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THE NEXT CENTURY ASTROPHYSICS PROGRAM

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INTRODUCTION

The Astrophysics Division within the NASA Office of Space Science and Applications (OSSA) has defined a set of major and moderate missions that are presently under study for flight sometime 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. (A glossary of the mission acronyms used in this chart is provided in Appendix B.) The missions are in three groups according 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 one-and-a-half years before the start of the C/D Phase, a non-advocate review (NAR) is held to ensure that the technology is at an appropriate stage of readiness for the construction phase to begin. Thus technology development is normally frozen as of the date of a successful NAR.

Figure 2 is a plot of wavelength coverage versus angular resolution (resolving power) for the set of missions from the very low radio frequencies through the high energy. (The high energy missions have fixed resolving power.) The 200 inch Hale telescope, the premier telescope during most of the late 20th century, is included for comparison. 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 effort

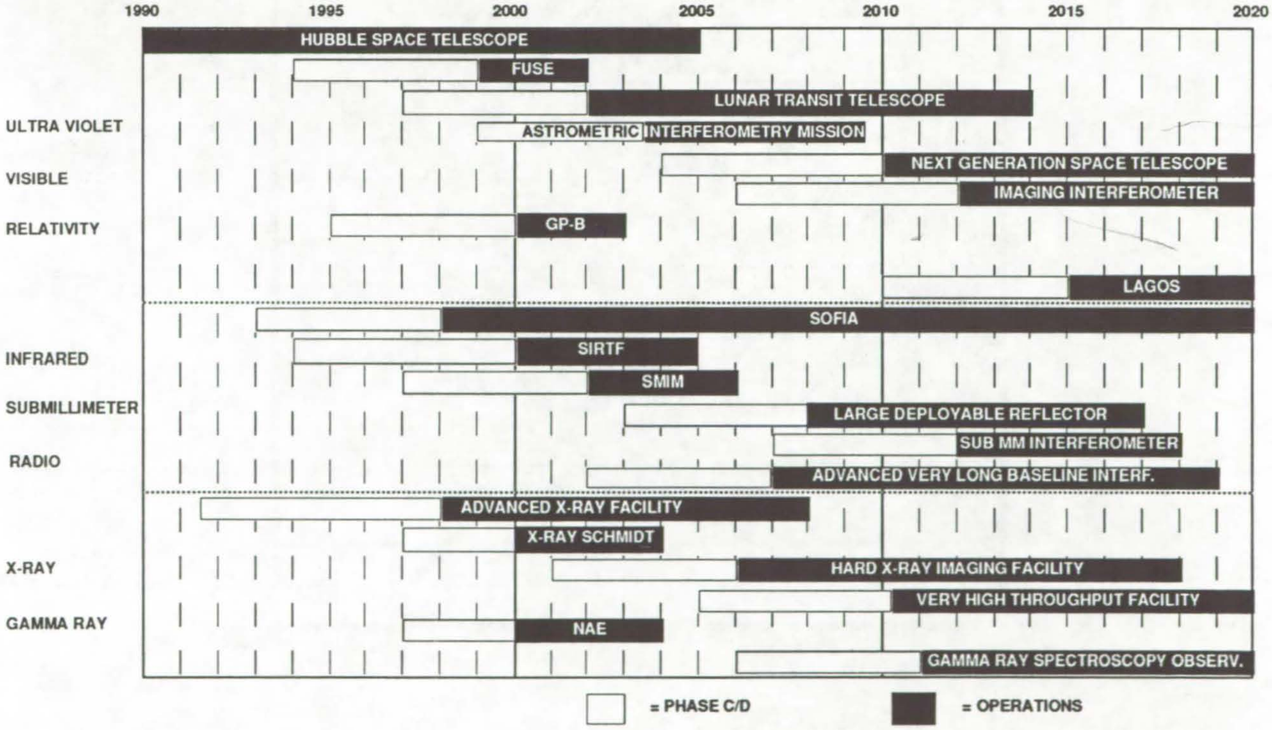

Figure 1. Next Century Astrophysics Program: Candidate major and moderate missions for launch during 1995-2000 (for technology planning purposes only).

