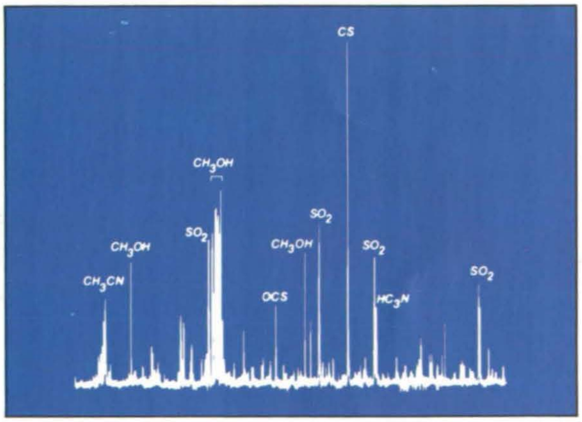
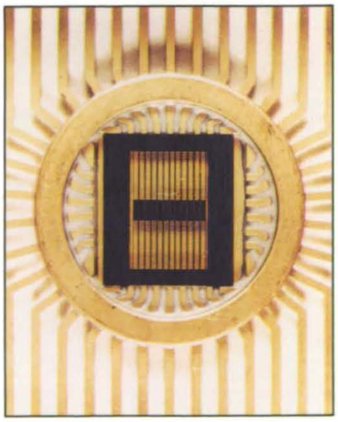
ASTROTECH 21
WORKSHOPS
SERIES III

VOLUME
2

SERIES III INTEGRATED TECHNOLOGY PLANNING

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





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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 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. Proceedings documents are published for each workshop. A summary report has also been prepared which synthesizes the results of the planning effort.

The Sensor Systems 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 electromagnetic radiation sensor 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 sensor technology.

Program plans and recommendations were prepared in four sensor areas: X-Ray and Gamma Ray Sensors, Ultraviolet and Visible Sensors, Direct Infrared Sensors, and Heterodyne Submillimeter-Wave Sensors. The workshop also covered Sensor Readout Electronics and Sensor Cooler Technology, and recommended coherent programs that couple the development of these closely related technologies with sensor development efforts.

PREFACE

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

The Astrotech 21 planning process has three phases. The first phase focused on the fundamental science objectives and the observational techniques used to realize these objectives. In the second phase, specific mission concepts were evaluated and their technology requirements were assessed. In the third phase, the technology needs and opportunities in various areas of technology were synthesized. This workshop on Sensor Systems Technology is part of this third and final phase in Astrotech 21 planning. Approximately 70 scientists and engineers drawn from universities, industry, NASA centers, and other government laboratories participated.

This volume provides a summary of the Astrotech 21 Sensor Systems Technology Workshop held in Pasadena, California, January 23 - 25, 1991. The goal of this workshop was to identify areas of sensor capabilities which require technology advances in order to meet the science goals of the Astrotech 21 mission set, and to recommend a coherent development program to achieve the required capabilities. To this end, six panels were assembled to address sensor technologies across the electromagnetic spectrum from the gamma-ray to the submillimeter-wave regimes, as well as the closely related technologies of sensor readout electronics and space cryocoolers. The primary content of this proceedings is the set of reports prepared by the six panel chairs and their team members. These reports describe the panels' analyses of the Astrotech 21 mission set requirements, an assessment of the current capabilities and future promise of the relevant sensor technologies, and their specific recommendations to NASA for a development plan to achieve the desired sensor performance. To place these reports in context, this volume first recaps the purpose and evolution of the Astrotech 21 Plan, the view of the mission set at the time of the workshop, and the structure and goals of the workshop itself. A listing of the panel participants, their affiliations, and a glossary of acronyms and abbreviations utilized in the Proceedings are provided in the appendices.

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WORKSHOP PROCEEDINGS:
SENSOR SYSTEMS FOR SPACE ASTROPHYSICS IN THE 21st CENTURY

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SERIES III INTEGRATED TECHNOLOGY PLANNING

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

Editor

Barbara A. Wilson

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Cover illustrations.

Top: Near-infrared image of the Milky Way obtained by NASA's Cosmic Background Explorer Satellite.

Bottom left: Submillimeter wave emission spectrum of the Orion Nebula obtained from a ground-based telescope.

Bottom right: 1x12 monolithic array of X-ray calorimeters.

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WORKSHOP PROCEEDINGS: SENSOR SYSTEMS FOR SPACE ASTROPHYSICS IN THE 21ST CENTURY

EXECUTIVE SUMMARY

INTRODUCTION

This proceedings provides a summary of the Astrotech 21 Sensor Technology Workshop held in Pasadena, CA, on January 23-25, 1991. Six panels were convened for this workshop: X-Ray and Gamma-Ray Sensors, Ultraviolet and Visible Sensors, Direct Infrared Sensors, Heterodyne Submillimeter-Wave Sensors, Sensor Readout Electronics, and Sensor Cooler Technology. The primary content of this proceedings is the set of reports prepared by the panel chairs with the assistance of their team members. The reports describe the panels' combined analysis of the Astrotech 21 mission set requirements in the area of electromagnetic radiation sensors, their assessment of the current capabilities and future promise of the relevant sensor technologies, and their specific recommendations to NASA for a development plan to achieve the desired performance in the necessary time frame. The scope of the panels' discussions covered sensors of electromagnetic radiation across the spectrum from the millimeter-wave to gamma-ray regime, 1 mm (300 GHz) to 0.0001 Å (10 MeV), as well as the closely related areas of sensor readout electronics and sensor cooler technologies. To place these reports in context, this volume first recaps the purpose and evolution of the Astrotech 21 plan, the view of the mission set at the time of the workshop, and the structure and goals of the workshop itself.

In general, the spectral regions with the least developed sensor technologies were identified as the gamma-ray, the far and very far infrared (IR), and the submillimeter-wave regimes. These spectral ranges are also expected to play important roles in future astrophysics missions, and the absence of drivers outside of space-based missions for the development of these sensors make NASA support imperative. Sensor readout technology for large arrays, especially in the IR ranges, was also identified as being relatively immature, primarily because funding for readout development has historically lagged that of the sensors. The most highly evolved sensor systems exist for light visible to the human eye, undoubtedly not by coincidence. However, the Ultraviolet and Visible Sensor Panel expressed serious concern that the future of the industrial base that supports the advanced charge-coupled device (CCD) technology may be in jeopardy. Specific areas of space cryocooler capabilities were also judged to be inadequate to meet the needs of future astrophysics missions, and even in areas where the technology is reasonably well developed, more intensive flight testing was strongly recommended.

HIGH-ENERGY SENSORS

The panel examining the gamma-ray and X-ray regions identified five high-priority areas for further development. In order of importance for the Astrotech 21 mission set, these are high-resolution gamma-ray spectroscopy, cryogenic detectors, X-ray CCDs, and position sensitive detectors for the higher energy ranges. High-energy sensor technologies are still in their infancy, and these advances will enable whole new areas of investigation as individual X- and gamma-ray sources can be resolved, and their emission spectra can be independently probed.

Orders of magnitude enhancements in sensitivity and position resolution are desired for high-resolution spectroscopy in the gamma-ray range, with the development of position-sensitive arrays of Ge detectors and advanced JFET electronics considered the most critical. Performance advances in cryogenic detector technology were also judged to offer significant benefits, especially through further development of sensitive calorimeter arrays and low-temperature amplifier and readout electronics. An investigation of emerging superconductor-based technologies such as superconducting granule detectors and tunnel junction detector and readout technologies was also recommended.

The success of CCD technology in the visible provides strong arguments in favor of their extension to the X-ray regime for missions, such as AXAF, where improved low- and high-energy response, lower dark currents, radiation hardening, large formats, and "smart" readout techniques are recommended for support.

Finally, the development of position-sensitive detectors was recommended for the 5-500 keV and 500 keV - 2 MeV ranges, with an emphasis on increased stopping power and position resolution offered by high-pressure gas and liquid xenon interaction chambers, and solid-state scintillator approaches. Large-scale solid scintillators would also benefit from the development of low-profile optical readout and active and passive coded-mask technologies. Further development of low-temperature, low-noise amplifier and readout technologies was also noted as important for most of these technologies.

ULTRAVIOLET AND VISIBLE SENSORS

The Ultraviolet and Visible Sensor Panel, which considered the wavelength range from the extreme ultraviolet (EUV) to the near infrared (IR), identified the ultraviolet (UV) and EUV ranges as the most demanding of technology advances. The key issues in this regime are UV sensitivity, solar (visible) blindness, and large array format. High quantum efficiency (QE) CCD arrays offer many advantages for large arrays, but will also require the development of extremely efficient visible-light-rejecting filters. UV photocathodes are naturally solar blind, but significant development will be needed to improve the imaging capabilities of photoemissive systems. An emphasis on the development of high-count-rate, high-density imaging microchannel plates (MCPs) and associated readout technologies was recommended.

The panel felt that the entire effort in visible sensors should be focused on further advances in CCD technology, with its demonstrated high performance in this wavelength range. The primary enhancements desired are increased format size, calling for faster readout rates without degrading the read noise. Radiation hardness and degradation by contamination are also issues that need to be addressed. The panel also cautioned that there is cause for concern over the future viability of the existing industrial base in advanced CCD technology.

Finally, the panel also addressed needs in the near-IR regime. Since this overlapped with the charter of the Direct IR Sensor Panel, discussion was focused on benefits for this wavelength range that can accrue from the UV-visible sensor heritage. The history of success of CCDs in the visible prompted a recommendation for an extension of this technology into the near IR based on both Si technology and new materials.

DIRECT INFRARED SENSORS

The Direct Infrared Sensor Panel covered a wide wavelength range from 1 - 1,000 μm, encompassing a concomitantly large range of sensor technologies, and split their recommendations into four distinct subranges. These are: near IR (1 - 5 μm), mid IR (5 - 30 μm), far IR (30 - 200 μm), and very far IR (200 - 1,000 μm). They also noted a natural distinction between the needs of low-background (LB) versus moderate-background (MB) missions. The ultimate in sensitivity is paramount for the former, and larger formats, higher operating temperatures and larger dynamic range are key issues for the latter. Overall the panel recommended development in five areas: large arrays of photon detectors and bolometers, photon counting technologies, higher operating temperature near- and mid-IR detectors, advanced impurity-band-conduction (IBC) devices for the far and very-far IR, and improved low-noise and cryogenic readout electronics for most wavelength ranges. It was also noted that advances in IR technology can greatly impact astrophysical sciences through the information gained in this rich region of molecule-specific emission and absorption bands, and that future IR missions can benefit greatly by building on the technology base developed for SIRTF and HST.

In the near IR, the primary focus is on increased format size in hybrid arrays operating at higher temperatures, and the development of a photon-counting technology based on small-bandgap superlattices or Si:As solid-state photomultiplier (SSPM) technology. Higher operating temperature, large-format arrays are key issues for MB mid-IR applications. Mid-IR photon-counting detectors critical for LB missions have been demonstrated, but further development and an appropriate readout technology are still required. Sensor technology in the far IR is dominated by recent advances in IBC technology, and the panel recommends continued work on Si and Ge IBC development, leading to larger arrays with high-performance readout capabilities, and eventually photon counting beyond 30 μm in Ge-based SSPMs. Finally, the very-far IR requirements for sensitive, arrayable technologies call for the development of low-noise cryogenic readout and MUX capabilities appropriate for bolometer arrays and breakthroughs in new approaches such as bandgap-engineered semiconductor and superconductor technologies. The panel noted that NASA's far IR needs are unique, and that the agency must expect to bear full funding and management responsibility for the necessary development programs.

HETERODYNE SUBMILLIMETER-WAVE SENSORS

Recently NASA has begun to place considerable emphasis on the development of heterodyne sensor capabilities in the submillimeter-wave range because its potential payoff in high-resolution spectroscopy of molecular transitions which can serve as signatures of cold gases and particles in planetary, stellar and interstellar objects. For future astrophysics missions, it can enable investigations of cold (dark) matter, the dominant constituent of the known universe. Nevertheless, heterodyne technology in this wavelength range is still in its early stages and considerable development is required to extend the sensitivity into the rewarding THz regime. The Heterodyne Submillimeter-Wave Sensors Panel identified four categories in which improvements are required to meet the science goals of the Astrotech 21 mission set. These are local oscillator (LO) sources, mixers, focal plane arrays, and back end spectrometers.

Extending the LO power into the THz regime calls for advances in fundamental oscillator and multiplier technologies. These include higher frequency Gunn diodes and the development of alternate semiconductor and superconductor sources, improved-efficiency GaAs Schottky varactors or other novel multiplier devices, and innovative approaches in multiplier circuits such as micromachined waveguides or quasi-optical structures.

The primary shortcoming of current mixer technologies is the low efficiency with which LO and incoming signal power are converted to intermediated frequency (IF) signal for detection in the THz range. Thus the development programs for high-efficiency, low-noise THz mixers and higher power THz LO sources should be closely coupled. The panel recommends an intensified development program in superconductor-insulator-superconductor (SIS) and conventional semiconductor Schottky-barrier diode (SBD) mixers, as well as the support of novel approaches including planar GaAs SBDs, Ge IBC photoconductors, and new high- and low-T_C superconductor materials and structures, and innovative mixer architectures.

The ground-breaking entry into the area of focal-plane array technologies planned for LDR will require the development of planar mixer arrays, and will benefit from the development of emerging technologies such as micromachined and quasi-optical structures. Increases in IF spectrometer bandwidth and channel number will also be required to fully utilize the greatly increased information content offered by advanced receiver front ends.

SENSOR READOUT ELECTRONICS

Coordination of the development programs advocated by the Sensor Readout Technology Panel and the wavelength-specific sensor panels was considered of paramount importance and was accomplished through joint splinter-group discussions. In the report of the Readout Panel, recommendations are grouped by technology thrusts, rather than by sensor wavelength, thereby highlighting commonalities across different wavelength regimes. Development plans in five areas are proposed: low-noise cryogenic readout, technologies for sub-electron read noise, and advances in packaging, focal-plane interface technologies, and readout architectures. In most areas, aggressive programs with early starts are strongly urged in order to bring about the performance improvements on the required time scales.

Cryogenic readout capabilities are required for 2-4 K and 0.1 K operation for the far-IR and high-energy sensors, and development of emerging semiconductor and superconductor electronics is advocated. The low signal levels common to the majority of astrophysics missions demand a reduction in read noise to below the one-electron level, for which floating-well and source-follower electronics offer promising approaches. A need for new approaches in packaging, focal-plane interface, and readout architectures is driven by the push to ever larger arrays across all wavelengths. In particular, this panel recommends the support of development in the areas of large-format monolithic and buttable arrays, thermal compartmentalization, monolithic analog-to-digital (A/D) converters, optical readout approaches, and event-driven readout architectures.

SENSOR COOLER TECHNOLOGY

The Sensor Cooler Technology Panel discussions were similarly coordinated with those of other panels through joint splinter sessions. Three primary areas of space cryocooler performance were identified as most critical to the Astrotech 21 mission goals. These are, without any implied prioritization, (i) long-life vibration-free refrigerators for high pointing-accuracy imaging missions, (ii) mechanical refrigerators for 2-5 K cooling of direct IR and heterodyne submillimeter-wave sensors, and (iii) expanded R&D of promising backup technologies, both as an insurance against the risk of inadequacies in cooling system performance for these highly visible large-telescope missions, and as a means to take advantage of enabling capabilities offered by emerging technologies.

Specifically, the panel recommends support for the development of sorption and turbo-Brayton technologies for vibrationless cooling, multiple-stage mechanical systems incorporating turbo-Brayton, Stirling, Joule-Thomson (J-T), magnetic refrigerator and pulse-tube approaches to achieve the desired 2-5 K cooling performance, and innovative emerging technologies such as dilution and ^{4}He-^{3}He Stirling technologies, low vibration thermoelectric coolers (TEC) and pulse-tube refrigerators, and parasitic heat load reduction schemes. In addition, the panel strongly urges NASA to initiate a focused program in flight testing of cooler technologies, utilizing multiple, low-risk (class D) flight experiments.

The joint splinter sessions also brought to light the need for sensor system design to include an assessment of the natural break points in cooler technology capabilities, where a small relaxation of thermal specifications, resulting only in marginal degradation in sensor performance, can effectively avoid an undesirable jump in cooler system complexity. In particular, because of the vastly improved efficiency of providing cooling above the liquefaction point of He, the sensor community should strive to meet as many objectives as possible using temperatures in the 4-5 K range or higher.

Barbara A.Wilson
June 1991

SECTION I. BACKGROUND MATERIAL

ASTROTECH 21 PROGRAM OVERVIEW

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

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

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

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

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

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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

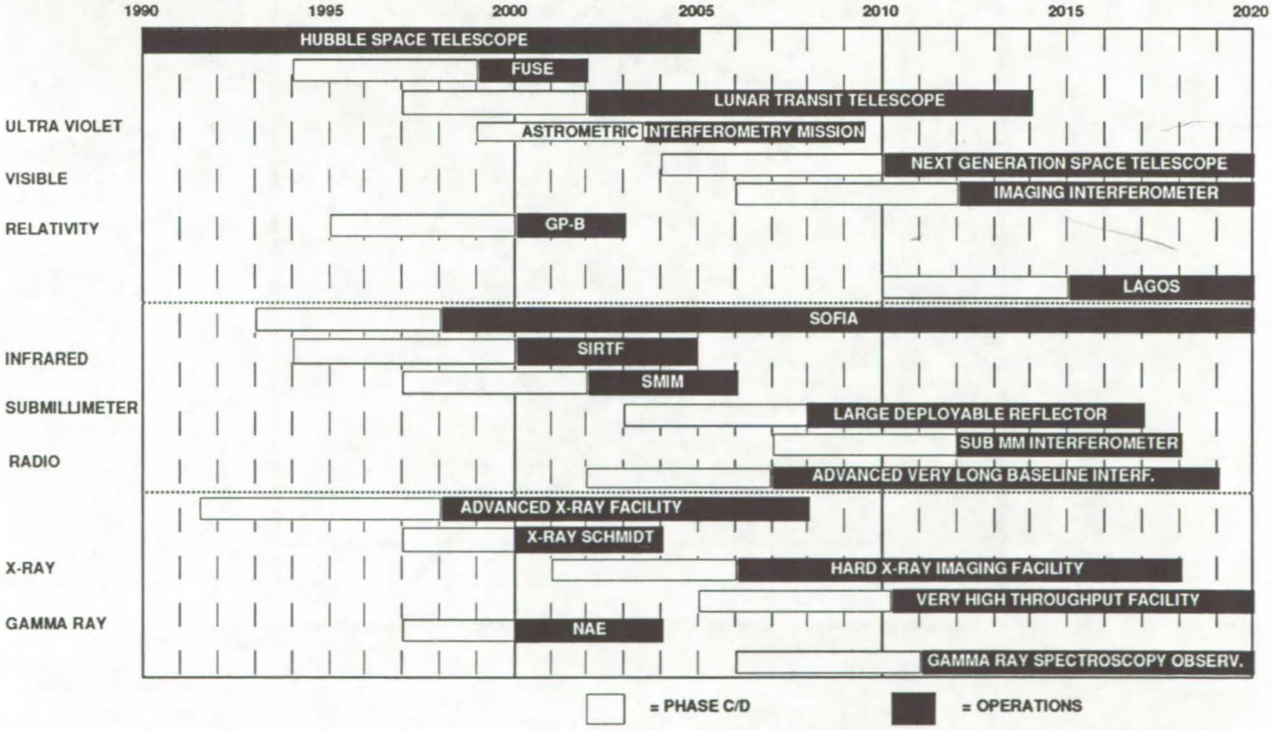

Figure 1. Next Century Astrophysics Program: Candidate major and moderate missions for launch during 1995-2000 (for technology planning purposes only).

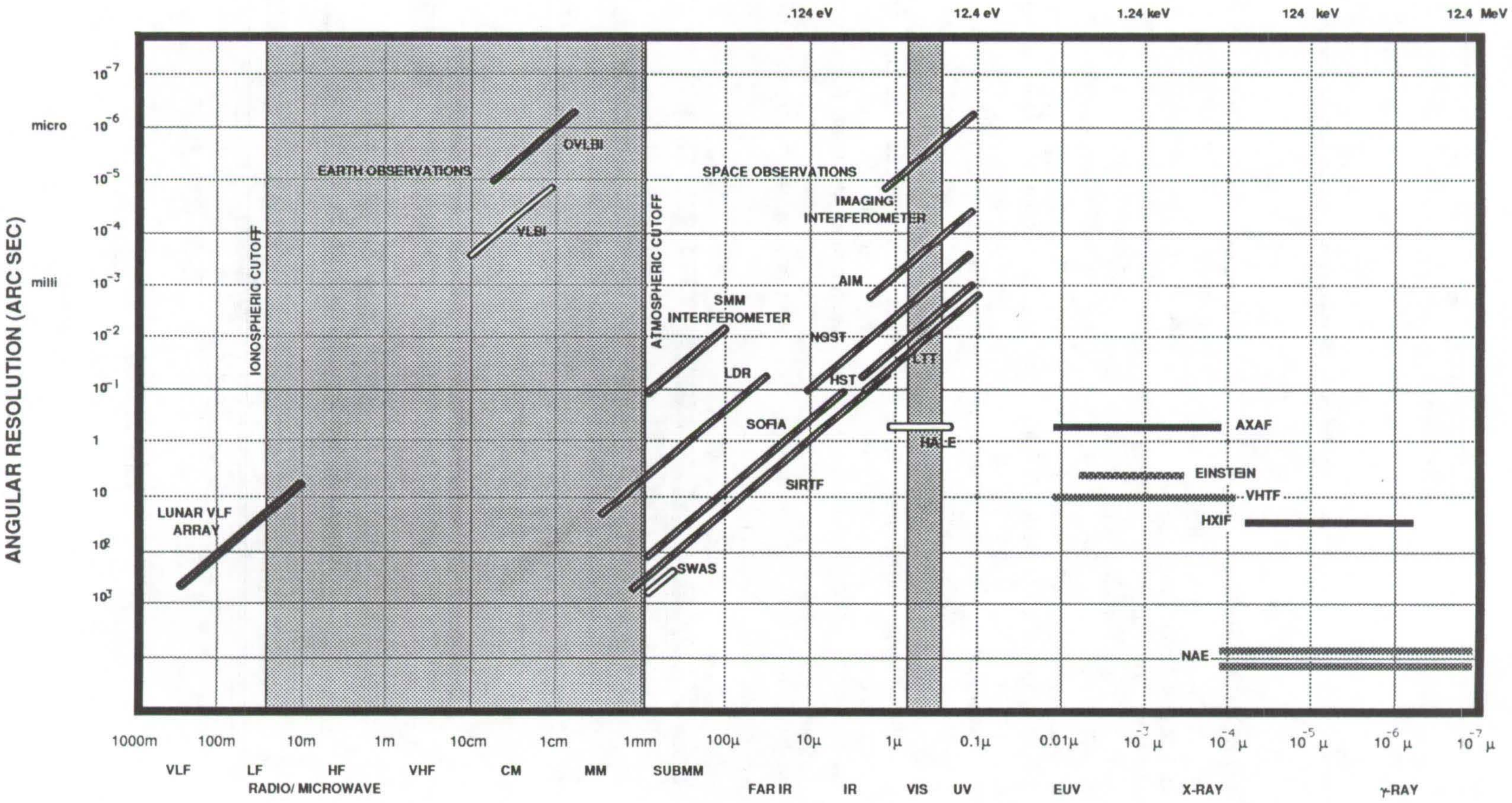

Figure 2. Angular resolution versus wavelength for future astronomical instruments.

