort will provide for research into pair-wise and n-wise pupil plane techniques. It will develop both types of pupils along with the eventual fabrication and test of a beam combiner (both approaches). The *Image Plane* development effort will concentrate on the development of an n-wise image plane combination culminating in the fabrication and test of a beam combiner. Table 44 summarizes both of these technologies.

Table 44. Required Developments In Beam Combiner Technology

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Pupil Plane Beam Combination	Simple Case Under Construction	Advanced Pair-Wise Pupil Input Beams : ≥ 3 Build and Test Pair-Wise Pupil Plane Beam Combiner Cryogenic Application	'94	'93 - '94
	No Existing Capabilities	N-Wise Pupil Input Beams : ≥ 3 Build and Test N-Wise Pupil Plane Beam Combiner Cryogenic Application	'96	'94 - '96
Image Plane Beam Combination	No Existing Capabilities	N-Wise Image Plane Input Beams : ≥ 3 Build and Test N-Wise Image Plane Beam Combiner Cryogenic Application	'97	'95 - '97

OPTICAL MATERIALS ISSUES

Table 45 summarizes the recommended developments within this area. A discussion of the individual topics addressed here follows.

Far Infrared Materials/Components - The far infrared region (beyond 20 μm) is sadly neglected as far as development of components, materials, and coatings. Although this transition region to the submillimeter regime is of interest to astronomers, there is no military or commercial

Table 45. Required Developments In Optical Components Technology

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Far IR Materials	Free-Standing Possible, Short Wavelength Units are Fragile and Need Supporting Substrate Well Developed at 10.6 µm	Free Standing and Supported Metal Grids and Meshes Transmissive Elements $\lambda > 10.6$ µm	'96, '04	'92 - '03
Binary Optics	Major Development Has Been for IR Beam Control	Combined Binary and Refractive Designs	'96, '03	'92 - '98
UV Windows	Good Transmission for Plane Windows Poor Transmission For Curved Windows	Good UV Transmission for Curved Windows	'96, '03	'92 - '04
EUV Coatings	Reflectance @ $\lambda \approx 1000$ Å : 45%	Reflectance @ $\lambda \approx 1000$ Å : 80%	'93, '03	'92 - '04
X-Ray Windows	Low Transmission, Small Windows : ≤ 6 mm Diameter	Beryllium Vapor Deposition for Windows > 6 mm Diamond Vapor Deposition for Windows > 6 mm Tungsten or Silicon Etched Strongbacks	'96	'92 - '96
X-Ray Reflection Coating	Reflecting Multilayer Dichroics @ 44 Å	Measurement and Characterization of Multilayer Coated Gratings	'96, '03	'92 - '03

interest so there has hardly been any funding into its development. For the far IR region, the materials for transmissive elements and their antireflection coatings need to be developed. The major problems for the antireflection coatings are a lack of measured materials, and the difficulty of putting them on in sufficient thicknesses without self-destruction caused by thin film stresses. Metal grids and meshes, which are so important in the submillimeter region, also need to be extended in the far IR region for making filters. Since the mesh size scales with the wavelength, these become increasingly difficult to produce as the descent is made from the submillimeter to the infrared region. The delicate meshes can no longer be freestanding, which introduces substrate transmission problems. Future missions that will encompass the far IR region such as SIRTF and LDR would be greatly enhanced by the development of materials and filters for the far IR region.

Binary Optics - Binary optics have developed recently as a convenient way of manufacturing diffractive optical elements. Their strong chromatic aberration can be used to balance the chromatic aberration of the refractive elements in the system and so reduce the number of refractive elements necessary. Binary optical elements have great potential for improving the design of achromatic cameras and for making achromatic correctors. Further development is necessary to improve their diffraction efficiency and to develop manufacturing experience with them. Binary optics could be used for achromatic cameras with extended wavelength ranges for NGST and HST.

UV Windows - High transmission flat ultraviolet windows are available. The same is not true for curved ultraviolet windows. Current polishing techniques on curved crystal windows (e.g., magnesium fluoride and lithium fluoride) lower their transmission in comparison to flat windows. For HST and NGST, domed and aspheric windows will be needed. In order to realize good transmission from these, further study is needed into the polishing methods for these windows.