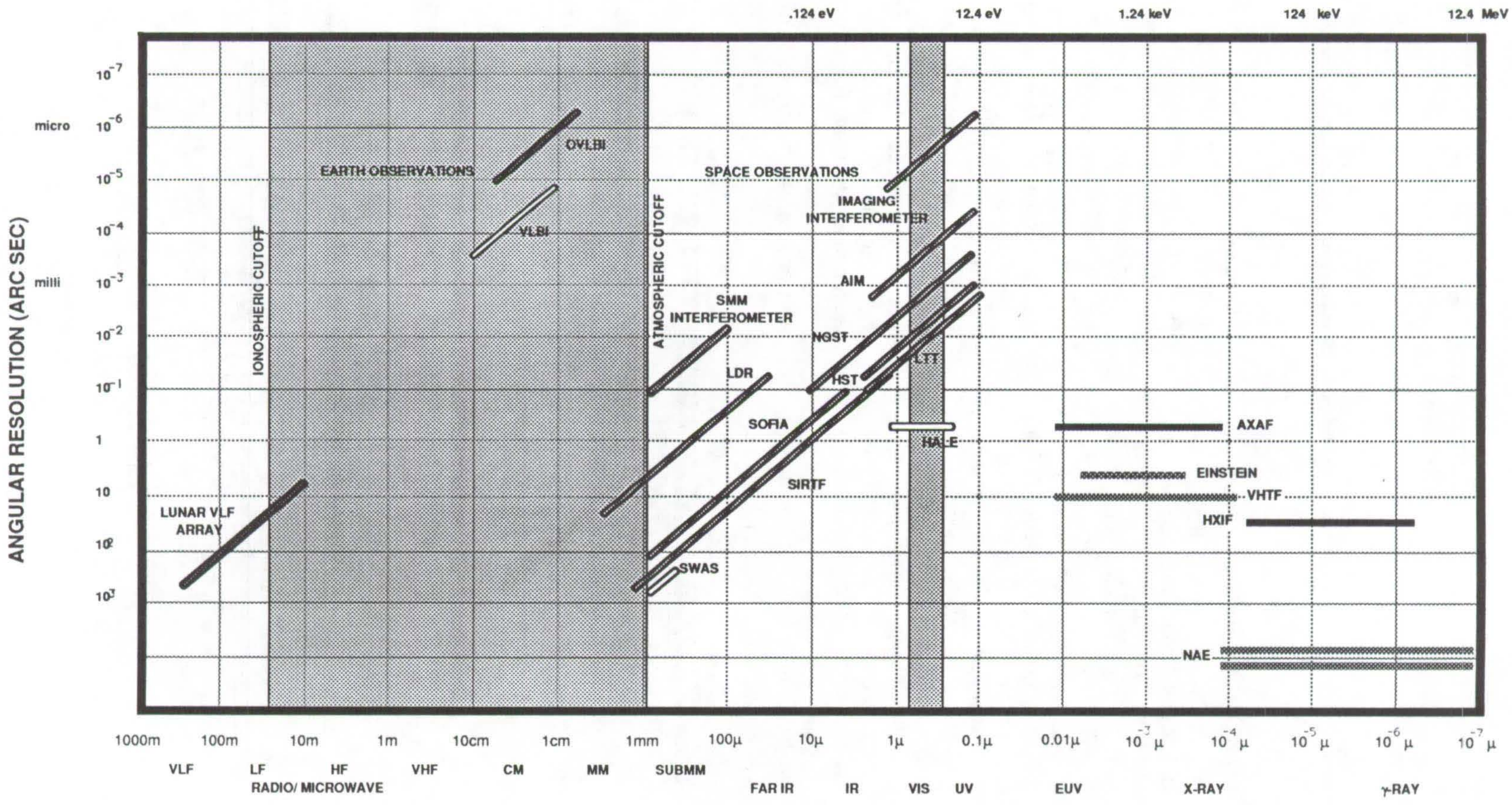

Figure 2. Angular resolution versus wavelength for future astronomical instruments.

is focused, indicate where observations must be made from space because the atmosphere is largely opaque at these wavelengths.