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.

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SENSOR TECHNOLOGY WORKSHOP: STRUCTURE AND GOALS

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The Sensor Technology Workshop was held in Pasadena, CA, on January 23 - 25, 1991, as the second in a series of Integrated Technology workshops 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 electromagnetic radiation sensors, and to recommend a plan to develop the required capabilities that are not currently available. To this end, a set of panels was selected, and a two-day meeting was convened in Pasadena. Sensor requirements spanning the entire electromagnetic spectrum were addresses by four panels, with responsibility for gamma-ray and X-ray sensors, ultraviolet and visible sensors, direct infrared sensors, and heterodyne submillimeter-wave sensors, respectively. Because of the close relationship of readout electronics and cooler technology to the sensors themselves, it was decided to include these topics explicitly in the workshop, and two additional panels were convened to cover these areas. The panel chairs and participants are listed in Appendix A.

Prior to their arrival at the meeting, panel members received a briefing package prepared by the workshop chair which contained information on the Astrotech 21 mission set and science goals, and draft listings of (i) the sensor requirements not met by current technology and (ii) 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 straw man versions of their panels' reports 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 of the materials prepared 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 reports from the sensor panels with those of the panels covering associated technologies, the Sensor Readout Electronics and Sensor Cooler Technology Panels sent representatives to each of the sensor panels for part of the first morning to carry on joint discussions. The Readout and Cooler Panels then reassembled for the remainder of their discussions. 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 as the body of this proceedings.

The panel reports first describe the sensor 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 sensor areas in which advances are required, and the relative importance of the desired capabilities to the mission goals. To provide an understanding of the advancements and rate of progress of sensor capabilities in each area, comparison tables are provided highlighting sensor specifications for representative past and future missions, including missions from the Astrotech 21 set, and a snapshot of current state-of-the-art technology, represented by capabilities which have been recently demonstrated in the laboratory. The reports go on to discuss approaches which offer promise in eventually overcoming remaining shortcomings in sensor 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 sensor 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 and scope of effort are defined for each development program. To ensure uniformity of terminology among the recommendations generated by the six different panels, a consistent definition of program scope was identified at the workshop. 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. The three defined ranges are (i) small - 1 - 3 lead personnel plus a comparably sized support staff, (ii) moderate - 3 - 10 lead personnel plus support staff, and (iii) large - 10 - 30 lead personnel plus support staff, possibly with additional significant equipment or facilities expenses. Even with these consistent scope definitions, some variations among the panels' interpretations of these definitions undoubtedly still remain.

It is important to keep in mind that the panels' charter was specifically to focus on those technologies and sensor 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, such as Eos or planetary exploration. They also exclude technologies which 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 (and probably unrealistic) 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 sensor specifications, will be defined, requiring continued sensor development beyond the limited scope considered here. Similarly, missions among the Astrotech 21 set, for which the panels found no evidence of sensor performance needs beyond current capabilities, are not discussed in the reports. These include the gravity and relativity missions, GP-B, GRACE and LAGOS, and the SOFIA mission, whose role at the time of the workshop was viewed primarily as a stratospheric testbed for new technologies being developed for other missions.

The Astrotech 21 mission set is part of an evolving plan, and consequently mission definitions, priorities, and requirements have continued to change during the period in which this Proceedings was being prepared. As much as possible, references to these missions have been updated to reflect the status as of July 1991, when the completed document was submitted for printing.

Because the names of the NASA missions and instruments appear repeatedly in this proceedings, in most cases the acronym is used, and to save space, definitions are provided only in Appendix B at the end of the report. Other acronyms utilized in the Proceedings are generally defined at their first use in each report, and are also included in Appendix B. Note that the use of Roman numerals II or III following a mission acronym is used to refer to refurbishments of the original mission equipment.

SECTION II. PANEL REPORTS

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Report of the X-Ray and Gamma-Ray Sensors Panel

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INTRODUCTION

As one of the youngest wavelength ranges to be opened up for astronomical observations, the X- and gamma-ray regions have grown from an infancy of proportional counters and emulsion stacks to instruments as sophisticated as can be developed by collaborative efforts of the individual observers' groups. While these individuals have carried detector design to an advanced state, detector development has most often been pursued as a side effort of an observing program tied to a sounding rocket or balloon proposal. While proportional counters could be developed with "garage-sized" efforts using apparatus that can be found in any good physics lab, many of the new detector ideas with the greatest promise require expertise and equipment far outside the range an individual astronomy organization can be reasonably expected to possess. Thus further development will require explicit support and an appropriate level of funding. The next generation of instruments promises order-of-magnitude improvements in sensitivity and resolution, and will greatly expand the available discovery spaces. New high-energy sensors will provide unique capabilities for exploring objects as exotic as black holes and neutron stars, as well as directly addressing fundamental questions about the origin of the elements and the composition of the universe. Figure 1 provides an example of the unique information that can be obtained through high-energy measurements.

The charge to this panel was to examine the needs of the Astrotech 21 mission set in regards to X- and gamma-ray detectors and to propose a commensurate plan for the development of the technologies required to meet these needs. The capabilities required for future X- and gamma-ray missions, and the promising technologies for achieving those capabilities have been examined in a series of previous works. Prior to the workshop, the panel chair reviewed the results of these efforts, including the reports of the program working groups, the proceedings of the Taos Workshop (*High-Energy Astrophysics in the 21st Century*, AIP Conference Proceedings # 211, P. C. Joss, ed., AIP, 1990), the proceedings of the Annapolis Workshop (*Astrophysics from the Moon*, AIP Conference Proceedings #207, M. J. Mumma and H. J. Smith, eds., AIP, 1990), and the list of topics that had been submitted during recent proposal calls of the High-Energy Astrophysics Branch of the Astrophysics Division at NASA headquarters. From these, the promising sensor concepts relevant to astrophysics missions were extracted, as a starting point for the panel discussions at the workshop itself.

Discussion of the panel lead to a further narrowing of the field to focus on technologies relevant to the proposed set of missions and instruments which form the Astrotech 21 mission set. The particular technology areas and development schedules were also chosen to guarantee that detectors would be developed on an appropriate schedule to meet the technology freeze dates of the mission set. Thus there may be promising technologies which are absent if they did not appear to be demanded by the candidate missions, or if development of such technologies before the relevant freeze date was not deemed feasible. This may seem somewhat arbitrary, since the mission set is very much a moving target, as various basing options go in and out of vogue. Nevertheless, many aspects of the sensors required for these mission concepts remain stationary even if locations, sizes, and schedules of the selected missions were to change. The panel grouped the selected technologies and found them to fall naturally into five areas. A summary list of these areas is provided in Table I. The items are ordered by a

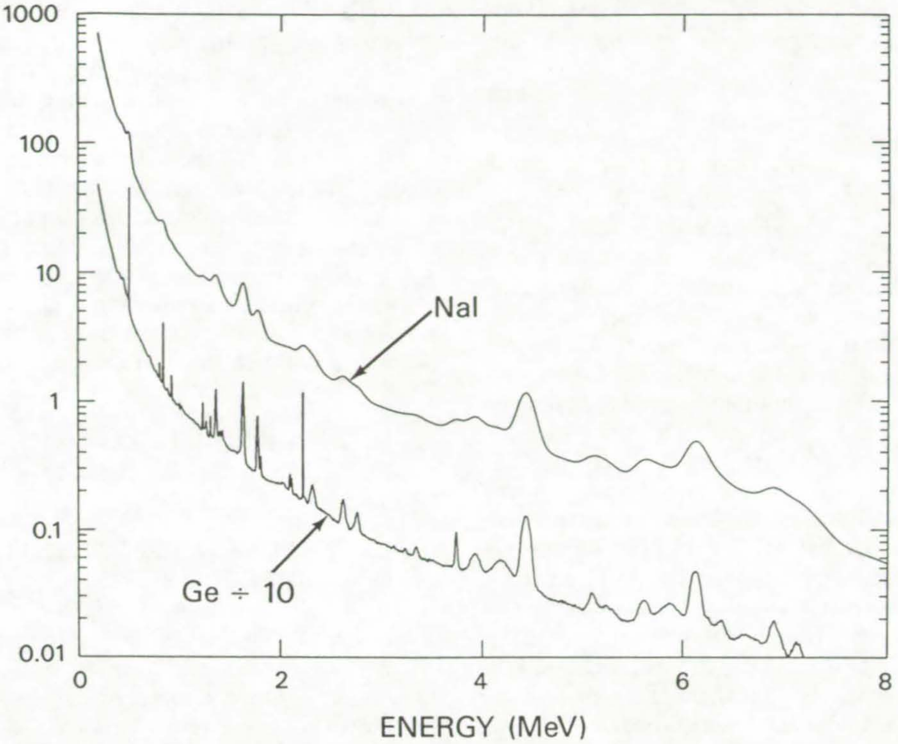

Figure 1. Detector response to model solar flare illustrates the increase in information available as gamma-ray spectrometers evolve from conventional sodium iodide detectors to cooled, high purity germanium detectors.

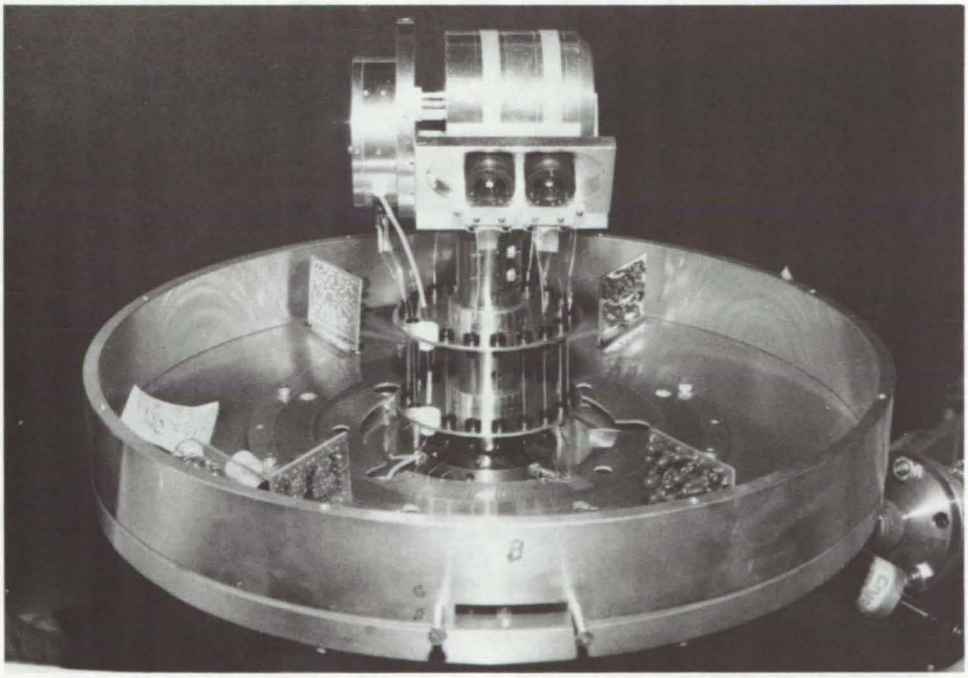

Figure 2. Photo of a position-sensitive germanium detector. Visible are the crystal, electrical contacts, FETs, feed throughs, and pre-amps. (Crystal vacuum housing is not shown.)

priority determined by consideration of technology need dates and promise; however, all five areas are deserving of support now.

In order to view the development history and prognosis of these detector technologies in the context of space implementation, Tables II A and B provide a comparison of performance specifications for past, current and future NASA gamma-ray and X-ray missions. In the gamma-ray region (Table II A), the Energetic Gamma-Ray Experiment Telescope of the Gamma Ray Observatory (GRO/EGRET) and the balloon instrument, the Advanced Compton Telescope (ACT), have been selected to serve as examples of detector technologies that have already flown, and that have already been developed for an upcoming mission, respectively. NAE and GRSO are used as a representative examples of near- and far-term Astrotech 21 missions, for which additional technology development will be required. A similar chart for X-ray detectors is provided in Table II B, where the existing capabilities are exemplified by the Einstein Observatory Imaging Proportional Counter (HEAO II / IPC) and AXAF CCD instruments, and future requirements by instruments for HXIF, VHTF, and replacement instruments for AXAF.

These tables clearly demonstrate the relative immaturity of detector capabilities in these spectral ranges, as well as the large gaps that exist between existing technology and the performance desired for missions in the Astrotech 21 set. In addition, because the need for sensitive, high-energy detectors is unique to NASA, the agency must expect to bear the full funding responsibility to bring about the desired development. In the remainder of this report, each of the five areas recommended by the panel for special attention will be discussed in order of priority. Within each area, the suggested technology development entries are also listed in order of priority. If the entire program cannot be supported initially, the panel recommends that the items at the top of the lists under each area be funded first.

HIGH RESOLUTION GAMMA-RAY SPECTROSCOPIC DETECTORS

A. Technology Assessment

Missions such as NAE and GRSO require 10 keV - 10 MeV detectors with greatly improved sensitivity (more than a factor of 100 better) and orders of magnitude improved imaging capabilities (to a few arc seconds), which will require position sensitivity to < 1 mm. Adding spatial resolution to Ge spectrometers will allow observers to simultaneously realize their existing capabilities for high resolution spectroscopy with the position finding capabilities of coded-aperture or Compton

Table I. Technology Areas Recommended for Development

Technology Area	Requirements	Missions	Freeze Date
High-resolution gamma-ray spectroscopy for 10 keV to 10 MeV	Large volume, high sensitivity Spatial resolution < 1 mm Energy resolution E/ΔE > 1000	NAE GRSO	'94 '04
Cryogenic detectors for range of few eV to few hundred keV	Large format, $(10)^2$ to $(2000)^2$ Energy res.: ≤ 0.5 eV at 100 eV ≤ 5 eV at 8 keV ≤ 100 eV at 100 keV	HXIF, AXAF II * XST AXAF III VHTF GRSO	'95 '96 '00 '03 '04
Advanced X-ray CCDs for 100 eV to 10 keV with smart readouts	QE > 90% Energy res. = 60 eV Spatial res. = 15 - 50 μm Detector size = 1 - 4 cm Radiation hard	AXAF II XST AXAF III VHTF	'95 '96 '00 '03
Position sensitive detectors for 5 - 500 keV (gas & liquid volume interaction chambers)	Pos. res. = 200 μm - 0.5 mm Energy res. E/ΔE ~ 10 - 100	HXIF VHTF GRSO	'00 '03 '04
Large position sensitive detectors for 200 keV - 2 MeV (solid volume interaction chambers)	Area > few m^2 High stopping power 2D resolution to 1-2 mm	HXIF GRSO	'00 '04

* Terminologies II & III refer to 2nd and 3rd generation instruments.

Table IIA. Gamma-Ray Capabilities for NASA Missions

Development Status	Flown in Space	Developed for Space	Under Development	Desired for Future Mission
Sample Mission	GRO/EGRET	Balloon/ACT	NAE	GRSO
Quantum efficiency & energy range (MeV)	30% 20-3000	40% 100-1000	70% 0.1-10	70% 0.1-10
Energy resolution (E/ΔE)	10	10	1000	> 1,000
Spatial resolution	~ mm	~ mm	7 cm	< 1 mm
Readout technology	Digital spark chamber	Photomultiplier tube	FET	Power < 5 nW/pixel Time constant < 5 μs

Table IIB. X-Ray Capabilities for NASA Missions

Development Status	Flown in Space	Developed for Space	Under Development	Desired for Future Mission
Sample Mission	HEAO II / IPC	AXAF / CCD	AXAF II	VHTF
Array format / area	$(100)^2$	$(500)^2$	$(700)^2$	$(1000)^2$
Pixel size (μm)	1000	60	40	20
Quantum efficiency & range (keV)	~ 60% 0.4-4	~ 75% 0.3 - 8	> 90% 0.1 - 10	> 90% 0.1 - 20
Energy resolution (FWHM, eV)	600	90	60	60
Readout technology	Wire grids	Conventional CCD	Re-sampling	"Smart"

telescope schemes. At the present, Ge spectrometers are available in a moderate size (7 cm diameter) and are occasionally partitioned into two segments for background rejection. To meet the requirements of future missions will require larger crystals, with lower backgrounds, and position sensitive readout techniques. (Fig 2.)

B. Development Plan

The recommended areas of technology development are summarized in Table III. The position-sensitive Ge detector array development should be a moderate-sized program, designed to proceed from the initial success with segmentation of Ge detectors for background rejection, to the position sensing needed to create future imaging spectrometers. The development of large, single crystal Ge spectrometers is an optional large-scale program. Much benefit has been gained from the previous advances in detector size, which has allowed more collecting area to be flown (with something like the number of detectors being held constant). While larger spectrometers have larger photopeak efficiencies, a study should first be done to see if astronomers think that larger crystals, which are unlikely to be produced for any need other than astronomy, are actually worth the investment this would require, or if the resources would be better spent assuring a larger supply of detectors in the sizes available now. For high-resolution Ge spectrometers, the Junction field-effect transistor (JFET) must be carefully integrated with the Ge crystal in the detector housing and so is considered part of the detector assembly rather than part of the separate readout electronics. Advanced JFETs, optimized for gamma-ray spectroscopy use, would require a small development program. This effort would fund the creation of JFETs specifically designed and mounted for compatibility (capacitance, operating temperature range, etc.) with Ge spectrometers. Finally, it would

Table III. High Resolution Gamma-Ray Spectroscopic Detectors

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Development of position-sensitive Ge detector arrays	Discrete detectors	1D demo 2D demo	91 - 94 93 - 96	Moderate
Large, high-quality Ge detectors	7 cm (diameter)	10 cm	91 - 94	Large
Advanced JFET development	Off-the-shelf JFETs with large 1/f noise	Low-power, < 5 nW Time constant < 5 µs 85 - 90 K operation Lower 1/f noise	93 - 97	Small
Solid-state drift chamber	Concept only	Feasibility Demo for GRSO	93 - 95 95 - 98	Small Small

be useful to carry out a small program to test which may offer a better combination of spectral/spatial resolution than existing techniques.

CRYOGENIC X-RAY AND GAMMA-RAY DETECTORS

A. Technology Assessment

Large-format detectors for the energy range of a few eV to a few hundred keV with much improved energy resolution are desired for a variety of X- and gamma-ray missions including AXAF refurbishments, HXIF, VHTF and GRSO. Formats of $(10)^2$ to $(2000)^2$ are desired in order to make it practical to determine spatial structures and investigate large numbers of different sources. A one to two order-of-magnitude improvement in energy resolution will enable spectroscopic determinations of compositions and physical conditions of the sources. The term "cryogenic detectors" is used here to cover several innovative technologies which offer great potential benefits, but which require cooling to liquid helium temperature or lower. The first of these techniques is "quantum calorimetry", where the temperature rise from the absorption of individual photons is measured to determine the energy of that photon. While the principle was suggested three decades ago, it has languished until the GSFC/University of Wisconsin collaboration revived the technique, by demonstrating spectrometers capable of performing in the next generation of observatories. The idea that performance increases could be large enough to justify the overhead of cryogenic cooling, sparked inquiries into other type of detectors. Most of these other investigations are focused in two areas: new thermometry techniques (capacitive readout, kinetic inductors, etc.) and in direct detection by absorbing photons in superconducting films attached to tunnel junctions. A third technique involves sensing the changes in a magnetic field applied to an array of supeconducting granules. When initially cooled down, the field is excluded from the interiors of the granules by the Meissner effect. When a photon is absorbed by a granule, that granule is heated above its transition temperature, enters the normal metallic state, and the field rushes into the formerly excluded volume. The detection of the flipping of individual granules has been demonstrated.

B. Development Plan

The areas of technology development recommended are summarized in Table IV. The development of calorimeter technologies represents a continuation from the detectors developed for the AXAF spectrometer to extend the range of sensitivity to higher energy resolution, and to add spatial resolution. It should begin with a moderate program in devices using semiconductor thermometry, with additional small programs to evaluate alternative thermometry technologies such as kinetic inductors, dielectrics and tunnel junctions. After down selection to the most promising option, the development should continue at a moderate level until the desired energy resolution has been achieved, with a mission deadline of 2003 - 2004 to impact VHTF and GRSO.

Amplifier and readout technologies need to be developed in close concert with the detectors, which operate near 4 K and 0.1 K. Both readout items listed address the difficulties of using Si JFETs, which must be operated near 100 K to avoid carrier freeze-out. The 4 K development would be amplifier elements such as Ge JFETs, which could be run at temperatures where it would not be necessary to shield the detectors from the FETs' thermal radiation. Without the need to intercept radiation from hot FETs, many more pixels could be accommodated. The superconducting electronics element is a placeholder for emerging technologies which may permit replacement for FETs.

Table IV. Cryogenic Detectors

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Semiconductor calorimeter arrays	Format: 1x12 arrays E res: 7 eV at 6 keV	Format: $(10)^2$ to $(2000)^2$ E res: ≤ 0.5 eV at 100 eV ≤ 5 eV at 10 keV ≤ 100 eV at 100 keV	Now - 95	Moderate
Alternate thermometries	Concept	Selection of best	93 - 98	Several small
		Development of best	98 - 03	Moderate
Amplifier & readout technologies				
Semiconducting electronics	~100 K	4 K operation	93 - 95	Moderate
Superconducting electronics	Concept	0.1 K operation	94 - 00	Moderate
Superconducting granules	Concept	Feasibility	93 - 98	Small
Development of high energy res		Demonstration	98 - 04	Moderate
Development of readout		Demonstration	98 - 04	Moderate
Tunnel junction fabrication	Concept			
Evaluate different materials		Selection of best	93 - 96	Few small
Tunnel junction readouts		Selection of best	96 - 00	Moderate
Discrete devices		Position sensing	95 - 00	Moderate
Development of arrays		Demonstration	99 - 03	Moderate

The program for investigation of superconducting granule detectors starts small with some additional demonstrations of the feasibility of the technique. If arrays of granules can be fabricated with the required uniformity of properties, the program size is increased to bring the technology further along, perhaps adding a spectral ability by measuring the interval between the time the grain goes normal and when in re-enters the superconducting state.

The final item, development of tunnel junction arrays and readout, offers great promise for imaging X-ray spectrometers, and offers some promise for an advanced Compton telescope for the GRSO era, if manufacturing techniques for producing the required stopping power and area can be developed. There are several different properties which must simultaneously be realized in materials of a tunnel junction used as a detector. The films must have an adequate stopping power for the photons to be detected, but this stopping power cannot be achieved by increasing film thicknesses if a sizable fraction of the quasi-particles created by the absorption are lost while propagating across the film. The combinations of materials used in these junctions must be compatible with each other and the environment, so that the detector is sufficiently robust to survive fabrication and testing, which has not been the case with the detectors demonstrated so far.