EUV High Reflection Coating - High reflectance coatings for gratings and mirrors in the extreme UV region (below 1200 Å) are needed. The FUSE mission will require highly reflective silicon carbide surfaces at 1000 Å. These coatings will need to be developed. The reflectance of freshly deposited aluminum films is good, but unfortunately decreases rapidly with hydrocarbon contamination. The use of fresh aluminum films in EUV astrophysics missions will require the development of in-orbit deposition techniques. If NGST is to be operated below 1000 Å this will be a necessary technique for obtaining high reflectances for the mirrors in the optical instruments.

X-Ray Windows

Beryllium and Diamond Windows for Soft X-Rays - Many types of x-ray detectors require windows. Windows are often used to protect the active elements of the detector against contamination or to contain gas, as in a proportional counter. Future missions will require large format (several tens of centimeters in diameter) windows capable of passing x-rays down to energies of a few tenths of keV. While window development is, perhaps, a mundane task compared to much of the technology that will be generated by Astrotech 21, the successful development of windows meeting the requirements listed below would be a very useful technology that would find wide application in many x-ray astronomy missions.

The windows to be developed should have the following characteristics. First, they should have low energy cutoffs of a few tenths of keV. Second, the windows must cover large apertures. Future missions will have both longer focal length telescopes (with larger plate scales) and, hopefully, wider field optics. In either case, a large area detector is required. The availability of windows that are several tens of centimeters in diameter, and that have only a small fraction of the area blocked by the supporting structure, would increase the efficiency of these missions. Third, the windows should have a very low UV transmission and a very low level of pin holes. Many types of x-ray detectors, particularly semiconductor devices and photoemissive coatings on microchannel plates, are sensitive to photons in the UV region. Since the spectra of most astrophysical sources rise rapidly at low energies, even a small leakage of UV can swamp the x-ray signal. Therefore, very low levels of UV transmission (below 10^{-6}) are required. Fourth, the windows should be impermeable to gasses. This is important for both gas-filled detectors and for making sealed detectors. Fifth, the window must have uniform transmission over its entire surface. While nonuniformities in window transmission can be calibrated and corrected, availability of uniform windows would greatly reduce the systematic errors associated with some types of measurements (primarily photometry and polarimetry). Window transmission uniform to 1% at the low energy end of the band pass would be desirable. Sixth, the windows should be able to withstand a differential pressure of 1 atmosphere. This differential pressure requirement is necessary for some applications, like proportional counters, where the window is used to contain gas. However, detectors that operate at vacuum would also benefit because the vacuum systems necessary to protect these detectors while on the ground could be greatly simplified. Finally, windows should be developed for operation at cryogenic temperatures for use with cooled detectors.

The current leading technologies for soft x-ray windows are thin metal films and rolled beryllium. At present, the only large area beryllium windows available are rolled beryllium foils. The rolled beryllium foils meet the requirements listed above, except for uniformity of transmission. The rolling process introduces thickness variations that lead to nonuniform transmission. Improvement in the uniformity of rolled foils is likely to require a new approach rather than refinement of current techniques. Thin metal films supported by organic films or metal meshes are currently available from several suppliers. Available windows meet the low cutoff and uniformity requirements and are close to meeting the impermeability and size requirements. However, the windows do not meet the pressure requirements, except with the use of relatively low transmission mesh and strong back supports and there are some difficulties in obtaining UV rejection and eliminating pin holes.

Deposition of metal films is the most promising candidate for future improvements in soft x-ray windows. One important technology which needs to be developed is beryllium deposition. Currently, there is no U.S. manufacturer with beryllium vapor deposition facilities. Because of the toxic nature of beryllium, a dedicated vapor deposition machine is required. No individual program, other than Astrotech 21, is likely to make funds for the acquisition of such a machine available. The use of beryllium would permit the use of thicker films (since the atomic number of beryllium is very low), alleviating difficulties with UV transmission and pin holes. Use of beryllium also eliminates the multiple edges associated with higher atomic number or composite foils.

Another important deposition technology is diamond chemical vapor deposition. Carbon has desirable filter properties, similar to those of beryllium. In addition, diamond films have excellent mechanical properties. The strength of diamond films could allow one to greatly reduce the amount of support required, thereby increasing the transmission of the window.

The third technology that must be developed, particularly to obtain windows capable of withstanding large pressure differentials, is improved mesh support production. The primary technique for producing meshes is photolithography. With standard lithography techniques, the aspect ratio of the mesh is limited, the height of a mesh bar cannot exceed about twice its width. New techniques, including anisotropic etching, could make possible strong mesh supports with higher transmission.

