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SECTION IV (Cont'd)
WORKSHOP PANEL REPORT:

6. ADVANCED OPTICAL INSTRUMENTS TECHNOLOGY

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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

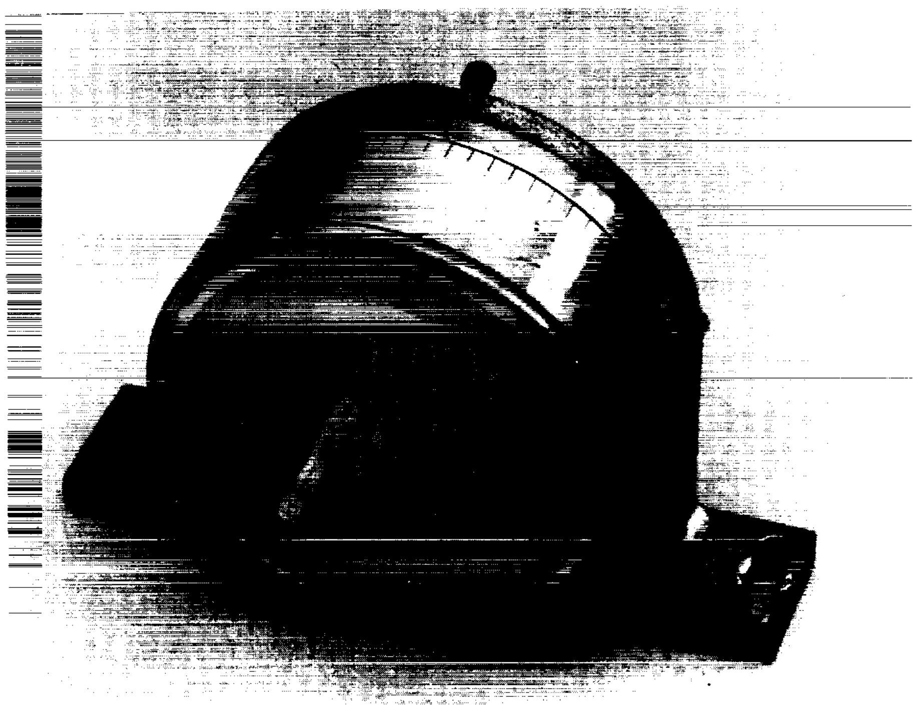

Figure 44. Cryogenic Fabry-Perot Etalon for Far R – A 3-cm diameter fixed separation Fabry-Perot that can be cooled to 4 K. The design uses free-standing metal meshes that can be repeatedly cooled with reproducible spacing of 1 part in 10^6. (Courtesy of Herbert M. Pickett.)

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 @ $\lambda = 1000$ 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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15. Supplementary Notes

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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