ADVANCED X-RAY CCDs

A. Technology Assessment

AXAF II and III, XST and VHTF require radiation-hard, large-format arrays with improved sensitivity, especially in the high-energy range. Although CCDs do not have the energy resolution possible with the cryogenic detectors just discussed, they can be made in a much larger format taking advantage of the industrial base, and they do not require liquid helium temperatures. For XST and the AXAF refurbishments, advanced X-ray CCD arrays would provide: (i) extended on-orbit operating life with improved energy resolution through the elimination of radiation-induced degradation of the charge-transfer efficiency (CTE); (ii) more than an order-of-magnitude improvement in the response in the important 0.1 - 0.5 keV bands; (iii) increased quantum efficiency at 10 keV by a factor of 2-3; (iv) order-of-magnitude extension of the dynamic range for bright-source observation. Since VHTF requires a large number (~ 20) 100-cm^2 focal planes, the reduced-dark current and passive cooling capability offered by CCD technology will be essential. Existing technologies also fall short in the area of readout techniques for large arrays. Currently, the readout of a large CCD requires a large dead-time while the pixels are shifted out. For most fields, the X-ray images will be sparse, and the linear readout of the entire chip represents much wasted time. Improved "smart" readout techniques would allow the sampling bandwidth to be dedicated to the parts of the chip where signals are located.

B. Development Plan

The suggested areas for technology development are shown in Table V. Although significant charge-coupled device (CCD) development will be performed for commercial industrial uses, and some will be recommended by the other wavelength panels, the X-ray requirements for CCDs are unique and will not be met except by a focused development effort. The focal planes of some of the optical systems envisioned for future missions are larger than the size that we can reasonably expect to fabricate reliably, so we require formats that allow abutting individual chips. Among the other unique requirements are increased depletion depths, to extend to higher X-ray energies, and smaller "dead" layers, either from gate structure or regions with low mobilities, to extend to lower energies. Some of the early work could actually be carried out in parallel, new devices could be fabricated to attempt to improve both radiation resistance and bandpass. Improved high energy response will require the use of high resistivity substrates which would allow the creation of deeper depletion regions. Technologies worthy of consideration for lowering the dark current include guard-ring or edge-diode structures, ultra low impurity wafer materials, and intermediate gate structures.

A large program is recommended for the development of readout electronics. There are several advanced readout techniques to be investigated; in addition to improvements to on-chip amplifiers for lowering read noise levels, advances such as array segmentation techniques, 3-D focal plane approaches and parallel register structures. There is also the possibility of circuitry to take advantage of the sparse nature of most X-ray fields, either by selective readout of sections of the CCD where signals are present, or by constructing "smart pixels", which do not require any output bandwidth until an X-ray photon is collected.

POSITION-SENSITIVE DETECTORS

A. Technology Assessment

The development of high-pressure gas and/or liquid chamber technologies for the detection of 5 - 500 keV photons is recommended. Current gas counters do not provide adequate position resolution to meet the requirements of missions such as HXIF, VHTF and GRSO, for which sufficient position identification is desired in order to individually identify the sources of hard X-ray and gamma-ray sources. Improved volume interaction chambers, either liquid or high-pressure gas, will be required.

B. Development Plan

The recommended development program can be split into six parts, as summarized in Table VI. In this area it is less clear which of several contenders will emerge as the optimal choices for the fairly different requirements for the three candidate missions. High stopping power is of great importance for HXIF and GRSO, energy resolution for GRSO, very fine position resolution over a small detector for VHTF, and moderate position resolution over a large detector for HXIF. The panel recommends a small-scale

Table V. Advanced X-Ray CCDs

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Radiation hardening	Radiation-induced CTE degradation	Invulnerable to protons, neutrons and electrons	93 - 96	Moderate
Improved low-energy response	QE < 5%	QE > 90% 0.1 - 0.5 keV	93 - 96	Moderate
Improved high-energy response	QE < 40%	QE > 90% at 10 keV	93 - 97	Small
Lower readout noise	2 e^- rms	0.2 e^- rms	07 - 00	Moderate
Advanced readout techniques	Concepts	Smart readouts for large arrays	93 - 96	Large

Table VI. Position-Sensitive Detectors (Gas & Liquid Chambers)

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Improved multistep & fluorescence gating	Laboratory demo	Flight worthy	93 - 99	Small
High-pressure gas counters with readouts	Concept	Demonstration $E/\Delta E = 10\text{-}100$ Spatial res ~ 200 μm	95 - 99	Small
Liquid Xe detector	Concept	Demonstration $E/\Delta E = 10\text{-}100$ Spatial res ~ 200 μm	95 - 99	Small
Development to meet requirements for VHTF	None	Prototype(s)	00 - 03	Moderate
Development to meet requirements of GRSO	None	Prototype(s)	00 - 04	Moderate

effort, with an early start, to develop improved multistep or fluorescence-gating techniques. Additional small programs are recommended for methods to increase the detector pressure in gas-chamber detectors, and to develop fiber-optic readouts. A small program is also suggested to develop liquid Xe detectors. Additional work at a moderate level of effort will be required following the development of these capabilities to meet the stopping power and energy resolution required for GRSO, and the very fine position resolution for VHTF.

LARGE POSITION-SENSITIVE DETECTORS

A. Technology Assessment

For higher energy photons in the 0.02 to 2 MeV range, it is necessary to achieve the greater stopping power offered by solid scintillators. HXIF and GRSO require large area (> a few square meters), and two-dimensional position sensing accurate to 1 - 2 mm. This must simultaneously be realized in a system with backgrounds low enough to permit sensitivity at the 10^{-6}-10^{-7} photons/cm^2-sec level. These detector capabilities will enable high-sensitivity surveys with a ~ 1 arc-min resolution, leading to the anticipated identification of > 10,000 high-energy sources. This will permit class studies of active galactic nuclei (AGN), the variability of these AGN, and detailed studies of compact objects such as neutron stars and black holes.

B. Development Plan

A set of five technology development programs is recommended, as detailed in Table VII. First, a moderate program is recommended to develop and optimize solid scintillator materials, to meet the sensitivity requirements. Realistic implementation of solid-state scintillators also requires the development of low-profile, position-sensitive optical readout, and passive and active coded mask development, recommended for moderate- and small-scale programs, respectively. As an alternate to optical readout, the development of low-profile photomultiplier tubes (PMTs) or of photodetectors of Si or other materials, including the "solid state PMT" technologies, could be considered. Coded mask development may also involve small optical sensors for readout of scintillators in active mask elements. Finally, following the demonstration of the basic capabilities, the final focused development must be undertaken to meet the position resolution and stopping power for the high-energy ranges of HXIF and GRSO.

SUMMARY

Overall five major areas of technology are recommended for development in order to meet the science requirements of the Astrotech 21 mission set. These are detectors for high-resolution gamma-ray spectroscopy, cryogenic detectors for improved X-ray spectral and spatial resolution, advanced X-ray CCDs for higher energy resolution, larger format, and extension to higher energies, and liquid and solid position-sensitive detectors for improved stopping power in the energy ranges 5 - 500 keV and 0.2 - 2 MeV, respectively. Development plans designed to

Table VII. Large Position-Sensitive Detectors (Solid Scintillators)

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Scintillator material development & optimization	Concepts	Demonstration	93 - 97	Moderate
Low-profile, position-sensitive optical readout	Concepts	Demonstrations	93 - 96	Moderate
Passive & active coded mask technologies	Concepts	Demonstrations	93 - 96	Small
Advanced development focused on HXIF requirements	None	Prototype(s)	97 - 00	Moderate
Advanced development focused on GRSO requirements	None	Prototype(s)	00 - 04	Moderate

achieve the desired capabilities on the time scales required by the technology freeze dates have been recommended in each of these areas. For high-resolution gamma-ray spectroscopy, the focus is on the development of large-area arrays and associated advanced readout technologies. New cryogenic technologies are desired to increase the energy resolution beyond that available with existing semiconductor calorimeter arrays. Imaging in the X-ray regime would greatly benefit from the development of radiation-hard CCDs with improved low- and high-energy sensitivities, and smart readout techniques. Finally, the development of improved gas, liquid and solid volume interaction chambers could greatly increase the sensitivity of detectors in the highest energy ranges where the stopping power currently limits the response. Each of the development programs shows an artificial end at the technology freeze date of the last relevant mission of the Astrotech 21 set, namely 2000 - 2004. In fact, new missions will be coming over the planning horizon during this time, and we expect that new technologies will be identified for development in order to have instruments which can meet the challenges of the subsequent generation of observatories.

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Report of the Ultraviolet and Visible Sensors Panel

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INTRODUCTION

The Ultraviolet and Visible Sensors Panel was originally chartered to review the advanced technology developments required for the wavelength range from 0.1 to 2.5 microns for astrophysics missions in the first part of the twenty-first century. The initial discussions of the panel centered on the designated wavelength range. It was agreed that the panel's considerations should be extended to cover the wavelength range from 0.01 to 0.1 microns in order to overlap with the deliberations of the X-ray and Gamma Ray Sensors Panel and not leave a gap in the extreme ultraviolet (EUV) spectral region at wavelengths below 0.1 microns. It was also decided, for reasons based on differing science goals and technologies, to split the wavelength range up into three domains; specifically, 0.01 to 0.3 microns, 0.3 to 0.9 microns, and 0.9 to 2.5 microns. A consensus was reached on the performance requirements and recommendations for technology development in all three wavelength ranges, as described in the next three sections of the report.

0.01 TO 0.3 MICRONS

A. Technology Assessment

One of the primary requirements in the 0.01 to 0.3 μm wavelength range is to effectively reject visible-light radiation which, for many astrophysical objects, has an intensity many orders of magnitude greater than that of the ultraviolet and far-ultraviolet emissions. Because of this difficulty, and the relative immaturity of sensor technologies for the ultraviolet (UV), this wavelength range was considered the most demanding of development among those considered by this panel. Historically, photoemissive cathode technologies have offered the best performance across much of the UV range. However, the potentially superior imaging capabilities and sensitivity of CCDs offer inducement to extend their range into the UV, and CCDs may play a growing role in future missions, if efficient short-pass filters can be developed, the problems of contamination of cooled CCDs can be solved and an increase in sensitivity by back thinning can be achieved.

In the context of past and future NASA missions, Table IA summarizes existing and desired performance of photoemissive cathode technologies in the UV. The High Resolution Imager (HRI) on the Einstein Observatory is shown as an example of what has already been flown, and the Extreme Ultraviolet Explorer (EUVE) provides an example of technology already developed for an upcoming mission. In order to assess the capabilities currently under development and those desired for future astrophysics missions, the third column shows the performance that has been demonstrated to date in the laboratory for the Space Telescope Imaging Spectrograph (STIS), a refurbishment instrument for HST, and NGST is selected as an example of a more distant future mission. Equivalent information on CCD technologies is provided in Table IB. HST instruments WF/PC 1 and 2 are selected to represent an instrument already flown in space and one developed for an upcoming mission, respectively. NGST is again used as an example of a more distant future mission. Although a complete discussion of detector performance in the visible wavelength range is reserved for the following section, the CCD specifications are very similar, and have been included in Table IB for convenience.

TABLE IA. UV Capabilities for NASA Missions (Emissive Photocathodes)

Development Status	Flown in Space	Developed for Space	Demonstrated in Laboratory	Desired for Future Mission
Sample Mission	Einstein Observatory	EUVE	HST II / STIS	NGST
Array size	1850 x 1850	650 x 650 (2048 electronic bins)	2k x 2k	4k x 4k
Pixel size (µm)	15	50 (circular)	25	5
Quantum efficiency for range (µm)	> 20% < 0.1	> 30% < 0.1	> 30% < 0.12	> 50% 0.01 to ≥ 0.1
Dark count ($cm^{-1}s^{-1}$)	0.2	< 0.3	< 0.3	< 0.3
Read rate local ($s^{-1}pixel^{-1}$) and total (s^{-1})	< 10 $< 10^5$	40 $> 10^4$	100 $> 8 \times 10^6$	1000 $\geq 10^8$
Cosmic ray Discrimination	No	No	No	Discrimination
Tube Structure	Open	Open	Sealed & open	Sealed & open

TABLE IB. UV and Visible Sensor Capabilities for NASA Missions (CCDs)

Development Status	Flown in Space	Developed for Space	Demonstrated in Laboratory	Desired for Future Mission
Sample Mission	HST WF/PC 1	HST WF/PC 2	N/A	NGST
Visible blindness	$< 10^{-4}$	$< 10^{-9}$	$< 10^{-9}$ with filter	$< 10^{-9}$ for imaging
Array size	800 x 800	800 x 800	4k x 4k	≥ 15k x 15k
QE for 0.1 - 0.4 µm QE for 0.4 - 1.0 µm	> 15% > 15%	> 25% > 25%	30% > 60%	> 80% > 80%
Well capacity (e^-) @ pixel size (µm)	30,000 @ 15	40,000 @ 7	40,000 @ 7	100,000 @ 5
Read noise (e^- rms)	10	2	0.4	0.1
Read rate (pixels s^{-1}) @ read noise (e^- rms)	50,000 @ 10	50,000 @ 2	50,000 @ 0.4	100,000 @ 0.1
Operating temperature	- 95 °C	- 60 °C	- 20 °C	20 °C
Mosaic capability	No	No	Buttable for line array	Buttable for 2-D mosaic

B. Development Plan

A number of technical advances are required, both for missions which have an immediate need, such as FUSE and HST, as well as for the advanced missions that will occur in the first part of the next century. A summary of the areas recommended for development is provided in Table II.

The primary requirement for this wavelength range is for simultaneous high-efficiency and "*solar-blind*", i.e. "*visible-blind*", response. There are three technology areas which the panel recommends for development. The first is high-quantum-efficiency ultraviolet photocathodes which have an inherently low sensitivity at wavelengths beyond 0.3 microns. These are required for the photo-emissive detector systems such as the imaging microchannel plate (MCP) detector systems.

TABLE II. Technology Development Recommended for 0.01 to 0.3 Microns

Technology Development	First Mission Impacted	Program Dates	Program Size
• **High-efficiency "solar blind" detectors:**			
a. High QE photocathodes	FUSE	91-93	small/moderate
b. High QE CCDs	HST / ORI	91-95	large
c. High-transmission UV filters	HST / ORI	92-95	small/moderate
• **Improved MCPs:**			
a. New glass MCPs	FUSE	91-93	moderate
b. Advanced-technology MCPs	NGST	93-98	large/major
• **Advanced MCP readout systems:**			
a. Small pixel size	FUSE	91-93	moderate
b. Large format	HST / STIS	91-95	moderate/large
c. High dynamic range	HST / ORI	91-95	moderate/large
• **New materials:**			
a. Non-Si CCDs, high-bandgap sensors	NGST	93-98	large
b. Opaque negative-affinity photocathodes	NGST	93-98	moderate/large
• **Cryogenic 3-D detectors:**			
a. Simultaneous 2-D spatial, energy resolution	NGST	93-00	small

The second recommended development area is for high quantum efficiency (QE) charge-coupled devices (CCDs) or other high-bandgap detector concepts. A number of means are being investigated for increasing the QE of CCDs in the UV, such as thinning, coating with down-converting phosphors, and ion implantation. Approaches such as SiC photodiodes or other novel high-bandgap intrinsic detectors are also promising approaches. The panel did not feel that it was its responsibility to discuss the relative merits or likelihood of success of the various approaches. Suffice to say, that any investigation in this area that shows promise should be investigated. The third requirement is for high-transmission UV filters that have a very low transmission at wavelengths longer than 0.3 μm, which will be required if inherently solar-blind detectors have not been demonstrated in time for future UV missions. A number of investigations into filters of this type are currently under way, but success to date has been relatively limited.

It was also felt that there was a need for improved MCPs to provide the basis for the imaging photo-emissive detector systems for this wavelength range. Improvements are required to the reduced lead silicate glass (RLSG) MCPs and there is a need to initiate now the development of advanced-technology MCPs (AT-MCPs), fabricated by lithographic semiconductor techniques. The requirements for these improved MCPs are listed in Table III.

Concurrent with this development, there is a need to develop advanced MCP read-out systems emphasizing small pixel size, large formats, and systems which can provide the high dynamic range that would be needed, for example, for a third-generation ultraviolet camera for HST. The requirements for these read-out systems are specified in more detail in Table IV.

Looking further ahead, it was felt that basic research in new materials technology was also required. For CCDs, investigations of large-bandgap non-silicon CCDs could produce a detector which has an inherently high level of rejection of visible light radiation, thereby bypassing the stringent requirements on visible-blocking filters. Similarly, the development of high-work-function opaque negative-affinity photocathodes would produce photoemissive detector systems with very high quantum efficiencies in the ultraviolet, and very low sensitivities at wavelengths longer than about 0.25 to 0.3 microns. The specific parameters desired for these CCDs (and negative-affinity photocathodes) are for large bandgaps (and work functions) ≥ 4 eV. There is currently no demonstrated capability for either technology, or any significant development already under way.

Finally, looking even further into the future, it was recommended that basic investigations into novel three-dimensional detector systems which can provide simultaneously two-dimensional spatial information and energy resolution should be initiated. Suggestions for these cryogenic detector systems have already been made, but obviously, at this point in

TABLE III. Status and Requirements for High-Gain MCPs

Developed:	Diameter ~ 100 mm Spatial uniformity ~ 25 to 50 μm (multi-fiber defects) Channel diameter 10 μm Dark count rate < 0.3 counts cm^{-2} s^{-1} Maximum count rate ~ 50 counts channel^{-1} s^{-1} (12-μm channels) Lifetime ~ 10 C cm^{-2}
Under development:	Channel diameter 8 μm Square channels (60-μm to 25-μm channels) Curved plates Dark count rate < 0.03 counts cm^{-2} s^{-1} Maximum count rate ~ 100 counts channel^{-1} s^{-1} (12-μm channels) Lifetime TBD
Required:	Diameter ~ 100 mm No spatial distortion (AT-MCPs) Square channels (6-μm channels) Dark count < 0.01 counts cm^{-2} s^{-1} (anti-coincidence) Maximum count rate > 10^3 counts channel^{-1} s^{-1} (6-μm channels) Lifetime > 30 C cm^{-2}

TABLE IV. Status and Requirements for MCP Read-out Systems

Developed:	~1 k x 1 k Spatial resolution 14 μm to 25 μm Position sensitivity ~ 1 μm Maximum count rate ~ 10^6 counts s^{-1}
Under development:	~ 2 k x 2 k Spatial resolution 14 μm to 25 μm Position sensitivity ~ 1 μm Maximum count rate ~ 2 x 10^6 - 10^7 counts s^{-1}
Required:	~ 4 k x 4 k Spatial resolution 10 μm Position sensitivity < 1 μm Maximum count rate >> 10^7 counts s^{-1} Buttable for mosaics

time, studies are limited to conceptual analyses and fundamental laboratory investigations. The desired performance parameters for these detectors are for large-format arrays (~ 1k x 1k) with simultaneous energy resolution, $E/\Delta E > 10$.

0.3 TO 0.9 MICRONS

A. Technology Assessment

For the wavelength range from 0.3 to 0.9 μm, it was felt that the entire effort should be directed toward the further development of silicon CCDs because of their potentially very high quantum efficiencies in this wavelength range. It was also felt that a major effort should be made toward improving the packaging of these CCDs, since in many cases to date, the performance of the CCDs has been degraded by the undesirable aspects of their packaging. An overview in the context of NASA missions of the state-of-the-art and desired CCD performance in the visible was provided in Table IB in the previous section.

NASA has played a key role in the development of CCD technology. Starting in 1974, NASA recognized the potential of CCD arrays, which at that time were available in 100 x 100 formats and with ~ 100 e⁻ rms readout noise, and sponsored their further development. This initial program culminated in the CCD arrays which were flown on Galileo and the Hubble Space Telescope, with format and read noise of 800 x 800 and 10 e⁻ rms, respectively. This advance in technology is graphically demonstrated in figure 1, in which a modern 4096 x 4096 CCD array fabricated by LORAL is compared to the vidicon detectors used on the Voyager mission. Continuing NASA-sponsored work seeks to further improve format size and readout noise, as well as to increase the sensitivity, to extend the range across an unprecedented spectral range (1 Å - 11,000 Å), and to improve manufacturing yield and reliability, including radiation hardness.

B. Development Plan

Future astrophysics missions require, simultaneously, a very high quantum efficiency, a deep full-well capacity, large format, low read noise at a high read rate, and a device that can be radiation hardened. It was felt by the panel that if a quantum efficiency of > 80% and a read noise of the order of, or less than, 1 e⁻ rms could be achieved, there would be no need for the development of photon-counting detectors for this wavelength range, since the CCDs could meet essentially all of the scientific requirements for the missions considered under the Astrotech 21 Program plan. Specific areas recommended by the panel for focused development of visible CCDs and CCD packaging are listed in Table V.

In the area of packaging, it was felt that the package should have low radiation emission, should be compatible with the flatness requirements of the optical system, should be compatible with the cleanliness requirements for the cooled CCD and, particularly; should be compatible with two-dimensional mosaicking of buttable CCDs. The possibility for cosmic ray discrimination, using anticoincidence counting of two CCDs mounted back-to-back, would also provide major advantages in observing efficiency, particularly for missions on the lunar surface.

0.9 TO 2.5 MICRONS

A. Technology Assessment

The near infrared region from 0.9 μm to 2.5 μm is covered in detail by the Direct Infrared Sensor Panel. Consequently, the UV and Visible Sensor Panel decided to focus their efforts in this wavelength range on aspects of the technology that might particularly benefit from the heritage of shorter wavelength detectors. The great success of visible CCD detectors in providing the ultimate in sensitivity, as well as offering large-format arrays, leads this panel to support efforts to develop similar technologies for the near IR.

TABLE V. Technology Development Recommended for 0.3 to 0.9 Microns

Technology Development	First Mission Impacted	Program Dates	Program Size
• **Si CCDs:**			
High Q.E.	HST II* / STIS	91-94	large
Deep full well	HST II / STIS	91-94	large
Large format	HST II / STIS	91-94	large
Low read noise	HST II / STIS	91-94	large
High read rate	LTT	92-95	moderate
Radiation hardened	LTT	92-95	large
• **CCD Packaging:**			
Low radiation	HST II / STIS	91-94	small
Thinned/flat	HST II / STIS	91-94	moderate
Cleanliness	HST II / STIS	91-94	moderate
Mosaic compatible	LTT	92-95	large
Cooling	LTT	92-95	moderate
Cosmic ray discrimination	LTT	92-95	large

* Terminology II refers to 2nd generation instruments.