Development of the windows described here should be possible within a few years. The development funding should be concentrated near the beginning of the Astrotech program. After the technology is developed a lower level of funding will be necessary to maintain the production facilities.

X-Ray Multilayer Coatings for Spectroscopy - An important new technology for reflection spectrometers is the use of multilayers. Multilayers used to enhance the reflectivity of the grating surface will permit the construction of near normal incidence spectrometers with high resolution and high efficiency.

There are two problems in the production of multilayer gratings. The first is the creation of multilayers with properties suitable for gratings. The second is imprinting the grating pattern on the multilayer. We assume that multilayer research will be funded by the materials research subdivision of Astrotech 21. This research will be applicable to both grating development and to normal incidence soft x-ray and EUV telescopes. The goals of the materials development is similar for the two applications. However, if necessary, materials development specifically for gratings could be funded later in the program. Two techniques are used to produce the grating pattern on the multilayer. One can either deposit multilayers on a grating or etch a grating on a multilayer. Both techniques should be developed.

The diffraction effects from the periodicity of the grating and the orthogonal periodicity of the multilayer combine to give multilayer gratings many useful properties. While several of the possibilities of this combination have been recognized and exploited, further research on the potential applications of multilayer grating could produce significant new advances. We recommend that emphasis should be placed on the measurement and characterization of the properties of multilayer grating and the development and fabrication of novel grating geometries.

STRAY LIGHT SUPPRESSION INSTRUMENTS

A. Technology Assessment

Stray light suppression is important for imaging faint objects and structure near to a bright point source. In astrophysics this occurs when imaging planets, circumstellar dust disks, and faint binary components. For looking at planets using their thermal emission at 10 µm, stray light levels of 10^{-4} are needed. For looking at planets from their near infrared, reflected light will require stray light levels of 10^{-6}.

Typical ways of suppressing scattered light are to use a coronagraph or a nulling interferometer after the telescope. In the laboratory, nulling interferometers can reduce stray light to the 10^{-3} level. Further development of both systems is required to reach the 10^{-4} and 10^{-6} levels required for planet identification.

Woods filters are important for visible light suppression while viewing in the ultraviolet region. Their application is currently limited by their lifetimes of 2 months in the laboratory. Obviously further work is required on increasing their lifetimes if these highly efficient filters are to be used on astrophysics missions. These filters would find immediate application on HST second generation instruments, NGST and FUSE.

B. Technology Development Plan

The stray light suppression effort focuses on the development of coronagraphs, nulling interferometers, and Woods filters. The coronagraph and nulling interferometer development would advance suppression levels to 10^{-4} – 10^{-6} for the visible and UV regimes. A laboratory demonstration for proof of concept would then be followed by a prototype flight system development. Suppression in the IR at 10^{-4} levels would also be developed. The Woods filters effort would concentrate on filter lifetime extension while maintaining high efficiency (i.e., 10^{-8}). Table 46 summarizes the recommended developments in this area.

Table 46. Required Developments In Stray Light Suppression Technology

TECHNOLOGY	STATE-OF-THE-ART	REQUIRED DEVELOPMENT	NEED DATES	TECH. DEV. TIME FRAME
Coronagraph/Nulling Interferometers	Laboratory Demonstration of 10^{-3} Suppression of Diffracted Light	Design and Develop Coronagraphs and Nulling Interferometers Suppression (Below Diffraction): 10^{-4} to 10^{-6} at VIS/UV 10^{-3} to 10^{-4}at IR	'96 '02	'93 - '02
Woods Filters	Lifetimes of ≈ 2 months	Filters for VIS and UV Imaging Suppression at 10^{-8} Lifetime > 5 yrs	'99	'93 - '99

TECHNOLOGIES WITH HIGH POTENTIAL

A. Technology Assessment

UV/IR Wide Bandwidth Fibers - Optical fibers have been useful in astronomy for transporting light from the telescope focal plane to the spectrometer entrance aperture. The fibers can be positioned in the focal plane so that the light from multiple objects can be guided to the spectrometer providing more light for the spectral measurement.

The application of optical fibers is currently limited by their spectral transmittance range. For the visible region, silica fibers provide good transmittance. For the ultraviolet, optical fibers can go down to 200 nm but their transmittance is only 35% per meter. For the 10 to 12 µm region, chalcogenide glasses can be used with a transmittance of 30% per meter. Improving the transmittance of ultraviolet and infrared fibers would enable multi-object spectrometer techniques to be applied in these regions.