Extensions in spectral coverage are required in the gamma-ray regime (direct sensors) and submillimeter-wave range (heterodyne sensors), and increased performance in areas such as sensitivity, dynamic range, array size, spatial and energy resolution, and radiation hardness is desired across all wavelength ranges. An overview of the advances required in sensor capability for each of the three wavelength groups is provided in the following, 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.

HIGH ENERGY MISSIONS

The relevant parameters for the planned and proposed high-energy astrophysics missions are shown in Table 1. High-energy sensor technologies are still in their infancy. In the gamma-ray regime, orders of magnitude enhancements in sensitivity and position resolution 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 energy-resolving approaches and makes "3-D" detectors which can simultaneously provide energy and spatial information very attractive for future missions. Devices with CCD-like performance are desirable for large-format, high-sensitivity imaging in the X-ray regime. Further development of low-noise, cryogenic readout electronics will also be required.

Advanced X-Ray Astrophysics Facility (AXAF)

AXAF will be the third of the great observatories, and 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 1,700 cm^2. The energy response will be 0.09 - 10 keV. The focal plane detectors consist of a CCD array operating at 200 K and a 0.1 K calorimeter. AXAF will be placed in a 600 km, 28 degree Earth orbit in 1998.

Table 1. X-Ray / Gamma-Ray Mission Parameters and Sensor Requirements

Mission	AXAF	NAE	HXIF	VHTF	GRSO	XST
Location	600 km Earth orbit	Low Earth orbit	Free flyer	Moon or free flyer	Moon or free flyer	Low Earth orbit
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	0.2-5 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 & 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	1700 cm^2 grazing-incidence	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^2
Optics Temperature	Ambient	Ambient	Ambient	Ambient	Ambient	Ambient

X-Ray Schmidt

This telescope will provide wide field of view, high resolution observations of soft X-ray sources. The narrow passbands of the instrument provide good energy discrimination and may be tuned to specific emission lines to obtain images that are sensitive to temperature or density of the emitting region. It will study local objects and extra-galactic sources at high latitudes (QSOs). Included in its study of local phenomena (out to 200 pc) will be the density and location of dust clouds in the interstellar medium, origin and angular distribution of the soft diffuse x-ray flux, and surveys to investigate x-ray emission mechanisms as a function of spectral type (for stellar flaring, activity cycles, and stellar evolution). The telescope incorporates a 1 m diameter mirror and 1.4 m focal length optimized for a bandpass center of 0.13 keV with an energy bite of 2.6 eV. The detector (IPC, 25 mm Dia.) will have an FOV of 10° and angular resolution of 2.5 arc min using 1 mm pixels. Launch into Earth orbit is planned for ~ 2000.

Nuclear Astrophysics Experiment (NAE)

The Nuclear Astrophysics Experiment is an orbiting, high-resolution, gamma-ray telescope which will provide much higher spectral resolution and sensitivity than previous gamma-ray missions. It will investigate nucleosynthesis in supernovae, 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 2,600 cm^3 volume. The cooled Ge detectors will be sensitive from 10 keV to 10 Mev. The location will be a 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 making 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 a coded aperture with a collecting area of up to 30 m^2. 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 10 keV, but it will have a much greater collecting area of up to 30 m^2. The telescope and detectors will be at ambient temperature. Launch into Earth orbit is planned for ~ 2010.

Gamma Ray Spectroscopy Observatory (GRSO)

This gamma ray telescope, located on the Moon (or as a future low Earth orbit free-flyer), would 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 option), could be movable so that a source could be tracked. High sensitivity would come from an array of 19 Ge detectors of large volume. The high angular resolution would 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 would be candidate objects for study by the GRSO.