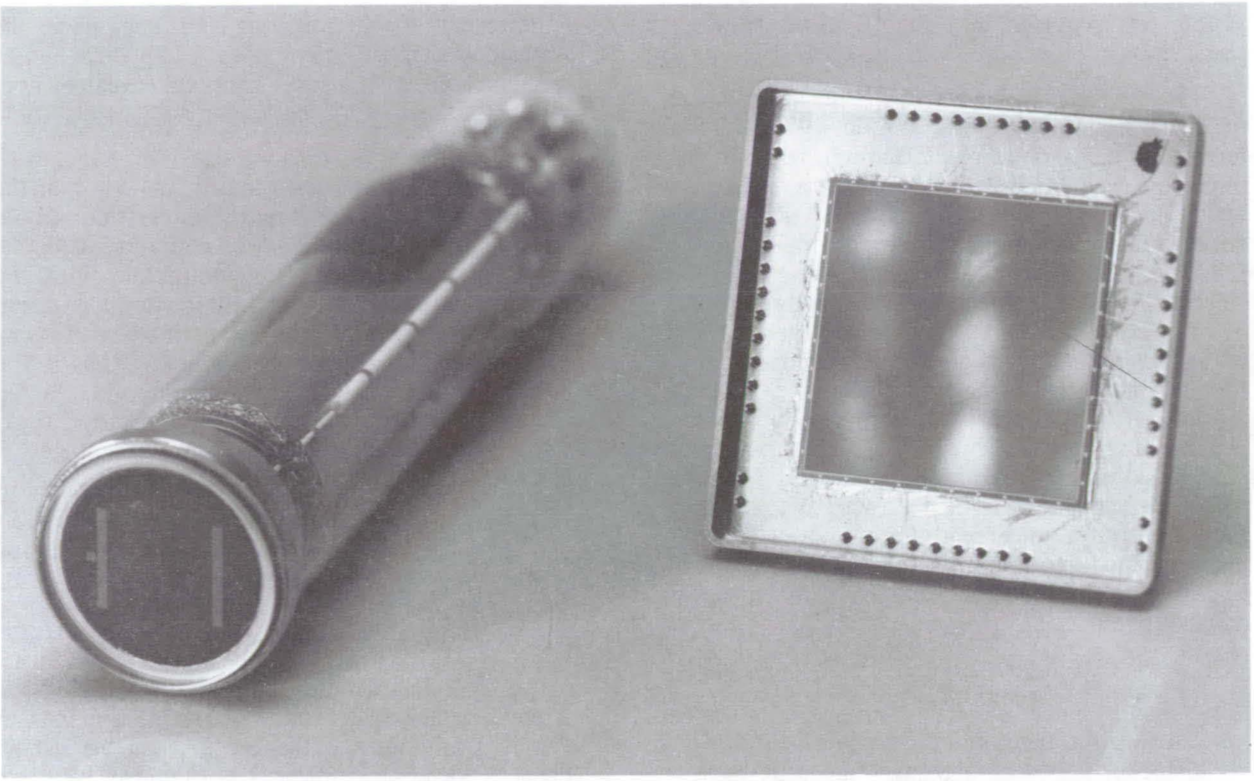

Figure 1. Comparison of a vidicon image tube developed in the early 1970's and used on the Voyager program with a state-of-the-art planar CCD array illustrating the advances in visible imaging technology during the last 20 years. The vidicon tube was scanned in an 800 x 800 array format with 15 x 15 µm pixels and was fabricated by the General Electrodynamics Corporation and has operated successfully for 15 years on the Voyager spacecraft. The CCD is a 4096 x 4096 array with 7.5 µm pixels fabricated by LORAL Corporation and has been demonstrated in the laboratory but is not yet qualified for flight.

B. Development Plan

Specifically, the panel recommends investigations of novel CCD structures such as the Direct Shottky Injection Focal Plane Array where the first material could have a very high near-IR quantum efficiency such as Ge, InSb, or HgCdTe. It was also felt that an investigation into new materials for this wavelength range should be undertaken for advanced missions such as the NGST, where the lead time is sufficient for a longer term materials development effort. These recommendations are shown in Table VI. Some concern was also expressed that the technology in this wavelength range would be subject to classification by DoD because of its military applications.

TECHNOLOGY DEVELOPMENT ISSUES

In its final discussions, the Panel felt that there were a number of additional issues that should be highlighted in the Astrotech 21 report. These issues are summarized in Table VII.

First, it should be clearly noted that there is no industrial or DoD requirement for CCDs with the performance characteristics required for astrophysics space missions. Consequently, NASA, as an agency, should be prepared to bear the full cost of developing these devices. Similarly, for the large-format MCPs, there is only a limited industrial requirement to meet the needs of the cathode ray tube industry. NASA must also be prepared to bear essentially the full cost of the development of these large-format MCPs. It was also noted that there are a very limited number of industrial sources for CCDs and MCPs with the performance characteristics required for astrophysics space missions, and that anticipated reductions in their funding as existing projects are completed may place their continued existence in jeopardy. Further, at this time, the development of large-format UV and visible-light detectors, specifically, silicon CCDs and MCPs, is currently funded almost solely by one NASA project; namely, the Second-Generation Hubble Space Telescope Imaging Spectrograph (STIS) being developed at the NASA Goddard Space Flight Center. Continuity of funding and level of

TABLE VI. Technology Development Recommended for 0.9 to 2.5 Microns

Technology Development	First Mission Impacted	Program Dates	Program Size
Monolithic Near-IR Arrays:			
Si	HST-ORI	93-96	Small
Ge	HST-ORI	93-96	Small
InSb	LTT	93-96	Small
HgCdTe	MOI	91-94	Small
New materials	NGST	93-96	Small
Develop best option(s)		96-00	Moderate

TABLE VII. Technology Development Issues

- No industrial or DoD requirement for astrophysics quality CCDs.
- Limited industrial requirement for large-format MCPs.
- Limited number of industrial sources for CCDs and MCPs.
- Development of large-format UV and visible detectors (MCPs and CCDs) is currently funded almost solely by the HST / STIS instrument-development program.
- Continuity of funding and level of funding are critical to maintain these technologies.
- Very large arrays will require new data transmission and handling technologies which should be considered by the appropriate Astrotech 21 panel.

funding appropriate to attract the attention of the industrial corporations concerned is consequently critical to maintaining these technologies if they are to support the Astrotech 21 missions.

The final issue that was noted by this panel was that the very large array detectors will require new data-transmission technologies and new data-recording and data-handling technologies. While it is not the task of this workshop to review these technologies, it is hoped that an appropriate Astrotech 21 panel will review and report on the needs in this area.

SUMMARY

After reviewing the Astrotech 21 mission set and the currently available sensor technology, the Ultraviolet and Visible Sensors Panel concluded that there are a number of areas in which additional development will be required in order to meet the science objectives of these missions. Within the wavelength range considered by this panel, 0.01 to 2.5 µm, requirements for the high-energy part of the UV spectrum, 0.01 to 0.3 µm, were judged to be farthest from existing sensor capabilities. In this region, the focus is on the need for large format high-quantum efficiency, radiation hard "solar-blind" detectors. Options recommended for support include Si CCDs with visible-rejecting filters, high-efficiency photocathodes with improved MCPs and readouts, and non-Si CCDs. Cryogenic, "3-D" detectors were also called out as meriting support. For the 0.3 to 0.9 µm range, it was felt that the entire effort should be directed towards the further development of Si CCDs, which were deemed to offer the best option for high quantum efficiencies for these wavelengths. Development of both the CCDs themselves, as well as advanced focal-plane packaging, was recommended for support. The panel also expressed concern over the precarious position of the CCD technology base, and the need for additional funding to sustain it as current sources of support are phased out. In the near IR, 0.9 to 2.5 µm, the panel recommended support for the investigation of monolithic arrays. Finally, the panel noted that the implementation of very large arrays will require new data-transmission, data-recording and data-handling technologies.

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Report of the Direct Infrared Sensors Panel

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INTRODUCTION

The infrared (IR) regime is a particularly important wavelength range for future NASA missions. Direct and heterodyne spectroscopy in the IR and submillimeter-wave regimes offer crucial information on composition, by probing the rich region of vibration-rotation spectroscopy in which constituents can be identified by their spectral signatures. However, since the Earth's atmosphere is opaque across much of this regime, and despite sizeable investments in military technology, there has been little focused development of sensors for scientific applications in this region prior to the advent of space-based astronomy. Consequently, IR detector technology is considerably less mature than that for visible wavelengths. Nevertheless, recent advances are enabling high-quality imaging in the IR range, which is revealing new and complementary information in comparison to visible images of the same astronomical scene. Visible and IR images of the same region displayed in figure 1 graphically illustrate the potential of large-format IR arrays.

The Direct Infrared Sensors Panel was charged with assessing those sensing requirements in the near to very far infrared (1 - 1000 μm) for the Astrotech 21 mission set that are best addressed with direct infrared detectors (as opposed to heterodyne approaches). This very broad range of wavelengths encompasses very different requirements and detector technologies, and the panel decided to split the range into four spectral domains: 1 - 5 μm, 5 - 30 μm, 30 - 200 μm, and 200 - 1000 μm, which reflects a natural division among the relevant technologies.

After examining the mission set and associated sensor requirements, the panel also recognized that the mission set could be categorized into systems which provide low backgrounds to the detectors (either by liquid He cooling of the telescope optics, or through highly dispersive optics), and those missions, with passively cooled optics, which would operate with "moderate" backgrounds. Because of this natural grouping, and because of the limited amount of time at the workshop, the IR detector panel in most cases did not consider specific needs of particular missions. The moderate background missions in the set, which tend to require advanced technology at earlier dates, are designated "MB" in this report. Examples include the Lunar Transit Telescope, the Astrometric Interferometry Mission, the Next Generation Space Telescope, the Imaging Interferometer, and the low-resolution instruments of the Large Deployable Reflector. For these missions, detector technology needs are in general ones of higher operating temperature (to allow focal planes to operate with the simpler and lower-power closed-cycle coolers), large or very large array formats, and large charge-storage (well) capacity, optimized for moderate background levels of perhaps ~10^5 - 10^8 or more photons/s-pixel. The class of low-background ("LB") missions include SIRTF and "Son of SIRTF" (mission to beyond the asteroid belt). Importantly, detectors in high-spectral-resolution instruments on missions with passively-cooled optics, such as LDR, will be operating under low-background conditions. For these missions/instruments, the utmost in sensitivity is required, and minimum read noise and dark current are key parameters. These background levels may be down to

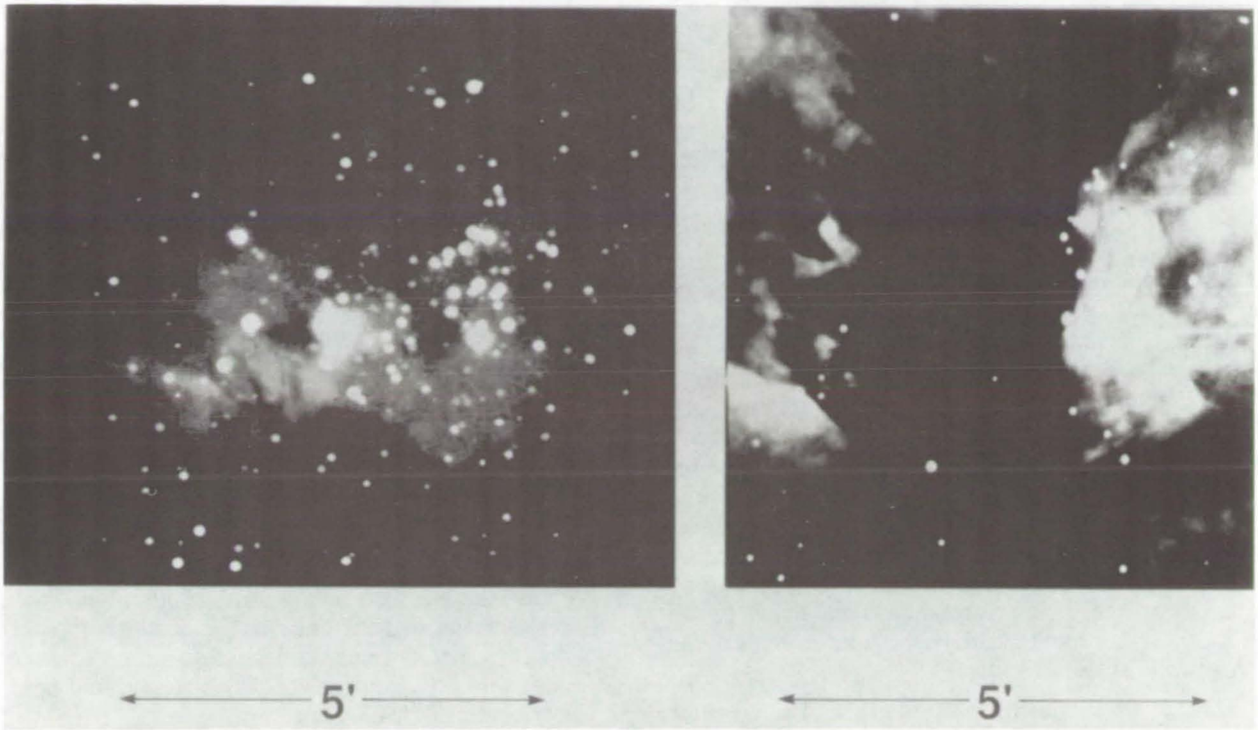

Figure 1. Infrared (left) and visible (right) images of star-forming region NGC 2024. Dust clouds which obscure much of the detail in the visible image are transparent to longer wavelength radiation. This comparison illustrates the wealth of information which will become available with the development of large-format IR arrays.

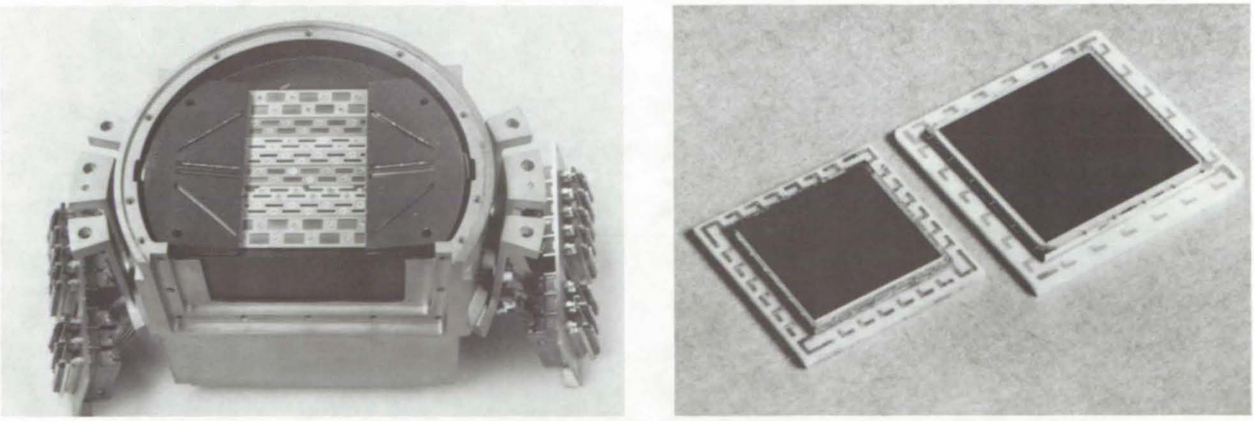

Figure 2.

Left: Array of discrete detectors used in the IRAS mission.

Right: State-of-the-art IR array demonstrating recent advances in two-dimensional array technology.

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(or below) levels of order 1 photon/s-pixel. For all missions, good quantum efficiency is a requirement. As will be discussed below, an alternate and powerful approach for LB sensing is that of photon counting detectors, which could essentially provide a noise-free detection capability.

To begin the assessment of IR detector requirements for the Astrotech 21 mission set, it is useful to review the recent development of sensor technologies for space applications in this spectral regime. Table I summarizes the state-of-the-art capabilities in each of the four IR spectral domains in terms of representative technologies that (i) have been flown on a previous NASA mission, (ii) have been demonstrated in the laboratory, (iii) are anticipated for an upcoming mission, and (iv) are desired for a more distant Astrotech 21 mission. This table highlights both the progression that has occurred in IR sensor technology development, as well as the remaining shortcomings in performance that need to be addressed, in order to achieve the science goals of the Astrotech 21 mission set.

To date the development of IR detector technologies has been supported primarily by NASA and DoD agencies (Fig. 2). Although DoD has supported development in various IR ranges, the strongest focus has been for the 3 - 5 and 8 - 12 μm ranges, which correspond to windows in the atmospheric absorption profile. Technology for military systems has been optimized for their operating environment, which typically involves fast scan rates, moderate to high backgrounds, and may be designed for significant nuclear environments. In contrast, detectors for astrophysics applications must be photometrically useful (not just able to detect the presence of a target), and they may be operated with slow frame rates and in the (comparatively) "mild" natural radiation environments of space. NASA's space-based, upward-viewing astrophysics interests have motivated support for additional wavelength ranges, especially the ≤ 2.5 μm region important for cosmological studies, and the far and very far IR, 30 - 1000 μm. The technologies which will be emerging from these development programs will, among other things, allow scientists to obtain the first large-scale images and detailed spectral signatures of a wide range of far-IR (typically very cool) objects and regions. These developments should produce not just single elements, but also arrays, of the novel scientific detectors needed for optimum application in space astrophysics systems, and be capable of extended integration times, photometric accuracy, low noise, low power dissipation, etc.

A top level listing of the sensing requirements and the IR detector technologies considered by the panel as most promising for missions in the Astrotech 21 set is presented in Table II. These requirements and technologies group naturally into

Table IA. Near IR (1 - 5 μm) Sensor Capabilities for NASA Missions

Development Status	Flown in Space	Demonstrated in Laboratory	Under Development for Space	Desired for Future Mission
Sample Mission Launch Date	COBE 1989	N/A	HST II / NICMOS ~ 1995	NGST ~ 2010
Detector	InSb	HgCdTe PV	HgCdTe PV	TBD
Array size & type	10 discrete detectors Discrete array	256x256 Integrated array	256x256 Integrated array	≥ 2k x 2k Integrated array
Readout type	JFET TIA	Switched MOSFET	Switched Si MOSFET	Integrating, low-noise FET
Quantum Efficiency, Spectral Range (μm)	70-85% (AR coated) 1 - 5	~ 65% 1 - 2.5	≥ 65% 1 - 2.5	≥ 80% 1 - 2.5
NEP (W/√Hz)	3×10^{-16}	5×10^{-18} (in 1 sec)	5×10^{-18} (in 1 sec)	7×10^{-20} (in 1 sec)
Read noise (e^- rms)	—	30	30	≤ 1
Integration time (s)	~ 1	1000	1000	1000
Operating temperature (K)	1.6	~ 60	~ 60	~ 60
Radiation susceptibility	Low	Low	Low	Low

Table IB. Mid IR (5 - 30 μm) Sensor Capabilities for NASA Missions

Development Status	Flown in Space	Demonstrated in Laboratory	Under Development for Space	Desired for Future Mission
Sample Mission	IRAS	N/A	SIRTF / IRS, IRAC	Imag. Int. / NGST
Launch Date	1983		~ 2000	~ 2012 / 2010
Detector	Si:As & Si:Sb PC	Si:As IBC	Si:As & Si:Sb IBC	Si:x IBC
Array size & type	31 discrete detectors Discrete array	10 x 50 Integrated array	128x128 Integrated array	≥ 2k x k Integrated array
Readout type	JFET TIA	Switched Si MOSFET	Switched Si MOSFET	Low-noise FET
Quantum Efficiency	~ 10% & 24%	~ 40%	~ 40%	~ 70 %
Spectral Range (μm)	8-15 & 15-30	5 - 28	5 - 40	3 - 40
NEP (W/√Hz)	3×10^{-16} & 6×10^{-17}	5×10^{-19} (in 1 sec)	5×10^{-19} (in 1 sec)	3×10^{-20} (in 1 sec)
Read noise (e^- rms)	Equivalent to ~ 400	≤ 50	≤ 50	≤ 1
Integration time (s)	0.3	100	1000	10,000
Operating temperature (K)	2.5	~ 4	~ 4	30 - 100
Radiation susceptibility	High	Low	Low	Low

Table IC. Far IR (30 - 200 μm) Sensor Capabilities for NASA Missions

Development Status	Flown in Space	Demonstrated in Laboratory	Under Development for Space	Desired for Future Mission
Sample Mission	IRAS	N/A	SIRTF / IRS & MIPS	LDR
Launch Date	1983		~ 2000	~ 2008
Detector	Ge:Ga (Bands III & IV)	Ge:Be, Ge:Ga, stressed Ge:Ga PC	Ge:Be, Ge:Ga, stressed Ge:Ga PC	Ge:x BIB
Array size & type	31 discrete sensors Discrete array	3x32, 3x32, 2x8 Stacked linear modules	16x32, 32x32, 2x16 Stacked linear modules	≥ 32 x 32 Planar integrated array
Readout type	JFET TIA	Integrating Si MOSFET	Integrating Si MOSFET	low-dissipation, low-noise FET
Quantum Efficiency	7% & 5%	≥ 10%	≥ 10%	> 40 %
Spectral Range (μm)	40 - 120	40 - 200	40 - 200	40 - 250
NEP (W/√Hz)	1×10^{16} & 6×10^{1}	~ 2×10^{-18} (in 1 sec)	≤ 2×10^{-18} (in 1 sec)	≤ 2×10^{-19} (in 1 sec)
Read noise (e^- rms)	Equivalent to ~ 400	~ 40	30, 40, 40	≤ 50
Integration time (s)	0.3	~ 10	1000	~ 100
Operating temperature (K)	2.5	~ 2	2.5, 1.9, 1.4	2
Radiation susceptibility	High	High	High	Low

Table ID. Very Far IR (200 - 1000 μm) Sensor Capabilities for NASA Missions

Development Status	Flown in Space	Demonstrated in Laboratory	Under Development for Space	Desired for Future Mission
Sample Mission Launch Date	COBE 1989	N/A	SIRTF / MIPS ~ 2000	LDR ~ 2008
Detector	Si bolometer	Ge & Si bolometers	Ge or Si bolometer	Ge or Si bolometer
Array size & type	2 & 4 in linear format, discrete array	≤ 8x8 discrete array	2x2 discrete array	32x32 integrated array
Readout	JFET	JFET	JFET or Si MOSFET	low-noise MUX TBD
Quantum Efficiency, Spectral Range (μm)	50% 120 to ≥ 1000	~50 % 200 - 1000	≥ 40% 200 - 700	~ 50% 200 - 1000
NEP (W/√Hz)	5×10^{-15}	$\leq 3 \times 10^{-17}$ (electrical)	$\leq 5 \times 10^{-17}$	$\leq 1 \times 10^{-16}$
Chopping frequency (Hz)	4.5, 32, 45	5	5	TBD
Operating temperature (K)	1.6	0.1	0.1	0.1, 0.3
Radiation susceptibility	Low	Low	Low	Low

Table II. Direct IR Detector Needs and Promising Technologies

	Near IR (1 - 5 μm)	Mid IR (5 - 36 μm)	Far IR (30- 200 μm)	Very Far IR (200 - 1,000 μm)
Materials	PV: InSb, HgCdTe Bandgap-Engineered, Photon-Counting or SSPM, etc.	Si:x IBC,HgCdTe, Bandgap-Engineered, etc.	Ge:x BIB, Bolometers (Semi- & Superconducting), Ge:x PC detectors, etc.	Bolometers (semi- & Superconducting), Narrow-Bandgap Semiconductors,SIS Direct Detectors, etc.
Readouts	Low-noise, low-dark-current, low power dissipation, radiation hard.	Low-noise, low-dark-current, low power dissipation, radiation hard.	Low-noise, low-dark-current, low power dissipation, radiation hard.	Low-noise, low-dark-current, low power dissipation, radiation hard.
Desired Format	$(1{,}000)^2$ - $(3{,}000)^2$	$(1{,}000)^2$	$(10)^2$ - $(100)^2$	$(10)^2$ - $(100)^2$
Mission & Technology Freeze Date	HST II '94 LTT '95 AIM '97	NGST '04 Imag. Int. '06	SMIM ' 95 LDR '03 SMMI '06	SMIM '95 LDR '03 SMMI '06

the same wavelength domains used in Table I. It is apparent that many of the development needs are clustered at the shorter IR wavelengths ($\lambda < 30$ μm), and that the primary drivers there are expanded format and low read noise. This report presents a comprehensive plan to develop technologies capable of meeting both near-term and long-term needs of the Astrotech 21 mission set. The areas identified by the panel as most urgently in need of development are shown in Table III. Each of these is discussed in turn in the remainder of this report.