Single Mode Fibers - Polarization preserving single mode fibers will be needed for connecting telescopes together in interferometer systems. These systems will be used for the Astrometric Interferometry Mission and the Lunar Imaging Interferometer. To enable a broader wavelength band to be used in these interferometers, it will be necessary to produce single mode fibers with reduced dispersion. The ideal goal would be to reduce the dispersion two orders of magnitude below current values.

B. Technology Development Plan

The development program will focus on advancing fiber technology. The initial phase of the development will address the characterization of fiber materials (e.g., polarization, attenuation, dispersion, transmittance, etc.) applicable to the IR and UV regimes. Research will also concentrate on new and advanced materials and the fabrication processes necessary for fiber development. Parallel efforts will address instrument and component designs incorporating the optical fiber technology. This will include applications to optical links, delay lines, and couplers for advanced interferometer concepts and the development of movable fibers, spatial light modulators, and new spectrographic techniques necessary for multi-object spectrographs operating at UV and IR wavelengths.

Table 47 summarizes recommended developments in this area.

Table 47. Developments In Technologies With High Potential

TECHNOLOGY	STATE-OF-THE-ART	REQUIRED DEVELOPMENT	NEED DATES	TECH. DEV. TIME FRAME
UV – IR Wide Bandwidth Fibers	Transmittance : 35% m^{-1} at $\lambda = 200$ nm 30% m^{-1} at $\lambda = 10 - 12$ µm	Fiber Design and Fabrication Transmittance : 90% m^{-1} at $\lambda = 200$ nm 90% m^{-1} at $\lambda = 10 - 12$ µm Improved Dispersion	'96, '97	'93 - '00
Single Mode Fibers	Low Dispersion For 1.3 – 1.5 µm	Low Dispersion For 0.2 – 1 µm	"97	'93 - '00

CONCLUSION

We have described the technology areas to be developed to improve the optical instruments that will be used on the future Astrotech 21 missions. The gains made possible through moderate investments in the development of optical instrument technology are enormous. For example, consider the cost of increasing the amount of the light at the detector by increasing the aperture of the telescope against the development of a higher efficiency diffraction grating.

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APPENDIX A

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APPENDIX B

ACRONYMS AND ABBREVIATIONS

SPACE MISSIONS

AIM	Astrometric Interferometry Mission
AIT	Astrometric Imaging Telescope
AXAF	Advanced X-Ray Astrophysics Facility
COBE	Cosmic Background Explorer
EUVE	Extreme Ultraviolet Explorer
FFT	Filled Arm Fizeau Telescope
FUSE	Far Ultraviolet Spectroscopic Explorer
GP-B	Gravity Probe-B
GRO	Gamma-Ray Observatory
GRSO	Gamma-Ray Spectroscopy Observatory
HST	Hubble Space Telescope
HXIF	Hard X-Ray Imaging Facility
II	Imaging Optical Interferometer (Imag. Interf.)
IRAS	Infrared Astronomical Satellite
LAGOS	Laser Gravity-Wave Observatory in Space
LDEF	Long-term Deployable Exposure Facility
LDR	Large Deployable Reflector
LOS	Line of Sight
LTT	Lunar Transit Telescope
LSI	Lunar Submillimeter Interferometer
LSMM	Lunar Submillimeter
MOI	Moderate Optical Interferometer
NAE	Nuclear Astrophysics Experiment
NGST	Next Generation Space Telescope
NTT	New Technology Telescope
OVLBI	Orbiting Very Long Baseline Interferometry
Radioastron	Soviet OVLBI mission
ROSAT	Roentgen Satellite
SALSA	Synthesis Array for Lunar Submillimeter Astronomy
SIRTF	Space Infrared Telescope Facility
SMILS	Submillimeter Imager and Line Survey
SMIM	Submillimeter Intermediate Mission
SMMI	Submillimeter Interferometer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SVLBI	Space Very Long Baseline Interferometer (Next Generation Orbiting)
VHTF	Very High Throughput Facility
VISTA	UV Visible Very Long Baseline Interferometric Space Telescope Array
VLBI	Very Long Baseline Interferometer
VSOP	VLBI Space Observatory Program (Japanese OVLBI mission)
WF/PC	Wide-Field and Planetary Camera (HST instrument)
WFXT	Wide Field X-ray Telescope
XST	X-Ray Schmidt Telescope
XMM	X-Ray Spectroscopic Mission