VISIBLE, ULTRAVIOLET, AND RELATIVITY MISSIONS

The relevant parameters for the missions in the visible and ultraviolet (UV) which require advances in sensor technology are summarized in Table 2. None of the relativity missions is considered a driver for new sensor technology, and, indeed, of the three wavelength groups, sensor capabilities in this group are by far the most advanced. This is particularly true in the visible, where the state of development of CCD technology is unrivaled in its combination of sensitivity and format size. Such advanced capabilities in this range have resulted from the focused development (primarily through NASA support) of ultra-sensitive imaging arrays for ground-based astronomy in this window of atmospheric transmission, as well as from a more general interest associated with the (not unrelated) sensitivity of the human eye to these wavelengths. Nevertheless, further advances are still desired for future space-based observatories, with the primary issues being UV sensitivity and solar (visible) blindness for the UV wavelengths, and larger format size across the UV and visible ranges. The implementation of larger formats will also require concomitant advances in high-speed, low-noise readout electronics.

Table 2. Ultraviolet / Visible Mission Parameters and Sensor Requirements

Mission	HST	LTT	AIM	NGST	Imag. Int.	FUSE
Location	Low Earth orbit	Moon	900 km Earth orbit	Moon or Earth orbit	Moon or Earth orbit	Earth orbit
Duration	15 years with servicing	10 years	5 - 10 years	15 years	10 years	~ 4 years
Wavelength / Energy Range	0.1 to 1 μm, upgrade to 2.5 μm	0.1 to 2.5 μm	0.1 to 2.5 μm	0.1 to 10 μm	0.1 to 10 μm	0.01 to 0.12 μm
Measurements	Imaging, spectroscopy, photometry	Imaging	Interferometric astrometry, imaging*	Imaging, spectroscopy	High-resolution spatial imaging, spectroscopy	High-resolution spectroscopy
Sensors	Large-format arrays, high dynamic range, low-noise	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	High energy resolution, high-sensitivity, photon-counting
Sensor Temperatures	80 K	~ 100 K	~ 200 K	< 100 K	TBD	TBD
Aperture	2.4 m	1 - 2 m	50 cm apertures, 2 - 30 m baseline	6 - 8 m	1.5 m apertures, 1 km baseline	70 cm
Optics Temperature	Ambient	100 K	Ambient	< 100 K	Ambient	Ambient

* = optional

Hubble Space Telescope (HST)

The Hubble Space Telescope 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-meter primary reflector and covers the spectral range from 0.1 to 1 μm. Future upgrades are expected to extend the coverage to 2.5 microns. 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 diffraction-limited operation; however, future replacement instruments are planned to compensate for this shortcoming internally, eventually providing 0.1 arcsec resolution.

Lunar Transit Telescope (LTT)

The Lunar Transit Telescope 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 degrees 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 one meter 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)

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, determine the presence of extra-solar planets through the star's orbital perturbations, and detect super-massive 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 microns, with an interferometric baseline of 2 to 20 meters. 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.

Next Generation Space Telescope (NGST)

The planned 15-year lifetime of HST will be completed in 2005. NGST is the follow-on mission. It will have a larger aperture and operate from 0.1 to 10 microns 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 redshifts Z > 1. The radiatively cooled aperture will be approximately 6 - 8 meters in diameter. The detectors will also be cooled to < 100 K. The launch date is ~ 2010, with a planned 15-year lifetime. The NGST can either be placed in Earth orbit, or on the surface of the Moon.

Imaging Optical Interferometer (Imag. Int.)

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, determine the structure of quasars and active galactic nuclei, and detect extra-solar planets. It will operate form 0.1 to 10 microns, have a baseline of up to 1 kilometer, and as many as ten, 1 - 1.5 meter 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.