LARGE-FORMAT ARRAYS

A. Technology Assessment

Table IV summarizes the status and approaches for the development of the very large arrays called for in the mission set. The present state-of-the-art is set

Table III. Direct IR Detector Technology Areas Recommended for Development

Technology Area	Desired Performance Specifications	Missions Impacted	Technology Freeze Date
Large-Format IR arrays	Larger array formats in all wavelength ranges	All	'94 - '06
Photon-Counting Detectors	Noise-free detection across entire IR wavelength range for LB missions/instruments	AIM NGST LDR	'97 '02 '03
Higher-temperature 10 μm detectors	Background-limited performance to ≥ 10 μm operating at ≥ 65K	LTT NGST	'95 '02
Ge BIB Detectors	High-sensitivity arrays with planar readouts for far-IR applications	SMIM LDR SMMI	'95 '03 '05
Improved Si:Sb IBC Arrays	Large-area arrays with high sensitivity, for wavelengths to 40 μm	LDR, Son of SIRTF	'03 TBD
Modified SIRTF Technology	Operation with higher background and at higher temperatures	All	'94 - '06
Readout Electronics	Lower read noise in all wavelength ranges, and LHe operating temperatures for far IR	All	'94 - '06

Table IV. Large-Format Arrays Technology Assessment

State-of-the-Art Technology	Key Components & Desired Level	Promising Technologies	Pros	Cons	Type of Mission
1-5 μm HgCdTe & InSb $(256)^2$ to $(512)^2$ & 5-30 μm Si:x IBC $(128)^2$	≥ $(1000)^2$ arrays for < 20 μm	Hybrid (In bump) arrays with Si MOS readouts	Si maturity	Onset of freeze-out	MB
		Monolithic arrays	No thermal mismatch	Processing maturity	
		Non-Si readouts	Some radiation hardness	Maturity	
30-120 μm Ge:x PC 3x32	> 30 μm Ge:x arrays	Stacked Si MOS, cascode or source-follower circuits	Si maturity, SIRTF heritage	Requires very low operating temperature	LB, MB, SMMM
		Planar Si readouts for Ge BIB	Packaging simplicity	Requires very low operating temperature	
120-200 μm Stressed Ge:Ga PC 5x5 & >200 μm bolometers 8x8	Array-compatible bolometer concepts	Supercond. concepts (tunnel junction, kinetic inductance, transition edge, etc.)	SQUID amplifier advancements	Still at idea stage	LB, MB, SMMM
		Si bolometer arrays	AXAF heritage	FET coupling	

by near-IR hybrid arrays, for which 256 x 256 formats have been demonstrated and 512 x 512 formats are under development. (This excludes conventional Schottky barrier technology, which, because of low quantum efficiency, was judged not to have direct applicability to future astrophysics missions). However, recent breakthroughs in similar device architectures, such as the heterojunction internal photoemission detector, may render such technologies viable in the future. At longer wavelengths, demonstrated format sizes are much smaller, but future requirements are also less demanding. The panel agreed that within industry, for wavelengths < 30 µm, there was a significant and sustained technological thrust toward larger IR array formats. NASA should monitor this work closely, but its funding in the near future should be confined to modest amounts of leverage money in carefully selected areas. At the level of 1000 x 1000 pixels, or perhaps one step larger, industrial developments may stop. At this point, if the agency were serious about additional advances, it would have to assume major funding responsibilities.

There was great skepticism among the panel that high-sensitivity IR array formats would exceed a few thousand on a side in the foreseeable future, even for the shorter IR wavelengths between about 1 and 20 µm. Today's most advanced IR arrays are hybrid devices with indium-bump interconnects, and this architecture is expected to remain state-of-the-art for a number of years. One expects physical limits (i.e., both a minimum practical indium column size and a maximum practical size for high-quality detector substrates) to constrain format sizes in hybrid arrays.

The recommended approaches toward large formats include continued development of hybrid arrays, exploration of monolithic approaches (e.g., HgCdTe-on-GaAs-on-Si monolithic structures or other novel approaches incorporating bandgap-engineered structures) which avoid the thermal mismatch and interconnect problems, and pursuit of readouts in GaAs or other alternatives to Si. It was also noted that one might design a telescope system to include a faceted mirror which would divide the beam into parts, as is being done for the second generation HST Wide-field and Planetary Camera (WF/PC II). Each of these parts can be directed to a hybrid 1000 x 1000 array, or a small mosaic of such arrays, to achieve a composite format of many thousand on a side. However, this introduces significant optical-system complexity, which would be best to avoid in future instruments, if possible.

For wavelengths beyond 30 µm, the stacked Si MOS approach presently under development for SIRTF was endorsed for future requirements. Both the cascode (which provides gain) and the simple source-follower circuits should be pursued. When germanium impurity-band-conduction (IBC) technology reaches a state of maturity such that arrays are feasible, an appropriate planar readout technology would also have to be supported. (Rockwell International Science Center, leader in Ge-based IBC technology, refers to these devices as "blocked-impurity-band" or "BIB" detectors, and this terminology is adopted here for Ge-based devices.) For both approaches, the arrays and their readouts must be optimized for operation at low (< 2 or 3 K) temperature and low (down to 10's of mV) biases.

To achieve bolometer arrays with formats larger than the present state-of-the-art (on the order of 50 elements), a dual approach of supporting innovative array-compatible superconducting concept(s), and continuing development of Si-based bolometer readouts (as is presently being pursued on the calorimeter for AXAF) was recommended. Recently, a number of low-T_c superconducting bolometer concepts have been identified, and advances in superconducting readouts based on superconductor quantum interference devices (SQUIDs) make arrays of this type much more attractive. These include (a) using the transition edge as a very accurate, essentially noise-free thermometer, (b) measuring the kinetic inductance of electrons in a superconducting film, and (c) using the critical current of a Josephson junction as a bolometer. Development of the detector/readout concept(s) judged to be most promising should be supported. In addition, the development of techniques for more effectively bringing out leads, coupling to preamplifiers, and multiplexing semiconductor (Si and Ge) bolometer arrays must continue.

B. Development Plan

Many of the pressing needs for very large format arrays come before the turn of the century, so significant resources must be directed to this challenge soon. A sustained, parallel activity is recommended, so that a range of promising approaches can be explored. A summary of the recommended development programs is provided in Table V. With significant projects now under way in industry to push for arrays with dimensions at least as large as TV format (approx. 500 x 500), the proper strategy is to monitor and invest only modestly, if it appears that commercial technologies can be adapted. It is expected that industrial interests will fade after ~1000 x 1000 has been achieved, and advances beyond that point would likely be (1) NASA's responsibility, and (2) large in expense.

NASA should continue to sponsor work on Si-based hybrid IR array configurations, but also include investigations of concepts which are potentially superior in the far term. These include monolithic

Table V: Recommended Development Plan for Large-Format Arrays

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Arrays for ≤ 30 μm				
Multiple new approaches	Concepts	Feasibility	93 - 96	Few small
Large format	256 x 256	≥1000 x 1000	96 - 00	Large
Arrays for 30 - 200 μm				
Multiple new approaches	Concepts	Feasibility	93 - 96	Few small
Develop best approach	32 x 32	128 x 128	96 - 00	Large
Stacked Si MOS readouts	3 x 32	128 x 128	94 - 00	Moderate
Ge BIB readout arrays	None	128 x 128	94 - 00	Small
Bolometer arrays				
Semiconductor approaches	8 x 8	128 x 128	93 - 96	Few small
Superconductor approaches	Concepts	128 x 128	93 - 96	Few small
Develop best approach	Concepts	128 x 128	96 - 00	Moderate
Superconductor readout	SQUID	Matched to array	96 - 00	Small

(e.g., HgCdTe-on-GaAs-on-Si monolithic structures) and non-Si (e.g., GaAs) hybrid arrays. An evolutionary approach should be followed, with demonstration arrays built (and thoroughly characterized) in successively larger sizes. A developmental increment of at most 2x in linear dimension is recommended for the largest format arrays, and probably also for the (smaller) NASA-unique long-wavelength arrays of both photon detectors and bolometers.

For wavelengths beyond 30 μm, where NASA's detector array requirements are unique, significant progress is needed in both Ge:x photon detectors and bolometers. Also, this is the region where the general state of technological development is less advanced, and where novel ideas or approaches are especially needed. Progress tends to be limited by ideas (rather than money) in this regime, and comparatively small initial efforts are recommended. Parallel approaches toward developing long-wave readout technologies are needed. Work from the SIRTF program on stacked Si MOS readouts should be continued. When and if Ge:x BIB detectors appear to be within reach, work on a companion array-compatible readout technology must start (or have been under way, at a low level).

Bolometer arrays require coordinated development of the absorber/thermometer detector element and the readout or preamplifier. Promising approaches for both should be supported. There are presently a number of very interesting superconducting bolometer concepts (e.g., transition edge, kinetic inductance, tunnel junction) which appear to be suited to array construction; the most promising of these should be supported. When superconducting detector elements have been demonstrated, one should then couple them to SQUID readouts for an integrated array demonstration. Additionally, further advances in Si or Ge semiconductor bolometer arrays appear to be feasible. This would build directly on the advances made on the SIRTF and AXAF projects. As with the other technology subareas, a down-selection must be made after a few years, so that resources and talent can be concentrated on the most powerful technologies.

PHOTON-COUNTING DETECTORS

A. Technology Assessment

For future missions requiring very low read noise, and most especially for systems operating at the shorter IR wavelengths, an effective strategy is to develop photon-counting detector technology. This approach could provide essentially noiseless detection of individual photons, with inherently digital readout. As is shown in Table VI, the Si:As solid state photomultiplier (SSPM) is an emerging technology capable of photon counting, but its peak response is at much longer wavelengths than desired for observing in the 3 μm "window." The panel recommended that photon-counting devices for the 1 - 5 μm range, with the necessary electronic readouts, be developed. A promising approach is to explore various bandgap-engineered device concepts, which in theory could have wide spectral coverage. A parallel approach is to improve the ability of existing Si:As SSPM device technology to detect < 5 μm photons. Another approach, particularly for the near term, is to pursue detectors which have high inherent gain. In this case, a detector gain (of perhaps 10^2 - 10^3) would allow one to read out the detector with normal analog electronics, eliminating pulse height discriminators, counting circuits, etc. This route would have the advantage of simplicity, particularly for large arrays.

Table VI. Photon-Counting Detectors Technology Assessment

State-of-the-Art Technology	Key Components & Desired Level	Promising Technologies	Pros	Cons	Type of Mission
1-5 µm (Non-optimized) Si:As SSPM QE ~ 1%	1-5 µm photon counters & readouts	Small-bandgap superlattices (III-V, II-VI)	Possibly higher operating temp. & lower leakage	Unproven	LB
		Improved Si:As SSPM for 5 µm	Demonstrated at longer wavelengths	Unproven	
8-28 µm Si:As SSPM QE ~ 30% T ≤ 8 K	5-30 µm photon counters & readout	Si:As or Si:Sb SSPM & hybrid readout	Detectors demonstrated	Readout not demonstrated	LB
>30 µm None	>30 µm photon counters & readouts	Ge:Ga SSPM*	Wider spectral coverage	Ge BIB not yet mature	LB

* Assumes successful development of Ge BIB technology.

For wavelengths between about 5 and 28 µm, the development of Si:As SSPM detectors should continue, with support focused on demonstrating a workable readout concept. If Si:Sb IBC devices are successfully proven, it was recommended that an SSPM version of this detector, which would provide spectral coverage out to 35 - 40 µm, should be pursued. In a similar way, it was also suggested that a Ge:Ga version might eventually be investigated, when and if a mature basic Ge:Ga IBC technology is proven.

B. Development Plan

Recalling that high-resolution instruments will provide low backgrounds to detectors even on telescope systems operating under moderate background conditions, development efforts for photon counters should begin right away. As with the previous area, a number of parallel development efforts are recommended, each of which was judged to be moderate in scope. The development strategy is summarized in Table VII. Except for the matter of a readout for the SSPM (which is funding-limited), projects in this area are currently idea-limited.

The program for < 5 µm should support initial efforts in small-bandgap superlattice devices, where somewhat speculative but potentially superior approaches are possible. In parallel, work on a short-wavelength-optimized SSPM is recommended.

The SSPM is the recommended approach for >5 µm sensing needs. Continued development of the Si:As SSPM is clearly appropriate, and when the basic development steps for the new Si:Sb IBC

Table VII. Recommended Development Plan for Photon-Counting Detectors

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
1 - 5 µm				
Small-bandgap superlattices	Concepts	Feasibility	93 - 96	Small
Short-wavelength SSPM	Long-λ SSPM	Feasibility	93 - 96	Moderate
Develop best option		QE ≥ 30%, $(1,000)^2$ arrays	96 - 00	Moderate
Readout arrays	None	$(1,000)^2$ arrays	96 - 00	Small
5 - 30 µm				
Develop Si SSPM arrays	Discretes	$(128)^2$ arrays	96 - 00	Moderate
Si:Sb SSPM arrays	None	$(128)^2$ arrays	93 - 00	Small
Readout arrays	None	$(128)^2$ arrays	96 - 00	Small
30 - 200 µm				
Ge:Ga SSPM	None	$(128)^2$ arrays	93 - 00	Moderate

detector are successfully completed, an Si:Sb version of the SSPM would be attractive. Thinking even further into the future, with a similar argument, when the basic detector technology of the Ge BIB is proven, one would have the starting point from which a photon-counting version might be developed for the far and very far IR.

In each case, the recommended approach for these development programs would involve concentration on the performance of the unit cell detector, and then a very small array, and then incrementally larger arrays.

HIGHER-TEMPERATURE 1 - 10 μm ARRAYS

A. Technology Assessment

The moderate-background missions, of which the Lunar Transit Telescope, the Astrometric Interferometry Mission, and the Next Generation Space Telescope are examples, include the requirement for coverage extending into the thermal infrared with large format arrays. The initial requirements also discussed detector temperatures in the range 70 - 100 K, the temperatures one could expect to reach with a passively-cooled system. The panel assumed that the basic design drivers for these missions were simplicity and low power consumption, and that the plan included the use of relatively simple closed-cycle coolers to augment this passive cooling. Specialists from the cryogenics panel described various cooler breakpoints, which were consistent with projected detector requirements.

Presently, HgCdTe detectors are available which are optimized for moderate and higher backgrounds, and operating temperatures in about the 60 - 90 K range (Table VIII). High-performance Si:As IBC detectors are also available, but these require cooling to about 12 K or lower. None of the emerging bandgap-engineered technologies, including multi quantum well (QW) detectors (GaAs/GaAlAs), heterojunction internal photoemission (HIP) approaches (SiGe/Si and GaAs/AlGaAs), and narrow-bandgap type-II superlattice architectures has yet shown sufficiently low leakage current at liquid nitrogen temperatures, but this limitation is not predicted to be fundamental, and may yet be overcome.

A prime development opportunity identified was that of adapting the heavily-funded 10 μm HgCdTe technology base for somewhat lower temperatures. HgCdTe detectors (10 μm) are now thermally limited at temperatures of 90 - 100 K; higher sensitivity could be achieved by cooling to 30 - 40 K. At this temperature, one would anticipate coupling a background-limited HgCdTe detector to a relatively efficient and reliable cooler technology (e.g., two-stage Stirling). Also, small-bandgap superlattice technology may well provide good solutions in this area. The technology of III-V strained superlattices is relatively new, but it could in principle produce devices which are lower in leakage and which operate at a higher temperature than HgCdTe detectors with comparable spectral coverage and sensitivity. QW and HIP devices could also be refined and optimized for astrophysical requirements in this area. They offer the advantages of tailorable spectral response, but in present form have limited quantum efficiency. QW detectors are also awkward to incorporate in systems, since they require non-normal incidence of light.

B. Development Plan

Again, support of a number of parallel research and development projects is recommended in this area, as summarized in Table IX. The key approaches recommended for initial support (adaptation of HgCdTe detectors for ~30 kelvin, or higher, operation, and development of the small bandgap

Table VIII. Higher-Temperature 10 μm Detectors Technology Assessment

State-of-the-Art Technology	Key Components & Desired Level	Promising Technologies	Pros	Cons	Type of Mission
1-10 μm PV HgCdTe QE ~ 80% T = 40 - 60 K	Low-leakage intrinsic or intrinsic-like arrays QE ~ 50% T ~ 50 K	10 μm PV HgCdTe	Large technology base	Unproven below 50 K	MB
		Small-bandgap type-II superlattice detectors	Tailorable cutoff	Early stages of development	
		QW, HIP detectors	Tailorable cutoff	Non-normal incidence, QE	

Table IX. Recommended Development Plan for Higher-Temperature 10-μm Arrays

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Lower-temperature HgCdTe	≥ 90 K operation	Operation ≤ 30 K	93 - 96	Moderate
Type-II superlattice detectors	Early development	$(1{,}000)^2$ arrays	93 - 96	Moderate
QW Detectors	Arrays at 10 K	$(1{,}000)^2$ arrays	93 - 96	Moderate
HIP Detectors	Early development	$(1{,}000)^2$ arrays	93 - 96	Moderate
Develop best option		Background-limited performance, at 30 - 65 K	96 - 00	Moderate

superlattice) have some level of work under way, the former far greater than the latter. Because of this, initial progress would be limited by funding, rather than ideas. Projects in this area were recommended to be moderate in scope.

IBC (BIB) DETECTORS

A. Technology Assessment

Ge BIB detector technology was recognized to potentially offer a number of significant advantages for space astronomical applications (Table X). As with Si:As IBC detectors, Ge devices have very thin optically-active layers, and hence diminished radiation susceptibility; they are array-compatible with low cross talk, and one would expect their response to be more linear and well-behaved than that of bulk photoconductors. Presently, Ge BIB detectors are still developmental. A few discrete devices have been produced at Rockwell, with an intrinsic blocking layer deposited on a highly-doped, thick, IR-absorbing substrate. These detectors have proven the basic feasibility of the concept, and have demonstrated quantum efficiencies of a few percent. They require temperatures below 1.5 K to suppress dark current for SIRTF-type applications. The limiting factor in this activity is Ge processing technology, which must in part be relearned and in part be developed for the first time. Efforts are now focusing on producing a structure with epitaxial layers for both blocking and IR absorption, a necessary geometry for eventual array development. A parallel development at Lawrence Berkeley Laboratory has produced unoptimized boron ion-implanted Ge structures. While achieved quantum efficiencies are well below a percent, the devices have been fabricated with only a very thin (~1000 Å) IR active layer, and show excellent dark current characteristics.

Similarly, continued development of Si:Sb IBC detectors is recommended. As is shown in Table IX, the situation for Si:Sb is somewhat ahead of that for Ge:Ga; epitaxial Si:Sb detectors have been fabricated and will soon be tested. This technology draws directly on the relatively well-established Si:As IBC

Table X. IBC (BIB) Detectors Technology Assessment

State-of-the-Art Technology	Key Components & Desired Level	Promising Technologies	Pros	Cons	Type of Mission
40-200 μm Ge:Ga "bulk" BIB discrete devices QE ~ few % T < 1.5 K	Ge: x BIB arrays with QE ~ 30%	Epitaxial-layer Ge:Ga BIB detectors	Linear response, radiation hard, array compatible, low cross talk, simple structure	Processing problems	LB, MB, SMMM
		Ge:B ion-implanted BIB detectors	Same as above	Low QE?	
10-36 μm Si:Sb IBC discrete devices, cut off at 36 μm QE TBD	Si:Sb IBC arrays with QE ≥ 30%	Epitaxial-layer Si:Sb IBC detectors	Si:As IBC heritage, plus advantages of BIB listed above	Arrays not yet proven	LB, MB

technology base, and should offer the advantages which have been proven for Si:As. Si:Sb detectors and arrays would be important for SIRTF and for future missions, since they would provide a bridge across the gap between 28 and roughly 40 µm in which Ge:x detectors suffer from poor response due to lattice absorption.

B. Development Plan

The panel strongly endorsed continued development of Ge BIB detectors, as shown in Table XI. They could be applicable to a wide range of future missions, and their simple structure and radiation hardness could represent major engineering simplifications. Work should continue to focus on Ge epi-layer and ion-implantation technology. As was mentioned above, should backside-illuminated, thin-layer Ge BIB detector technology appear to be feasible, a companion planar readout technology will also be needed.

In the panel's opinion, it is very important to maintain support for the two groups (JPL/Rockwell, and Lawrence Berkeley Laboratory) presently working on this technology. There are enough basic unanswered questions in device design and processing that both of these efforts should be continued for perhaps five or more years, until well-founded technical choices can be made. Technical interchange and cross-fertilization between these groups are strongly recommended. Progress will be idea-limited, and costs are expected to be moderate, at least in the near term.

Continuation of funding is also recommended for Si:Sb IBC detector arrays; costs should be moderate. As the characteristics of the first epi-produced detectors and unit cell structures are established, progressive steps to small- and moderate-scale arrays should be taken. Initially, progress will be limited by funds, and by work force.

READOUT ELECTRONICS

A. Technology Assessment

Important aspects in the readout area are the general requirements for low-noise devices, circuits resistant to the radiation effects encountered in space, low power dissipation (to simplify cooling requirements), and large well capacity for systems operating with significant background levels. Table XII provides a more detailed description of the readout electronics issues. The future mission set includes a number of projects which call for 1 e^- rms read noise levels. Data on an Amber Engineering Si cascode FET circuit (~4 e^- input-referred read noise) have recently been obtained at the University of Arizona, which indicate that this goal may be within reach, since the device has not yet been optimized. However, the device presently requires operation above the Si freeze-out temperature of about 20 K. For large arrays, read noise of about 30 e^- has been achieved on the 256 x 256 NICMOS HgCdTe (2.5 µm cutoff) hybrid arrays, at 60 K. For extrinsic silicon arrays and temperatures in the 4 - 10 K range, read noises of about 12 e^- (scaled by gain within the detector) for the 10 x 50-element Rockwell array, and about 50 e^- for the 58 x 62-element Hughes array have been measured. The best non-Si low temperature readouts, in GaAs, appear to be capable of read noise in the 40 - 60 e^- range, in discrete devices or small arrays. Selected Si JFETs presently provide relatively good performance, but require operation at elevated temperatures (40 K or above) to run reliably.