OTHER ACRONYMS AND ABBREVIATIONS

ACG/P	Automated Cylinder Grinder/Polisher
AGN	Active Galactic Nuclei
AIP	American Institute of Physics
AOTF	Acousto-Optic Tunable Filter
Be	Beryllium
BRDF	Bidirectional Reflectance Distribution Function
CARA	California Research Association for Research in Astronomy
CCD	Charged Coupled Device
CCP	Chemically Controlled Polish
CSI	Control Structure Interaction
CTE	Coefficient of Thermal Expansion
CVD	Chemical Vapor Disposition
dB	decibel
deg	degree
DET	Detector
DoD	U.S. Department of Defense
ESA	European Space Agency
EUV	Extreme Ultraviolet
FOV	Field Of View
FUV	Far Ultraviolet
GHz	Gigahertz
Gr/Ep	Graphite-Epoxy
H1	Hyperboloid Mirror Number One, AXAF
HeNe	Helium Neon
HRMA	High Resolution Mirror Assembly
Hz	Hertz
IC	Instrument Chamber
IFS	Ion Figuring System
IR	Infrared
keV	kiloelectron volts
kHz	kilohertz
LaRC	Langley Research Center
LHe	Liquid Helium
LN_2	Liquid Nitrogen
MeV	Million Electron Volts
MIR	Mirror
MIT	Massachusetts Institute of Technology
mrad	milliradian
MSFC	Marshall Space Flight Center
NAR	Non-Advocate Review

OTHER ACRONYMS AND ABBREVIATIONS (Cont'd)

NDI	Normalized Detector Irradiance
nrad	nanoradian
NRL	Naval Research Laboratory
OAST	Office of Aeronautics and Space Technology
P1	Paraboloid Mirror Number One, AXAF
ppb	parts per billion
ppm	parts per million
prad	picoradian
PSF	Point Spread Function
PSR	Precision Segmented Reflector
p-v	peak to valley
PZT	Piezoelectric Transducer
RADC	Rome Air Force Development Center
REF	Reference
ROC	Radius of Curvature
RW	Reaction Wheel
SAO	Smithsonian Astrophysical Observatory
SAVI	Space Active Vibration Isolation
SDI	Space Defense Initiative
SEI	Space Exploration Initiative
SERC	Space Engineering Research Center
SiC	Silicon Carbide
SIs	Science Instruments
TBD	To Be Determined
USNO	United States Naval Observatory
UV	ultraviolet
VETA	Verification Engineering Test Article
VIS	Visible
WCE	Wavefront Control Experiment
XGA	X-ray Generator Facility
XRCF	X-Ray Calibration Facility

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16. Abstract

In 1989, the Astrophysics Division of the Office of Space Science and Applications initiated the planning of a technology development program, Astrotech 21, to develop the technological base for the Astrophysics missions developed in the period of years 1995 to 2015. An infusion of new technology is considered vital for achieving the advances in observational techniques needed for sustained scientific progress. Astrotech 21 was developed in cooperation with the Space Directorate of the Office of Aeronautics, Exploration and Technology, which will play a major role in its implementation. The Jet Propulsion Laboratory has led the planning of Astrotech 21 for the agency.

The Astrotech 21 plan was developed by means of three series of workshops dealing respectively with: Science Objectives and Observational Techniques, Mission Concepts and Technology Requirements, and Integrated Technology Planning. Traceability of technology plans and recommendations to missions requirements and impacts was emphasized. However, breakthrough technologies, whose ultimate applications cannot be anticipated, were also considered. A Proceedings publication is published for each workshop. A summary report has also been prepared that synthesizes the results of the planning effort.

The Optical Systems Technology for Space Astrophysics in the 21st Century Workshop was one of the three Integrated Technology Planning workshops. Its objectives were to develop an understanding of future mission requirements for advanced optical systems, and to recommend a comprehensive development program to achieve the required capabilities. Workshop participants were briefed on the astrophysical mission set, with an emphasis on those missions that drive advancements in optics technology.

Program plans and recommendations were prepared in six optics technology areas: Wavefront Sensing, Control, and Pointing; Fabrication; Materials and Structures; Optical Testing; Optical Systems Integrated Modeling; and Advanced Optical Instruments Technology.

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