Far Ultraviolet Spectroscopic Explorer (FUSE)

FUSE is an orbiting far-ultraviolet telescope which will operate primarily between 90 and 120 nanometers and secondarily down to 10 nanometers. 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. FUSE will have a 70 cm. diameter, glancing incidence telescope, and will be launched into Earth orbit in 1999. Mission lifetime is planned for four years. It will utilize state-of-the-art detectors such as large format microchannel plates or improved MAMA.

Gravity Probe - B (GP-B)

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. GP-B uses four precision gyroscopes suspended in a magnetically shielded, drag free environment. Less than one year in the planned 400 km polar Earth orbit should be sufficient to measure the relativity effects. This mission is not considered a driver for any new sensor technologies.

Laser Gravity-Wave Observatory in Space (LAGOS)

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 super-massive 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, but are not expected to place any special demands on the sensor elements themselves.

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 both direct and heterodyne sensor technologies are required for these missions. The primary drivers for direct infrared detector development are the need for enhanced sensitivity and radiation hardness for low-background (LB) measurements, especially at the longest wavelengths, and larger formats, higher operating temperatures and larger dynamic range for higher signal-level measurements. While imaging at longer wavelengths does not require as high a pixel count as in the visible to fully sample the image resolution, array technology is much less well developed in the far IR, and currently nonexistent in the very-far IR. In addition, the development of appropriate array readout electronics will also need to be initiated. For LB measurements, the development of a photon-counting technology for the IR would also be beneficial in eliminating analog noise from weak signals.

The main shortcoming of heterodyne capabilities is low sensitivity in the THz range. To improve the high-frequency performance, significant improvements will be required in local oscillator (LO) power and in mixer sensitivity. LDR also requires the first implementation of an array architecture in a submillimeter receiver. Increases in intermediate-frequency spectrometer bandwidth and channel number will also be required for fully utilize the greatly increased information content offered by advanced receiver front ends.

Table 3. Infrared / Submm / Radio Mission Parameters and Sensor Requirements

Mission	SOFIA	SIRTF	SMIM	LDR	SMMI	NGOVLBI
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
Duration	>20 years, 120-200 flights/yr.	3 - 6 years	2 - 4 years	10 - 15 years	10 years	10 years
Wavelength Range	IR - submm	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 LO
Sensor Temperatures	0.1-80 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 baseline	25 m
Optics Temperature	Ambient	Liquid He cooled	Passively cooled to ~ 150 K	Passively cooled to < 100 K	Passively cooled to < 100 K	TBD

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 developing and testing the next generation space instruments, and for training new astronomers. A 2.5-meter, 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. Note that SOFIA will act as a testbed for new IR and submm sensor systems and it may also serve as a driver for their development. However, it was not considered as a driver for their development at the time of this workshop.

Space Infrared Telescope Facility (SIRTF)

SIRTF is the second-generation cryogenically cooled infrared telescope following the successful Infrared Astronomical Satellite (IRAS). It will be the fourth of the Great Observatories. The scientific objectives include 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 meter 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 high Earth orbit with a 28 degree 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 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-meter aperture, with passively cooled optics, 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 both heterodyne detectors and bolometers cooled to liquid He temperatures. Launch date is planned for 2002. The mission lifetime, limited by the stored cryogen supply, is 2 - 4 years.

Large Deployable Reflector (LDR)

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, the anisotropy in the cosmic background, and the chemistry, distribution and energetics of molecular, atomic and ionic species. The 10 - 20 meter, passively cooled reflector will be placed in a circular 10,000 kilometer high Earth orbit. The focal plane instruments will cover the range from 30 to 1000 microns with both superconducting heterodyne and non-coherent (direct) detectors. The focal plane will be cooled to liquid He temperatures. Launch date is ~ 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 kilometer. 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 heterodyne detectors would operate at selected wavelengths from 100 to 800 μm. Operation on the Moon would begin in 2012.

Next Generation Orbiting Very Long Baseline Interferometer (NGOVLBI)

The second-generation VLBI experiments, following 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 u-v plane coverage. The space component of the NGOVLBI will be a 15-meter passively cooled 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 ~ 2000.