To meet the 1 e^- goal for readout electronics, the panel recommended continued work with Si MOS technology, based on good progress to date, and the high state of sophistication of silicon processing. One branch of Si MOS technology development is for elevated-background applications, where operation at temperatures above freeze-out is quite acceptable,

Table XI. Recommended Development Plan for IBC (BIB) Detectors

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Ge:Ga BIB Detectors				
Epitaxial-layer Ge BIB	QE few %	QE ≥ 30%	93 - 96	Small
Ion-implanted Ge BIB	QE < 1%	QE ≥ 30%	93 - 96	Small
Develop arrays in best option	No array capability	$(128)^2$ arrays	96 - 00	Moderate
Readout array development	None	Matched to sensors	96 - 00	Moderate
Si:Sb IBC Detectors				
Epitaxial-layer Si:Sb IBC	"bulk" detectors	QE ≥ 30% $(512)^2$ arrays	93 - 98	Moderate

Table XII. Readout Electronics Technology Assessment

State-of-the-Art Technology	Key Components & Desired Level	Promising Technologies	Pros	Cons	Type of Mission
For T > 20 K Si MOS discrete FETs ~ 4 e^- read noise	Si FETs 1 e^- read noise	Si MOS	Si maturity	Onset of freeze-out	MB, SMIM
	Stable-bias circuits (few mV)	MOS TIA & other innovative concepts	Si maturity	Power dissipation?	LB, MB, SMIM
For T < 20 K Si MOS array ~ 50 e^- read noise	Si FETs 1 e^- read noise at ≤ 4 K	Si MOS	Si maturity	Onset of freeze-out	LB
	Non-Si FETs 1 e^- read noise	GaAs, Ge, InSb, etc.	Superior low T properties	Immature technologies	Post-SIRTF, LB
For bolometers Si JFETs, few nv/√Hz at 40 K no MUX	Bolometer readout & MUX	Isolated Si, GaAs, superconducting devices, etc.	Optimized performance possible	Immature technologies	LB, MB, SMIM, LDR
Photon counting None	Photon counter readout & MUX	Si MOS, GaAs & other innovative concepts	Digital data chain, low power	Immature technologies	LB

and where read noise would not need to be especially low. Another branch would be for low-background applications, where low-noise, low-dark current would be sought with Si MOSFET readouts at temperatures down to the 2 - 4 K range. To meet the stable, low-bias requirements of long-wavelength IR detectors such as Ge:Ga BIBs, it was suggested that feedback circuits such as the capacitive trans-impedance amplifier (CTIA) held promise. Data from Rockwell at higher temperatures indicated these readouts could be successfully operated at reduced (100 nW/channel) power levels. Long-wavelength readout circuits would typically not have to have as many channels, since diffraction at these wavelengths provides an upper limit on the resolution elements within the field of view, and thus on the useful number of pixels in the focal plane. To supplement these approaches, and to reduce the influence of carrier freeze-out, FET development in alternate semiconductor materials such as GaAs, Ge, and possibly InSb, or others should be supported for longer term requirements.

Advances in bolometer development are presently limited by readout technology. The pressing requirements are for a low-noise FET which operates at or near the bolometer temperature, and for a credible bolometer multiplexing scheme. To meet these needs, it was suggested that novel concepts in Si (e.g., small FET structures produced on thermally- and electrically-isolating oxide layers) and other semiconductors be explored. Also, superconducting readouts may be particularly well-suited for applications with bolometers.

Development of photon counting detectors with significant internal gain would relieve the need for very-low-noise readout circuitry. To take full advantage of these detectors, which give an output pulse for each photon detected, the readout circuit should be able to operate as a digital counter. This avoids analog readout noise, as well as the power consumption associated with analog-digital conversion. The design of compact unit cells to interface with photon-counting detectors, and of circuitry for multiplexing of arrays, has not been very well explored, although some preliminary work has been done at Rockwell for SSPM readout. The panel recommended that, in conjunction with work on photon-counting detectors, development of the associated readouts be vigorously pursued.

The panel concluded that for astronomical applications sophisticated on-chip data processing was not a requirement. It is expected that investigators will continue to want the maximum amount of flexibility to analyze and correct their data for unanticipated effects encountered in space. Only modest amounts of data compression might be required, or even desired.

B. Development Plan

Given the long string of future astrophysics missions, and the central importance of readout electronics to overall detector/array performance, the panel recommended a long-term, steadily supported program to explore and develop a number of important technologies. Since MB missions tend to dominate in the near term, the strategy should be to emphasize approaches which are critical to them during early years, with appropriate milestones and branch points. However, the program must also provide for support of longer-range needs as well, since many of these are rather demanding, and will require concerted effort over longer time scales to be successful. Development of the two classes of electronics will also tend to support each other synergistically. The cost of this ongoing program was judged to be large, equivalent to about 10 workyears/yr. The development plan is summarized in Table XIII.

The panel recommended support for improvement of silicon MOS readout technologies, for applications both below and above the ~20 K freeze-out temperature. For LB, low-temperature applications, additional development of both the geometry and composition of the unit cell transistors, and the circuits in which these are used, is needed. In parallel, Si MOS circuits should also be pursued for the class of higher-temperature MB applications, which generally come sooner in the Astrotech mission set. The design of these Si devices would likely be different than that of the low-temperature versions, since they do not need to operate in such extreme environments or to such challenging performance specifications. Falling largely, but not exclusively, under the Si electronics category is the need for circuits which provide low, stable bias to detectors. These requirements could ultimately be folded into readout development projects as the basic unit cell performance is demonstrated.

Support should also be given to the recommended non-silicon readout concepts. NASA should monitor the efforts in GaAs and Ge and other materials systems presently under way in industry and universities, and where appropriate, set up projects which leverage this work. One should start with small exploratory efforts, which could be scaled up as feasibility is successfully demonstrated.

To meet the need for improved bolometer readouts, efforts should initially focus on achieving lower noise (≤1 nv/√Hz) with minimum power dissipation. The operating temperature of these readout electronics must also be lowered from the ~100 K presently needed for best Si JFET performance. Otherwise, the need to totally shield these high-temperature FETs from the view of the highly-sensitive far-IR bolometers will continue to require significant additional complexity in the focal-plane cryogenic system. This program should initially support at a modest level a number of promising approaches from the various Si and non-Si semiconductor options. After a period of 2-3 years, the field should be narrowed, with only the most promising approaches supported.

Support is recommended for exploring concepts for readouts and multiplexers for photon-counting detectors. Solutions to the various functions can potentially be implemented in, for example, Si MOS,

Table XIII. Recommended Development Plan for Readout Electronics

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
For > 20 K operation				
Si MOS	Discrete, ~ 4 e^-	Array compatible, ≤ 1 e^-	93 - 96	Small
MOS TIA, other new ideas	None	Array compatible, ≤ 1 e^-	93 - 96	Small
Develop best option		$(1,000)^2$ arrays	96 - 01	Moderate
For < 20 K operation				
Si MOS	Discrete, ~ 4 e^-	Array compatible, ≤ 1 e^-	93 - 96	Small
Non-Si FETs	None	Array compatible, ≤ 1 e^-	93 - 96	Small
Develop best option		$(1,000)^2$ arrays	96 - 00	Moderate
Bolometer FETs				
Semiconductor approaches	Si JFET	Array compatible, ≤ 1 e^-	93 - 96	Small
Superconducting devices	None	Array compatible, ≤ 1 e^-	93 - 96	Small
Develop best option		$(128)^2$ arrays	96 - 00	Moderate
For photon-counting detectors				
Si MOS	None	Array compatible	93 - 96	Small
GaAs or other new ideas	None	Array compatible	93 - 96	Small
Develop best option		$(1,000)^2$ arrays	96 - 00	Moderate

GaAs, and superconducting materials. Initially, support should be given to a number of innovative approaches; later, the most promising ones should be funded for the development of larger-scale array structures.

In all readout areas, the viability of the selected concepts should be demonstrated at the individual device level first; only after careful and thorough demonstration of performance on this scale, and possibly up to the level of small (≤ 20 elements) arrays, should demonstration models of progressively larger arrays be built and tested. In the course of development, as larger and larger structures are built and tested, readouts must be coupled to detector arrays, permitting the evaluation of detector/readout systems as complete focal planes.

ADAPTING SIRTF AND HST TECHNOLOGY BASE

In many cases, the technology options discussed above have their roots in IRAS, SIRTF, and HST II / NICMOS technology development programs. These were highlighted in Table I. Future missions must effectively utilize both the state of device technology and the body of operational expertise which have been built up for direct IR detectors in astronomical applications. Table XIV indicates that a range of technologies is now approaching a somewhat advanced state of development, particularly for very low background applications. The task at hand is to reevaluate and reoptimize these technologies for future missions, which typically involve backgrounds which are orders of magnitude higher, and/or higher detector operating temperatures. Note, however, that moderate-background missions will also likely include high-resolution spectroscopic instruments, which will operate at very low backgrounds, comparable to those of SIRTF. These instruments will directly benefit from the SIRTF technological heritage.

The panel recommended that a study and test program be set up to reevaluate and reoptimize this technology. There was concern, however, that key individuals from the SIRTF teams may not be available, due to their heavy commitments to that project; they could, however, train others to work in their laboratories. The costs of recharacterizing and reoptimizing SIRTF and HST II / NICMOS technology would only be moderate, and NASA would be able to preserve and exploit its sophisticated technological heritage in this area. One should first pursue those aspects of the SIRTF and NICMOS technologies which are most applicable to the near-term missions (i.e., the "MB" class, higher-temperature, large-format array applications). However, it is also important to start early on longer-term projects to assure that techniques are not lost, and to begin efforts to meet very challenging future requirements. In this recommendation area, one should utilize the existing characterization facilities

Table XIV. Adapting SIRTF Technology for Higher Backgrounds (or Higher Detector Temperatures)

State-of-the-Art Technology	Key Components & Desired Level	Promising Technologies	Pros	Cons	Type of Mission
10 K InSb arrays 256 x 256	Similar, but larger format and higher operating temperature	See Tables V - XIII	Initial development well under way. Labs, expertise developed.	Availability of key personnel	Most all
4K Si:As IBC arrays 10 x 50 & 58 x 62	Larger formats		Project development discipline		
2K Ge:Ga arrays 3 x 32	Larger formats				
1.5 K Ge:Ga BIB discrete	Array capability				
0.1 K bolometers	Array capability				
4 K readouts	Lower noise				
⇑ Technologies optimized for low backgrounds		⇑ Same "tools" optimized for 10^n times higher backgrounds ($n = 3,4,5,?$)		⇑ Total Cost moderate. Limited by $	

and expert personnel to the greatest possible extent. It would also be reasonable to support ground-based, balloon-borne, and airborne astronomical demonstrations as a means of characterizing SIRTF and HST detector technology under higher background conditions.

OTHER ISSUES

Discussions within the panel also touched on other general development issues. It was noted that there is a "critical mass" problem within the long-wavelength IR detector development community. These specialized groups tend to be small, and their progress is paced by the expertise and availability (and nonavailability) of a few key individuals. Additionally, there appeared to be room for improvements in the long-wavelength base technology. While important advances have been made on a number of fronts, limited resources have meant that some aspects of the technology have not received sufficient attention recently. An example is in the area of Ge:x detector material, where the best available boule of Ge:Ga, one now being reserved for possible use in SIRTF flight detectors, was produced *22 years ago*! An element of future support in this area should be reserved for such critical individuals and institutions.

This concern also extends to the industrial IR community. NASA has carried out some highly successful joint projects with companies such as Aerojet, Cincinnati Electronics, Hughes SBRC, and Rockwell (to list a sampling, in alphabetical order). With the possibility of significant changes in defense spending in the future, it will be important to the agency to maintain this critical resource through judicious funding.

Throughout the infrared, but especially for wavelengths beyond 30 µm, there is a need for novel ideas and approaches. In some cases, conventional bulk semiconductor technologies may be reaching their ultimate performance limits. Emerging technologies, such as those in the general area of bandgap-engineered layered structures and superconducting (both low-T_C and high-T_C) devices, hold promise as a means of meeting the ever-more stringent requirements of future missions.

Progress in developing IR detector technology is often limited by one's ability to accurately characterize the latest devices. This applies both at the device level (where, for example, novel equipment and approaches are needed to characterize Ge BIB epi-layers) and at the integrated detector or detector array level. A very important means of proving the technology, and of uncovering subtle effects that may remain hidden in the laboratory, is through ground-based, balloon-based, and airborne observing. An example is the discovery of "ghost images" in earlier InSb arrays, which were only discovered when the arrays were being used in an observational program. Funding for all of these aspects -- improved device and focal plane characterization tools, and support for demonstration testing on telescopes -- is recommended. All of these aspects were judged to be very important in sustaining progress.

SUMMARY

To summarize, the panel considered a wide range of options for IR technologies relevant to the science goals of the Astrotech 21 mission set. The challenges presented by the requirements for very large array formats and very low-noise readout electronics were judged to be the most demanding. The recommendations of the panel (Table III) include a desirable mix of technologies which are evolving from IRAS, SIRTF, and HST / NICMOS, and also novel, more speculative technologies which may pay large dividends in the long run. Detailed development plans were presented for each of these technology areas. While there are some aspects of the necessary NASA developments which will benefit from ongoing military or industrial interests, these are nowhere sufficient. Furthermore, for wavelengths > 30 µm, it is important for the agency to recognize that there is no other applicable work, and that it must bear full funding and management responsibility for the necessary development programs.

Report of the Heterodyne Submillimeter-Wave Sensors Panel

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INTRODUCTION

Heterodyne receiver technology for future NASA missions provides a particularly exciting development opportunity, in that entirely new areas of spectroscopy will be enabled if the frequency range of sensitive receivers can be pushed into the THz regime. In particular, the submm regime is rich with molecular transitions which can serve as signatures of cold gases and particles in planetary, stellar and interstellar objects. In addition, no array capability currently exists in the submillimeter wavelength regime, and this development offers enormous advantages for future imaging instruments. We stand at the threshold of realizing these capabilities through the implementation of advances in superconductor technology and semiconductor planar epitaxial growth and lithographic processing techniques. However, the development of these technologies in time to benefit the relevant missions will require an aggressive R&D program, and since NASA's needs in these areas are unique, the entire support for this effort will necessarily be borne by the agency.

The focus of the Heterodyne Submillimeter-Wave Sensors Panel was the heterodyne development required to meet the science goals of the Astrotech 21 mission set. The relevant missions include SMIM, NGOVLBI, LDR and SMMI, for which the specific requirements are summarized in Table I. Many of these performance specifications lie significantly beyond the capabilities of existing technology, and will require further advances. Previous development in this area has been supported by NASA and SDI. The NASA Office of Aeronautics, Exploration and Technology (OAET) has funded submillimeter heterodyne sensor development starting in 1988 under the Civil Space Technology Initiative (CSTI). The primary goal of this program is enhanced receiver performance above 200 GHz, where emission from molecular bands provides the most detailed information on the constituents and chemistry of the interstellar medium. Examples of emerging planar submillimeter receiver technology and of the richness of spectral information available in this frequency range are displayed in figures 1 and 2, respectively. The NASA Office of Space Science and Applications (OSSA) has also supported development in this area. In addition, one of the NASA University Centers of Excellence, the University of Michigan Space Terahertz Technology Center, was identified to carry out research in high-frequency devices and receivers. At about the same time, SDI started an effort in terahertz technology development for communications applications.

The shortcomings of existing heterodyne receiver capabilities vis-a-vis the performance specifications for the Astrotech 21 mission set fall into four categories; local oscillators (LO), mixers, focal-plane arrays, and spectrometers. In Table II a comparison is made of the specifications for (i) a recent submillimeter-wave space mission, Cosmic Background Explorer (COBE), (ii) an instrument on a mission to be launched this year, the Microwave Limb Sounder for the Upper Atmosphere Research Satellite (UARS/MLS), (iii) a mission to be launched in '95, the Submillimeter Wave Astronomy Satellite (SWAS), and (iv) for two representative Astrotech 21 missions, SMIM and LDR. COBE flew 50 and 90 GHz receivers, UARS/MLS has three heterodyne

Table I Astrotech 21 Mission Requirements Summary

Mission	SMIM	NGOVLBI	LDR		SMMI
Technology Freeze	1996	2000	2006		2006
Launch Date	2002	2006	2012		2012
Frequency Range (GHz)	400-1200	1-220	100-1200	1200-2000	1000 - 3000
Type of Receiver	SIS	HEMT/SIS	SIS	SBD	SIS
Sensitivity Specification (hv/k)	20	10	10	10	6
LO Power	50 µW	10 µW	1 mW	20 mW	100 µW
Number of Pixels	8 - 10	5	2 x 10 array	2 x 10 array	1 per antenna (12 antennas)
Operating Temperature	2-5 K	30 K & 4 K	2-5 K	40-60 K	2- 5 K
Heat Load (mW)	20	200/30-60	< 100	800	50
Operating Life (yrs)	2-4	10	10	10	10
Spectral Resolution	10^{-6}	—	10^{-6}	10^{-6}	10^{-6}
Spectral Channels	8000	---	2x10x1000	2x10x1000	1000 per receiver
IF Bandwidth	4 GHz	> 1 GHz	> 1 GHz	> 1 GHz	40 GHz
Preamp Noise Temperature	< 0.1 T_{sys}	< 3 K	< 0.1 T_{sys}	< 0.1 T_{sys}	< 0.1 T_{sys}
Special Requirements	Complete frequency coverage	VLBI-quality LO	Focal plane arrays and low-power, many-channel digital spectrometer		Phase stability

Table II Heterodyne Sensor Capabilities for NASA Missions

Development Status	Flown in Space for Space	Developed for Space	Under Development	Desired for Future Mission	Desired for Future Mission
Sample Mission	COBE	UARS/MLS	SWAS	SMIM	LDR
Launch Date	1989	1991	1995	~ 2002	~2008
LO	5 mW @ 90 GHz GaAs Gunn oscillator	1 mW @ 205 GHz GaAs Gunn oscillator with x3 whisker-contacted varactor	3 mW @ 275 GHz InP Gunn oscillator with x3 whisker-contacted varactor	100 µW @ 1200 GHz	20 mW @ 2000 GHz
Mixers	Planar diode in waveguide mount @ 90 GHz	Fundamental whisker-contacted GaAs SBD in waveguide with 200 hv/k @ 205 GHz, Rm. T operation	Harmonic whisker- contacted GaAs SBD in waveguide with 120 hv/k @ 557 GHz, 150 K operation	Fundamental SIS with 10 hv/k @ 1200 GHz, 2-4 K operation	SIS to 1200 GHz, SBD to 2000 GHz, with 10 hv/k @ 2000 GHz
Focal Plane Array	None	None	None	None	2x10 array
Spectrometer	NA	6 filter banks with range of fixed-resolution varying from 1 to 200 MHz, 16 channels per filter bank	1 AOS spectrometer 1.4 GHz BW 1 MHz res. 1400 channels	8-10 AOS spectrometers each with 1000 channels, 2 GHz BW & 2 MHz res.	2x10x1000 channels AOS spectrometers, 2 GHz BW, 2 MHz res.

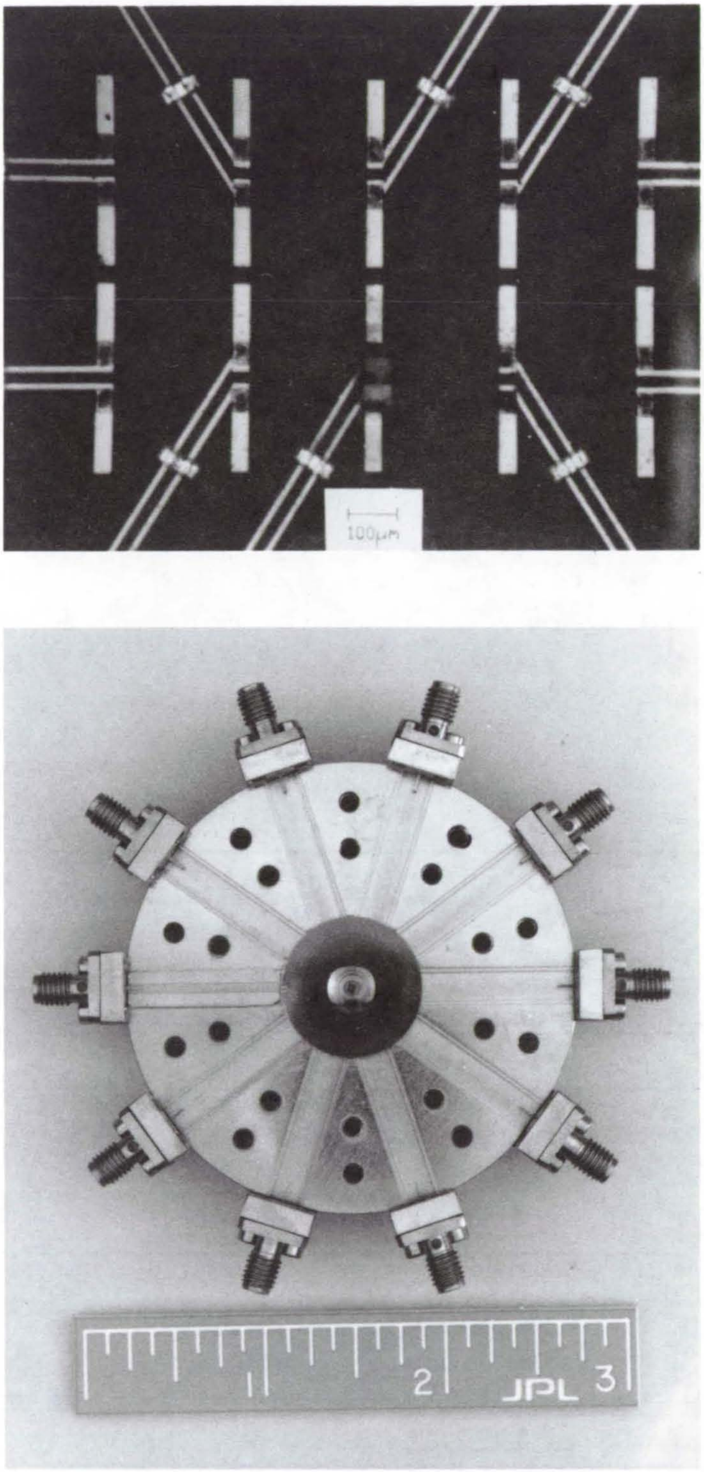

Figure 1. 230 GHz planar heterodyne array of superconducting tunnel junctions and dipole antennas on a dielectric-filled parabola (scale is in inches). This ten element array was fabricated at the Jet Propulsion Laboratory. The enlargement of the center region (top photo) shows the antenna elements.

