SECTION II
THE NEXT CENTURY ASTROPHYSICS PROGRAM

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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.

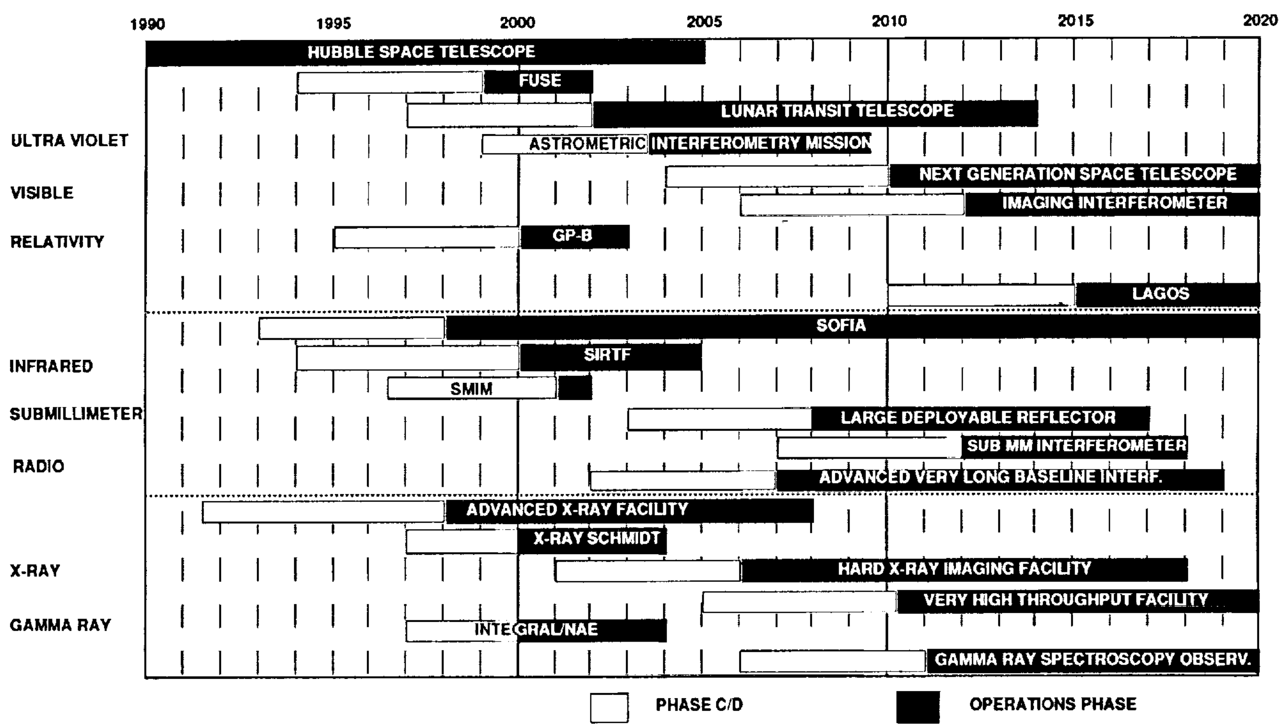

Figure 1. Next Century Astrophysics Program: Candidate Flagship and Intermediate Missions for Launch During 1995–2020 (for technology planning purposes only)

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 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)].

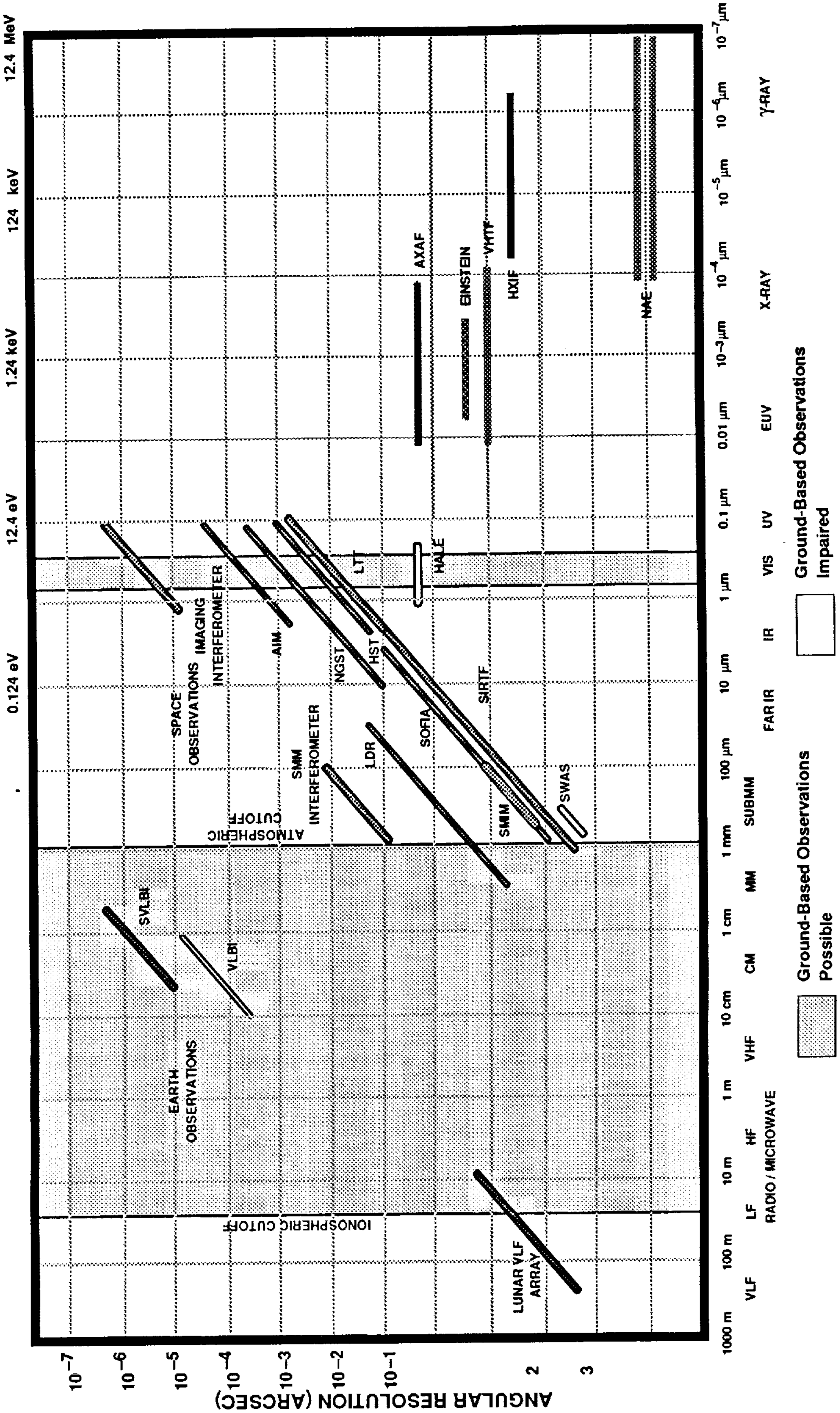

Figure 2. Angular Resolution versus Wavelength for Future Astrophysical Instruments

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

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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.

* 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