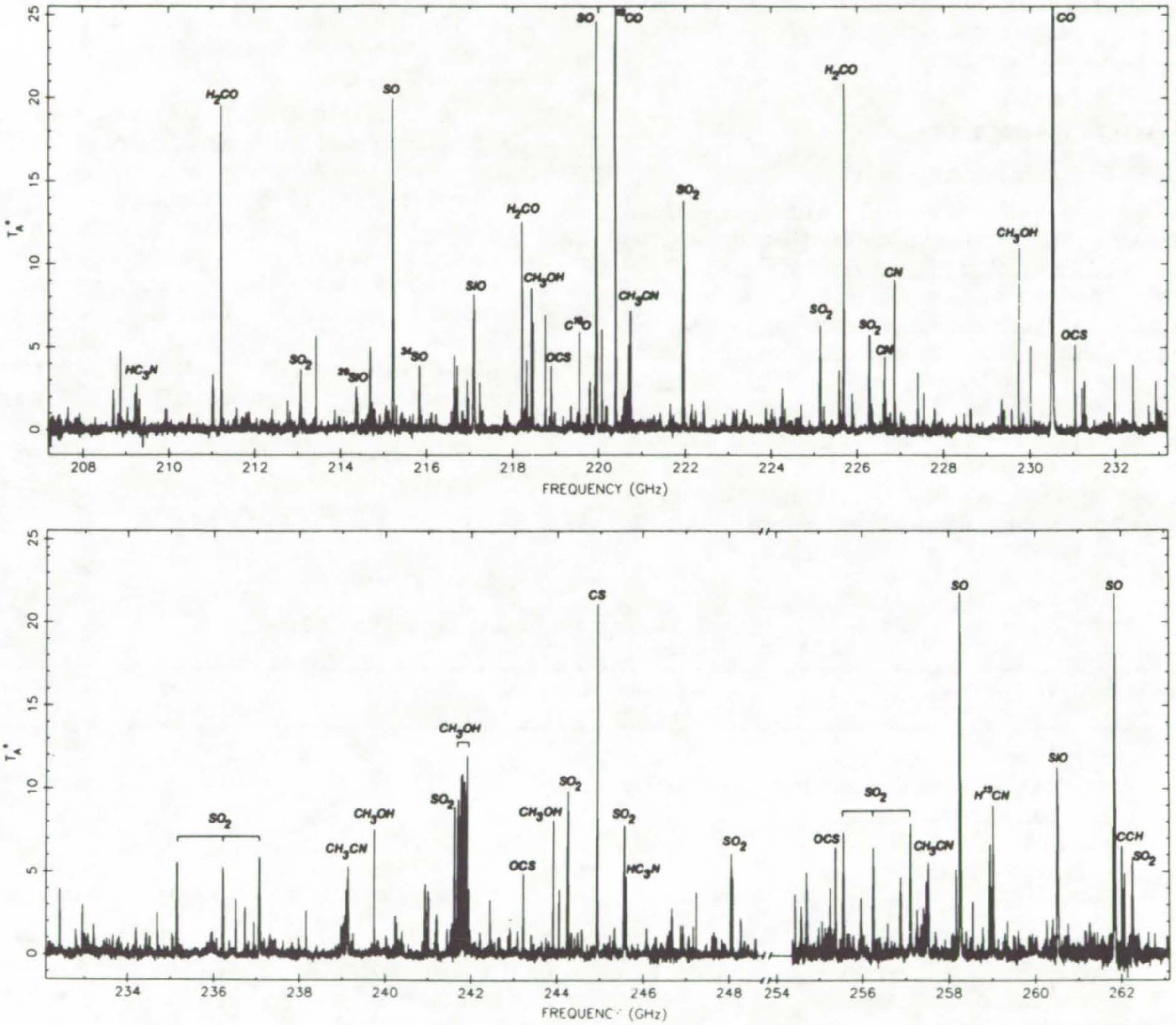

Figure 2. Emission spectrum of the Orion Nebula illustrative of the wealth of information on the molecular composition of interstellar clouds available in the millimeter and submillimeter wave range wave regime. This spectrum was obtained with a ground-based telescope.

radiometers at 63, 183 and 205 GHz, and SWAS will have two receivers at 480 and 560 GHz. This table clearly displays the progress that is being made in heterodyne detector capabilities, and highlights the advances that are still required. The remainder of this report addresses each of the four categories in turn, describing the emerging technologies which offer promise in meeting the measurement requirements of future astrophysics missions, and providing a development plan to achieve the desired performance on the required time scale.

LOCAL OSCILLATORS

A. Technology Assessment

As shown in Table II, SMIM, NGOVLBI, SMMI and LDR all require local oscillator (LO) performance which is beyond the current state-of-the-art. The current baseline technology for these missions is Gunn oscillators operating at 100 GHz coupled to a chain of whisker-contacted GaAs Schottky multipliers to reach the THz regime. However, to date no system with satisfactory output power has been demonstrated above 600 GHz. It is urgent that a satisfactory source be demonstrated above 1 THz as soon as possible; otherwise subharmonic mixers must be developed. From the panel's 1991 vantage point, there is also significant concern that the LDR requirement of 20 mW at 2 THz may not be possible to achieve with the baseline system, thus requiring the development of alternate technologies.

B. Development Plan

The panel recommends that the baseline technology be pursued vigorously, but that a number of innovative new concepts be tried also, as summarized in Table III.

The baseline design calls for whisker-contacted GaAs Schottky multipliers with factors of 2x2x3 to reach 1.2 THz. However, adequate conversion efficiency has not yet been demonstrated at THz frequencies, and multiple whisker-contacted devices are cause for serious concern in terms of system robustness. While the baseline technology needs to be pursued aggressively, the panel recommends additional support of emerging technologies based on bandgap engineered III-V heterojunction barrier structures offering the potential of higher conversion efficiency, especially at the highest frequencies, as well as a significant improvement in robustness. Higher order multipliers using symmetric CV diodes offer another possibility for increasing the conversion

Table III Local Oscillator Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Frequency multiplier devices				
Baseline GaAs Schottky varactors	< 700 GHZ	1200 GHz	91 - 96	Moderate
Planar GaAs Schottky varactors	< 200 GHz	1200 GHz	91 - 96	Small
Novel III-V varactors	< 200 GHz	1200 GHz	91 - 96	Small
Higher order varactors	< 200 GHz	1200 GHz	91 - 96	Small
Develop best option for > 1 THz		2000 GHz	96 - 01	Moderate
Frequency multiplier circuits				
Baseline metallic waveguide	< 700 GHZ	10% fixed bandwidth	91 - 96	Moderate
Micromachined waveguides	Concepts	Feasibility	91 - 96	Small
Quasi-optical structures	Concepts	Feasibility	91 - 96	Small
Quintuplers	Concepts	Feasibility	91 - 96	Small
Develop best option for > 1 THz		2000 GHz	96 - 01	Moderate
Oscillators for driving multipliers				
Baseline Gunn oscillator	1000 GHz, 50 mW	300 GHz, 10 mW	93 - 96	Small
Other mm-wave oscillators	Concepts	0.3-3 THz, 10 mW	93 - 96	Several small
Submm fundamental oscillators				
Quantum well	< 700 GHz, 1 μW	1200 GHz, 50 μW	91 - 96	Small
Josephson junction arrays	≤ 450 GHz	1200 GHz, 50 μW	91 - 96	Small
Power combining arrays	Concepts	1200 GHz, 50 μW	91 - 96	Small
Develop best option for > 1 THz		2000 GHz, 50 μW	96 - 01	Moderate

efficiency to THz frequencies. There is also concern that the currently available metallic waveguide structures may reach their limit at ~ 700 GHz, and not be appropriate for higher frequency operation. Possible solutions include quasi-optical structures, micromachined waveguides, overmoded waveguides or corner cube architectures.

Higher THz powers can also be achieved by augmenting the power of the fundamental oscillator to drive the multiplier chain. Fundamental oscillators in the submillimeter range are inherently more efficient than multiplied sources, but the technology is much less mature. Pushing millimeter-wave oscillators such as Gunn oscillators or IMPATT oscillators to higher frequencies with moderate power would also be useful to reduce the multiplication factor required to achieve the desired final-stage frequencies. Promising approaches for submillimeter-wave fundamental oscillators include the development of QW and Josephson tunnel junction technologies. Compact, tunable gas lasers or semiconductor laser structures are also possibilities for the LDR Schottky receiver.

Overall, the panel recommends a program equivalent to about a 15 lead person effort be focused on the LO problem, with about 40% of the resources being used to pursue the baseline technologies, and 60% to explore and develop alternate emerging technologies. It is also noted that the LO and mixer development programs should be tightly coupled.

MIXERS

A. Technology Assessment

As shown in Table II, some important requirements for mixer performance are not met by existing technologies, including the high frequency needs of SMIM and LDR. The baseline design for these missions is for Nb or NbN SIS mixers in a waveguide architecture to 700 GHz, and planar structures to 1200 GHz. GaAs Schottky barrier diode (SBD) mixers are baseline for frequencies above 1200 GHz. The precise dividing frequency between SIS and SBD implementation will be determined by the crossover frequency in its performance at the technology freeze date. A critical question is the ability of SIS mixers to operate adequately at frequencies above the superconductor energy gap (725 GHz for Nb). Josephson currents and RF losses in the superconductor may make Nb mixers unusable above this frequency, and the larger energy gap NbN has not yet been shown to work as well as Nb at any frequency. At the highest frequencies, where GaAs SBDs are baseline, there is concern over achieving the required sensitivity, as well as doubts about the robustness of the whisker-contacted devices.

B. Development Plan

Working in the baseline technologies, a number of possibilities should be pursued to extend the performance of these approaches towards the required mission specifications. These include the investigation of new alloys and insulators, NbN superconductor/insulator/normal metal (SIN) structures, and various novel architectures. Properties of the superconductors should also be measured in the higher frequency ranges - a demonstration of satisfactory operation at 1 THz is urgently needed.

Given the uncertainties inherent in the baseline technology, a number of alternate and fall-back approaches should also be investigated in parallel. Planar GaAs Schottky diode mixers, photoconductors such as Ge blocked-impurity-band (BIB) devices, high Tc SIS, and superconducting photoinductor detectors are worthy of consideration. In addition, other mixer geometries such as balanced mixers and subharmonically pumped mixers should be developed to ease the requirements on LO frequency.

Overall, the panel recommends that a ~ 12 lead person effort be maintained in this area, with about 70% going towards support of the baseline program. As noted before, the mixer development program should be closely coupled to the LO effort. Existing mixer technologies and the recommended development plan are summarized in Table IV.

FOCAL PLANE ARRAYS

A. Technology Assessment

This is a new technology requirement in the submm-wave regime, and although the development is progressing on schedule, it will require sustained support for some years to come. State-of-the-art capabilities in this area are still in the developmental phase, with prototypes for ground-based telescopes only now being built, and only for frequencies below 250 GHz. Multiple-pixel arrays bring a number of new problems to be overcome that are not present in discrete receivers. At the current time, the number of pixels envisioned is limited by LO power and spectrometer channel count. Other array-specific concerns include the coupling strength between the elements and the antenna and LO, as well as undesired coupling among elements and other parasitic effects, and heat dissipation of the IF amplifiers. There is currently no definitive baseline design for the LDR arrays, and new ideas need to be explored as they emerge.

B. Development Plan

Overall, the panel recommends that a ~3 lead person effort in array technology development be sustained, with new concepts investigated promptly.

Table IV Mixer Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Baseline Technology Devices				
Nb or NbN SIS mixers	Concepts	THz operation	91 - 93	Small
New alloys & insulators	Concepts	THz operation	91 - 94	Small
SIN structures	Concepts	THz operation	91 - 94	Small
Develop best option(s) for > 1 THz		Mission specs	93 - 98	Moderate
Alternate Device Approaches				
Planar GaAs mixers	200 GHz prototype	THz operation	91 - 94	Small
Ge BIB photoconductors	Concepts	THz operation	91 - 94	Small
Superconducting photoinductors	Concept	Feasibility	91 - 94	Small
High T_c SIS mixers	Concepts	THz operation	92 - 94	Small
Develop best option(s) for > 1 THz		Mission specs	93 - 98	Moderate
Baseline Mixer Circuits				
Metallic waveguide	200 GHz	THz operation	91 - 94	Small
Open structure mounts	Concepts	THz operation	91 - 94	Small
Develop best option(s) for > 1 THz		Mission specs	93 - 98	Moderate
Alternate Circuit Approaches				
Micro-machined waveguides	Concepts	Low losses	91 - 95	Small
Balanced mixers	< 200 GHz	THz operation	91 - 95	Small
Subharmonically pumped mixers	< 200 GHz	THz operation	91 - 95	Small
Develop best option (s) for > 1 THz		Mission specs	93 - 98	Moderate

Current ideas worth exploring include arrays of micromachined feedhorns, end fire slot antennas, and dielectric-filled parabola structures. The status of superconducting IF amplifiers and correlators being developed for other purposes should also be monitored, as they offer the potential for reduced power and heat loads. The suggested development plan is summarized in Table V.

SPECTROMETERS

A. Technology Assessment

Existing ground-based spectrometers would be adequate for SMIM and LDR except that they are stable only over a narrow temperature range, and have not been operated without human intervention over long periods of time. Smaller, lower-power designs with twice the bandwidth would be very desirable and should be possible. A considerable increase in the number of channels is also called for by the LDR array requirements.

B. Development Plan

The panel recommends that a 3 lead person effort be mounted to bring spectrometer technology to the required level of performance. This effort should include, in addition to the development of AOS technology, a monitoring of advances in digital circuits, since a digital spectrometer would ultimately be desirable to improve stability. The panel's recommendations are summarized in Table VI.

Table V Focal Plane Array Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Early array development	Ground-based design	250 GHz	91 - 93	Small
Extension to THz	Concepts	LDR specs	93 - 00	Moderate
Explore new concepts		Feasibility	91 - 96	Small
Develop best option(s)		LDR specs	96 - 01	Moderate

Table VI Spectrometer Technology Development

Technology Area	Current Technology	Program Goals	Program Dates	Program Size
Baseline Spectrometers				
AOS filter	1000 channels 1 MHz resolution	20, 000 channels 1 MHz resolution	91 - 95	Small
Digital spectrometer				
Monitor this technology	Concepts	Same as above	91 - 95	No funding
Develop for LDR if feasible		Mission specs	95 - 00	Small

SUMMARY

After reviewing the science goals of the Astrotech 21 mission set, and comparing the resulting receiver performance requirements with existing technology, the panel determined that there are significant unmet requirements in four areas; local oscillator power and mixer sensitivity in the THz regime, IF spectrometer channel count, and array technology in any form. A comprehensive development plan has been prepared to provide these capabilities in the time frame needed before technology freeze dates of the respective missions. It was also noted that the development of these capabilities has immense payoff for future astrophysics missions, as it opens entire new arenas of spectroscopy and imaging in the critical submm-wave regime rich in molecular transitions.

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Report of the Sensor Readout Electronics Panel

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INTRODUCTION

In many existing sensor arrays, it is the readout electronics that limits the overall system noise floor, rather than the detector itself. This is particularly the case for low-background imaging typically encountered in astrophysical missions. While the signal-to-noise ratio can be increased by increasing detector quantum efficiency, historically a substantially smaller effort has been applied to reducing the sensor readout electronics noise floor. A second general observation is that recent advances in materials, integrated circuit processing and circuit design techniques offer the possibility for significant enhancement in sensor readout performance for almost all imaging wavelengths. Thus it becomes imperative that any analysis of sensor requirements and development schedule include a coordinated analysis of readout issues. (See Fig. 1.)

Historically this has not been the case for NASA and SDI supported sensor development programs, where the effort was focused on the transducer part of the sensor, with the readout considered a conventional part of the control circuitry, and relegated to the later stages of system development. SDI has now recognized that readout technology may require comparable development effort, especially for large arrays and ultra-low noise applications, and sensor development programs must include a closely coupled effort on readout development from the start. This evolution in emphasis is apparent in SDI's new MODIL approach for infrared focal plane array development, and in their support of superconducting readout electronics. This panel strongly recommends that NASA adopt a similar approach, and support parallel, closely coupled efforts in sensor and readout development.

The focus of the Sensor Readout Electronics Panel was to assess the technology requirements for on-focal-plane signal processing and readout electronics for the Astrotech 21 mission set, and to generate a technology development plan to meet these needs. This analysis was to include all types of sensors for all regions of the electromagnetic spectrum. After examining the mission requirements, and comparing them to state-of-the-art technology, five major elements emerged as primary development needs in the area of sensor readout electronics. These elements are, in approximate priority order, (1) low-noise cryogenic readout electronics, (2) sub-electron read noise, (3) advanced packaging, (4) advanced focal-plane interface, and (5) advanced readout electronics architectures. For the most part, development of each of these elements stands to impact multiple missions and various sensor types, as summarized in Tables I and II, respectively.

In addition, a number of more generic issues were considered by the panel, including:

What are the VLSI technology needs to enable low-noise, low-power sensor readout?
How will very-low-temperature readout circuits required for very-long-wavelength IR detectors be achieved?
What role will 3-D microelectronics play in future sensor readout electronics?
What hybridization technology will be needed to achieve small pixels and large arrays?
What will be the role of superconducting materials and circuits on the focal plane?
What will be the role of "smart" readout architectures?
What role is there for focal-plane signal processing?
What are the limits of CCD multiplexer technology?

Table I. Technology Areas Recommended for Development

Technology Area	Desired Performance	Applicability Missions	Technology Freeze date
Low-noise cryogenic readout	0.1, 2 - 4 K	SIRTF	'92
	Micropower circuits	LTT	'95
	Reduction of 1/f noise	NGOVLBI	'00
		NGST	'02
Sub-electron read noise	< 1 e^- read noise	SIRTF	'92
		NAE, XST, HST III *	'95
		AXAF II, III	'95, '00
		AIM	'97
		HXIF	'99
		NGST	'02
		VHTF	'03
		GRSO	'04
		HST II, III	
Advanced packaging	Buttable-format arrays	SIRTF	'92
	Thermal compartmentalization	LTT, HST III	'95
		Imaging Int	'04
Advanced focal-plane interface	On-focal-plane A/D	SIRTF	'92
	Optical fiber link	XST, NAE	'95
		SMMI, HST III	'95
		AIM	'97
		NGOVLBI	'00
		NGST	'02
		VHTF	'03
		AXAF II, III	'95, 00
Advanced readout architectures	Event-driven readout	AXAF II, III	'95, '00
	Digital imager pixel	HXIF	'99
		VHTF	'03

* Terminologies II & III refer to 2nd and 3rd generation instruments.

These questions helped to focus the evolution of the recommended development plan. In the remainder of the report, the technology assessment and development plan for each of the five elements will be described in detail.

LOW-NOISE CRYOGENIC READOUT ELECTRONICS

A. Technology Assessment

Many of the missions described in the mission set, particularly in the infrared, require low-noise cryogenic readout electronics. There is a major, fundamental problem with conventional semiconductors operating at cryogenic temperatures. This is because the impurity atoms' electrons "freeze out" due to lack of sufficient thermal agitation. At moderately low temperatures (20-40K), the partial freeze-out of electrons results in excess noise, as electrons are unpredictably energized or frozen out of the conduction band. At lower temperatures, devices can cease to operate altogether.

There are several technical approaches to the problem. First, silicon can be fabricated to increase the number of impurity atoms. This decreases the freeze-out temperature and extends the device operating range. Acceptable silicon device performance has been demonstrated down to 12 K using a cryogenic process developed by TRW. (Lower temperature performance can be obtained with silicon p-type metal-oxide semiconductor (PMOS) technology but at an unacceptable cost in power.) A second approach is to use a semiconductor technology which doesn't require impurity atoms. Such a technology has been demonstrated at 77 K for digital circuits using gallium arsenide (GaAs) complementary heterojunction insulated-gate field-effect transistor (CHIGFET) technology, and is currently under exploratory investigation for very low temperature analog applications at JPL in a small contract with Honeywell. A third approach is the use of superconducting circuits. Some preliminary work has been performed at some aerospace companies for DoD applications.

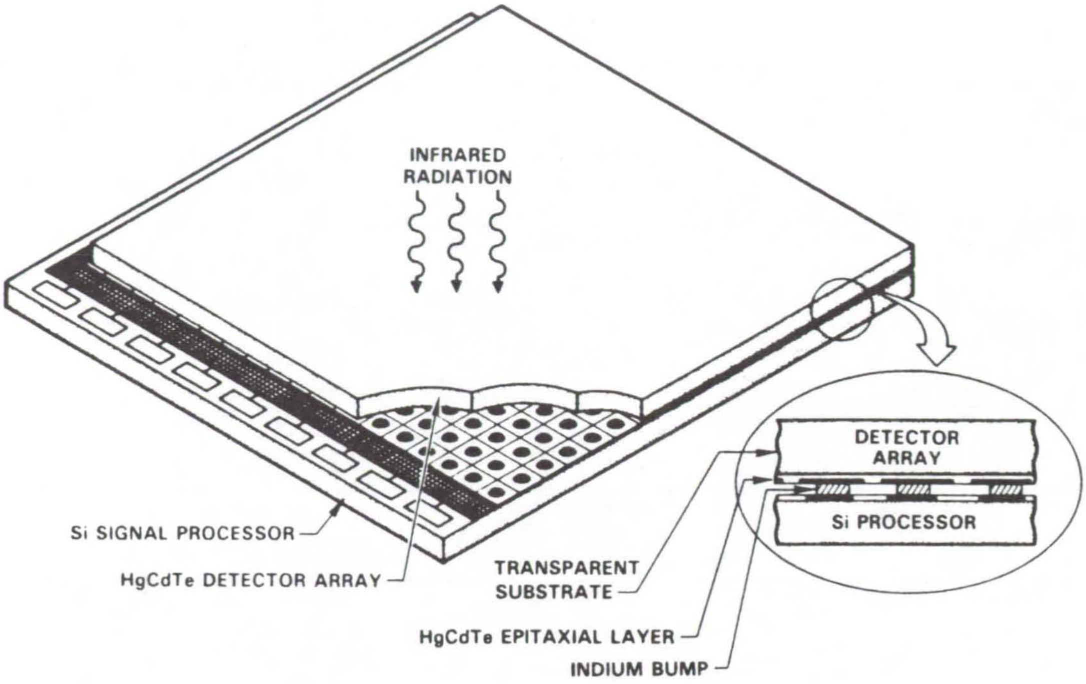

Figure 1. Hybrid focal plane architecture illustrating the intimate relationship between detectors and readout electronics. (From Bailey et al, IEEE Transactions on Electron Devices, **38**, page 1104, 1991.)

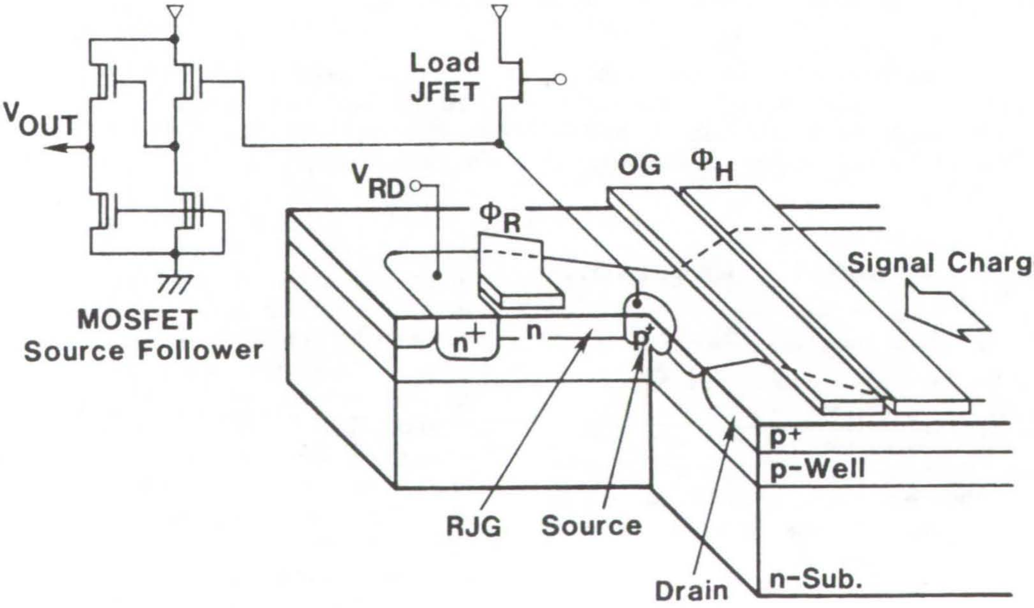

Figure 2. Low-noise JFET CCD output amplifier with high sensitivity. (From Mutoh et al, IEEE Transactions on Electron Devices, **38**, page 1048, 1991.)

Table II. Readout Electronics Technologies: Areas of Applications

Readout Technology Development Area	X-Ray & Gamma Ray	Ultraviolet & Visible	Direct Infrared	Heterodyne submillimeter
Low-noise cryogenic readout - 0.1 & 2-4 K - Micropower circuits - Reduction of 1/f noise	Bolometers, superconductors & Ge detectors	Cryogenic visible photodiode arrays	Bolometers & IBCs	IF amplifiers
Sub-electron read noise - Floating-well circuits - Source-follower MOS MUX	CCDs & superconducting X-ray detectors	CCDs & photodiode arrays	All very-low-background & spectroscopic measurements	N/A
Advanced packaging - Buttable format arrays - Thermal compartmentalization	Large mosaics	Large mosaics	Very long wave IR detectors	SIS arrays
Advanced focal-plane interface - On-focal-plane A/D - Optical fiber link	All cryogenic systems	All cryogenic systems	All cryogenic systems	All cryogenic systems
Advanced readout architectures - Event driven readout - Digital pixel imager	All low-signal applications	All low-signal applications	All low-signal applications	N/A

Operation at higher cryogenic temperatures is dominated by 1/f noise. This noise, investigated for decades, is still poorly understood yet can limit system performance in applications such as gamma ray detector preamplifiers. We have broken the area of cryogenic readout electronics into four sub areas:

(i) Operation at 2-4 K

Very long wavelength, direct detectors need to operate at extremely low temperatures, and are anticipated for inclusion in missions such as SIRTF, NGIR and NGOVLBI. At the present time, no viable technology has been demonstrated for operation at such low temperatures. We recommend an immediate augmentation of efforts in this area.

(ii) Cryogenic readout electronics at 0.1 K.

With the exception of low-temperature superconducting electronics, whose development is still at a very early stage, no technology exists at 0.1 K. Such a technology would represent a breakthrough and have a significant impact on broadband very long wavelength IR detector readout and thermal packaging. The CHIGFET technology may also represent a possible approach. We recommend a breakthrough thrust in this area.

(iii) Analog Micropower Circuits

For high-background applications, and for large arrays, the readout/multiplexer circuitry can constitute the dominant power drain in the focal plane. And since this dissipation occurs in a low-temperature part of the instrument, it is imperative that this dissipation be kept as low as possible, so as to avoid unreasonable demands on the cooling system. Thus the development of cryogenic readout electronics requires not only the development of low-noise devices but also of low-power circuits. The panel finds this to be a critical element of a cryogenic readout electronics plan. The circuits are typically customized for a particular detector application. Applications include all cryogenic IR missions.

(iv) Reduction of 1/f noise.

As described above, 1/f noise is an age old problem in semiconductor analog circuits. However, because it continues to limit amplifier performance the panel recommends renewed attempts to understand and reduce this noise. Operating temperature regimes of importance are 60-80 K (NAE, GRSO), 10-20 K (SIRTF, NGIR) and 2-4 K (SIRTF, NGIR).

B. Development Plan

This element requires very rapid resolution, as the results are needed in time for SIRTF. The desired characteristics are low-noise, low-power, radiation tolerant, cryogenic readout multiplexer arrays for device operating temperatures of 0.1, 2 - 4, and 80 K. The first step is to evaluate the contribution from different noise sources, in order to determine methods to reduce them. An early assessment of the feasibility of low-temperature superconductors for bolometer readout arrays is also recommended. Finally, 2 - 4 and 80 K readouts with < 1 e$^-$ rms read noise need to be demonstrated prior to the '94 technology freeze date for SIRTF. The development plan is summarized in Table III.

SUB-ELECTRON READ NOISE

A. Technology Assessment

Many of the missions call for one electron rms read noise, or less. These include HST, LTT, FUSE, AIM, NGST, II, SIRTF, AXAF, XST, HXIF, AND VHTF. Sub-electron read noise means that the probability of correctly measuring a single electron is greater than 50%, or that a given collection of electrons is converted to a voltage with an rms noise less than the electron-to-voltage conversion gain. The major limitation is obtaining sufficient sensitivity on the output amplifier to overcome white thermal and 1/f noise. The technical approaches are thus to either increase the sensitivity of the single node (i.e., reduce its capacitance) or reduce the conversion noise.

One source of conversion noise in CCD output amplifiers is the so-called kTC noise occurring when a capacitor is charged to a reset voltage, and then disconnected and left floating. In the past few years, an output amplifier design called the floating well amplifier (Fig. 2) has been developed in Japan which eliminates kTC noise. It also has high output sensitivity. Thus far, it has not been adopted by U.S. CCD manufacturers, but the method is understood. In source-follower MOS switched-array multiplexers (used in IR imagers) the noise level obtained is in the 10-50 electron rms range. It is generally believed that with development and possible use of floating well techniques, these readout circuits can also be brought to the one electron or less read noise level.

B. Development Plan

The panel recommends two thrusts in this area: (1) the development of the floating-well output amplifier, and (2) the development of ultra-low-noise source-follower MOS switched-array multiplexors. As for cryogenic readouts, these capabilities are required for SIRTF instruments, and thus must be developed before '94, as summarized in Table IV. However, additional optimization can be continued through the decade to benefit later missions.

ADVANCED PACKAGING

A. Technology Assessment

The Sensor Readout Electronics panel identified

Table III. Low-Noise Cryogenic Readouts

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Process technology noise evaluation (1/f, thermal)	Indefinite	Evaluation Noise reduction	92 - 94 94 - 95	Small Small
2 - 4 K readout circuits	15 K	Demonstration	92 - 95	Moderate
0.1 K low-temperature superconductor readout	Concept	Demonstration	92 - 93	Moderate
Analog micro-power device/circuit	500 mW input power	$\leq$ 10 mW input power	92 - 94	Moderate
80 K, < 10 e^- rms MUX	50 e^-	Demonstration	92 - 95	Small

Table IV. Sub-Electron Read Noise

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Floating-well output & amplifier	Exists in Japan	Elimination of kTC noise	92 - 93	Moderate
Source-follower MOS switched array MUX	$\leq$ 50 e^- read noise	< 1 e^- read noise	93 - 95	Small

advanced packaging as a critical component of sensor technology. While not falling into the sensor readout electronics panel's predefined area, for a sense of completeness it is included in our report. We see advanced packaging having three thrust components critical to ensuring that the mission set requirements can be met. These are large area infrared focal-plane arrays, large-area visible (CCD) focal-plane arrays, and thermal compartmentalization.

(i) Large area infrared focal-plane arrays.
The mission description for NGST suggests that array sizes of ≥ 10k x 10k are desired. While techniques to form a mosaic of focal-plane arrays have been explored in a DoD context, a methodology of such large arrays must be developed. For example, if hybrid IR imagers of size 512 x 512 can be demonstrated, then to achieve a size 20k x 20k will require some 1600 imagers in a focal-plane mosaic. Many of the panel members expressed reservations regarding the feasibility of such an approach. Nevertheless, significantly less ambitious mission requirements will still require an advancement in packaging methodology to achieve viability. A buttable mosaic array, as described above, is one approach to this problem. A more advanced solution would be the semi-monolithic integration of sensor readout electronics with a detector. For example, HgCdTe grown on a GaAs multiplexer substrate might be an approach to be considered. This is desirable because of the intrinsic match of thermal expansion coefficients between the materials. A third approach is the fully monolithic integration of the detector and multiplexer. For example, a GaAs quantum well infrared photodetector (QWIP) might be integrated with GaAs readout electronics to form the image sensor. This approach has not yet been demonstrated.

(ii) Large area/large format visible (CCD) arrays.
In conjunction with the visible detector panel, the sensor readout electronics panel considered the NGST mission requirement for 10k x 10k or larger pixel arrays. While CCD multiplexers/imagers have exhibited remarkable progress in the past years, array sizes of 10k x 10k will require significant improvement in the already near-perfect charge transfer efficiency and readout rate without degrading noise performance. In this case, use of a mosaic array of CCD imagers would be a more prudent readout strategy, with each imager having, say four-quadrant readout. (A buttable mosaic array also alleviates semiconductor fabrication yield concerns.) A methodology for packaging such a mosaic array may already exist in DoD applications. We recommend advanced development by NASA.

(iii) Thermal Compartmentalization
In many infrared focal-planes requiring low temperature operation, detector thermal isolation and readout electronics form conflicting requirements. There is a need to keep detectors at very low temperatures, yet maintain readout electronics at higher temperatures, to insure low noise readout and avoid self-warming of the sensor during readout. If the readout can be operated at higher temperatures, there is also a savings in cooling capacity at the sensor temperature, and a relaxation of the requirements for cryogenic readout technologies. It is also useful to keep the readout electronics at higher temperatures to ensure low-noise readout and avoid self-warming of the sensor during readout. Innovative approaches to thermal isolation and compartmentalization are required. The panel feels this is outside our area of expertise, but that it should be included in the report.

B. Development Plan

To meet the needs of mega-pixel readout, the panel suggests support in three areas. First, there should be support at a moderate level to develop hybrid, large-format IR array mosaics. Second, both hybrid and monolithic mosaicking of large-format CCD systems should be developed. Finally, innovative approaches to resolve the conflict between thermal isolation and readout interconnections should be addressed. The lead time for this development is rather short, as the capabilities are desired for missions such as XST, NAE, SMMI, and HST refurbishments with technology freeze dates starting in '95. However, additional development could also benefit missions with longer lead times. The development schedule is summarized in Table V.

ADVANCED FOCAL PLANE INTERFACE

A. Technology Assessment

Two elements of an advanced cryogenic system were discussed. Since cryogenic systems are, by nature, isolated from their surroundings, electrical signals are driven from the focal-plane, through long cables, to warm external electronics. From individual experience of panel members, it was noted that system performance often degrades by a factor of 2 to 4 between the focal-plane and the external world. It was also noted that a significant portion of dissipated heat on the focal-plane is due to the need to drive the cabling. While not called out as a requirement by particular missions, two technical approaches to

Table V. Advanced Packaging

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
IR detectors on Si or GaAs				
Develop various options	Concepts	Feasibility	92 - 94	Small
Develop best option	512 x 512	≥ 10k x 10k	94 - 97	Moderate
Integration of MUX & array				
Mechanical hybrids	512 x 512	1k x 1k	92 - 95	Moderate
Monolithic	Concepts	≥ 10k x 10k	94 - 97	Moderate
Compartmentalization				
Thermal isolation	Ad-hoc, situation-specific solutions	Generic solution, 2 - 5 times improvement in performance	92 - 93	Small
Implementation experiments			93 - 94	Small
Optimization			94 - 96	Moderate

reducing this scientific information degradation and Dewar heat load should be brought to the reader's attention. These are focal-plane data conversion and optical links.

(i) Focal-plane data conversion (A/D)

Relocation of the analog-to-digital conversion process from outside the Dewar will result in the benefits of increased immunity from electromagnetic interference (EMI) and a reduction in off-chip drive power, and offers the promise of increased scientific data return by lowering the system noise floor. In exchange, it adds back power dissipation on the focal plane for data conversion, and requires electrical isolation from the sensor multiplexer electronics. The panel was particularly intrigued by the possibility of superconducting A/D electronics since they consume little power and operate well at cryogenic (i.e., Dewar) temperatures.

(ii) Focal-plane Optical Fiber Links

Currently, electrical wires connect the cryogenic environment with the external warm environment. Optical fiber links offer intriguing opportunities to enhance system performance in several ways. First, optical fiber being small diameter glass "wire" reduces the parasitic heat load on the focal plane. Second, optical fibers are virtually immune from EMI, thus preventing external noise from infiltrating the focal-plane electronics. Third, focal-plane readout using optical means can reduce power dissipation on the focal plane. We see optical fiber potentially performing the following functions:

(a) Provides a link for external clock signals to the focal plane.

(b) Provides a readout channel to the external environment.

(c) Provides power optically to the focal plane. (Requires energy conversion on the focal plane.)

In particular, option (ii) in conjunction with a focal-plane A/D converter might significantly enhance overall system performance. We must emphasize that in each of these options we are not advocating putting an optical source (e.g., laser) on the focal plane. This would dissipate too much power and add system complexity. Rather, the source can be external, and in the case of option (ii), be modulated on the focal plane using very little power. A possible configuration is sketched in figure 3.

B. Development Plan

The two areas described above are recommended for support. The specific performance requirements are summarized in Table VI.

ADVANCED ARCHITECTURES

A. Technology Assessment

In most visible and IR sensor systems, the multiplexer is used to connect each detector to the output amplifier sequentially, one-at-a-time in some sort of raster scan mode. While this performs the readout function, in systems of increasing throughput requirements such a methodology may be less than optimum. Our panel has two recommendations for advanced sensor readout electronics architectures which do not fall into this category. We believe that exploration of advanced architectures may impact all sensor-based missions.

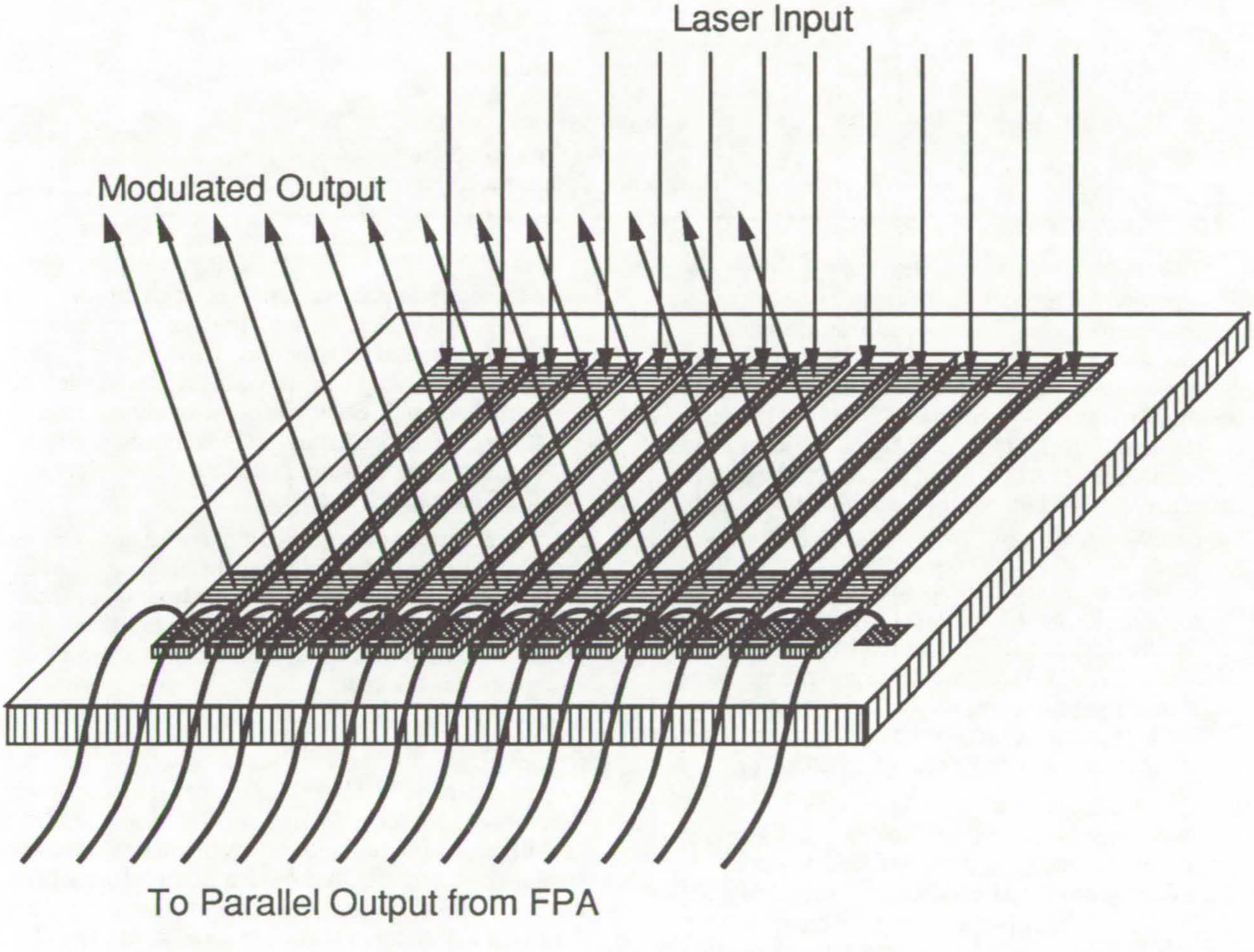

Figure 3. Schematic of an all-optical link between a cold focal plane and warmer system electronics. Optical fibers could be used to provide external clock signals and focal-plane power, as well as a signal readout channel. Advantages include a reduction in power dissipation and parasitic heat load on the focal plane, and immunity from electromagnetic interference.

Table VI. Advanced Focal-Plane Interface

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Monolithic A/D converter	Concepts	≥ 10 bits, kHz - MHz sample rate, μW power for ≤ 10 K, mW power for 80 K Parallel-serial MUX Digital data driver	93 - 98	Moderate
Optical readout	Concepts	≥ 10 bits analog range, μW power for ≤ 10 K, mW power for 80 K low-power driver/modulator low-power optical trans/receiver	93 - 98	Small

(i) Event-driven readout

In certain sensor systems, and in particular in the case of high energy photon sensing (e.g., x-ray) the array illumination may be sparse, with photon activity occurring only in a small portion of the array. It would be inefficient, and perhaps impractical, to fully scan the entire array at sufficient rate to ensure that single photon events are read out prior to the next event in that pixel. We propose investigating event-driven readout where a photon event triggers readout of that pixel. As an alternative, locally variable frame rate read out might also serve the high-throughput, sparse-illumination mission requirement. Note, these schemes are not equivalent to data compression, and do not result in any loss of image information.

(ii) Digital Imager Pixel

As a breakthrough thrust, the panel recommends the development of a digital imager pixel. In this very advanced concept, the output of each pixel is a digital count rather than an analog value. Successful implementation of this concept could result in making CCDs and IR analog multiplexers obsolete. It could (in time) achieve noiseless readout, provide unprecedented radiation hardness, increase dynamic range, and pave the way for a host of smart sensor architectures. Such a breakthrough will require a successful marriage of advanced VLSI and materials processing, including the development of 3-D microelectronics.

In addition to these two advanced architecture thrusts, the panel also felt that the readout of MCP arrays for UV sensors might benefit from other focal-plane readout technologies. However, there was insufficient time during the course of this workshop to explore this concept.

B. Development Plan

As detailed in Table VII, the panel recommends the development of an event-driven readout architecture to replace conventional full-array sampling schemes with a device that performs peak detection, storage and self-addressing readout. This approach will become critical as array sizes expand to 1k x 1k and beyond, where sampling of the entire

Table VII. Advanced Architectures

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Event-driven readout				
Explore options	Concepts	Feasibility	93 - 95	Few small
Develop best option(s)		~ 1×10^4 / s event rate, ~ 1×10^3 amplitude resolution, < 1 electron noise, 1×10^6 - 1×10^8 pixels, 1×10^3 dynamic range	95 - 99	Moderate

pixel count becomes prohibitively slow. Development should start with investigations of a number of potential approaches, each on a small scale, and following a down selection in '95, the best option(s) should be developed.

SUMMARY

This report summarizes the findings of the Sensor Readout Electronics Panel in regards to technology assessment and recommended development plans. In addition to two specific readout issues, cryogenic readouts and sub-electron read noise, the panel considered three advanced technology areas that impact the ability to achieve large-format sensor arrays. These are mega-pixel focal-plane packaging issues, focal-plane to data-processing module interfaces, and event-driven readout architectures. Development in each of these five areas was judged to have significant impact in enabling the sensor performance desired for the Astrotech 21 mission set. Other readout issues, such as on-focal-plane signal processing or other high-volume data acquisition applications important for Eos-type mapping, were determined not to be relevant for astrophysics science goals, and are explicitly excluded from this report.

Some of the recommendations from this panel are duplicated in the reports of the panels that considered specific wavelength ranges. This is to be expected, as many of the readout issues are intimately related to the specific detector architecture. However, the existence of a separate readout panel also enabled the identification of more generic issues, which could then be addressed with a unified development plan, thereby avoiding unnecessary duplication. Thus the strong interaction between the readout and detector panels in this workshop, and the unified approach to readout issues, engendered a useful cross-fertilization of ideas among the different detector communities.

Report of the Sensor Cooler Technology Panel

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INTRODUCTION

Cryogenic cooler performance is a critical system requirement for many space-based spectroscopy and imaging measurements. This is particularly true for measurements of weak signals, such as are typical for astrophysics missions, where it is often necessary to cool the focal-plane sensors and electronics to cryogenic temperatures in order to reduce focal-plane thermal noise sources below the signal levels to be measured. Among the key aspects in which further development in space cryocooler technology is required are the achievement of lower temperatures, larger heat loads, reduced vibration, and longer cooler lifetimes.

The focus of the Sensor Cooler Technology Panel was an analysis of the cryogenic cooler performance required to meet the Astrotech 21 mission set science objectives. A list of the mission set specifications and the pacing cooler technologies is provided in Table I. After a careful review of the mission set, the panel identified four general types of missions where existing cooler technology is expected to be insufficient or marginal. The four categories are:

- Long-life precision-pointing space telescope missions with observations at 2.5 to 10 µm. (HST II & III, NGST, Imag. Int.)
- Long-life missions requiring significant (> 100 mW) cooling capacity in the 2 to 5 K temperature range for periods of up to 15 years. (SMIM, NGOVLBI, LDR, SMMI)
- Long-life missions with subkelvin applications requiring ~ 10 µW of cooling at 0.1 K with heat sinking to 2 K. (SIRTF, SMIM, LDR, SMMI, AXAF)
- A number of missions which require low-vibration, high-capacity coolers in the 65 K temperature range. (GRSO, NAE)

The panel also reviewed current state-of-the-art capabilities and future potential of the various cryocooler technologies which either have been flown previously or are being considered for space applications. Figure 1 shows a compilation of the primary operating regions for these technologies in terms of the cooling temperature and cooling power ranges they can each be expected to offer. Working from the mission requirements in the context of this analysis of space cryocooler capabilities, the panel developed a four-element technology development strategy to meet the identified challenges of the Astrotech 21 mission set. The four areas recommended for development are:

- Long-life vibration-free refrigerator development for 10 - 20 K and 65 - 80 K temperature ranges for use on missions requiring precision pointing.
- 2 - 5 K mechanical refrigerator development for future long life infrared (IR) and submillimeter (submm) missions with lifetimes exceeding super-fluid He storage tank holding times.
- Flight testing of emerging prototype refrigerators to determine feasibility before they are committed to large, high-visibility astrophysics missions.
- R&D of promising backup technologies to mitigate against failure of one or more of the baseline technologies.

The specific performance requirements in these four areas, the missions impacted, and the associated technology freeze dates are summarized in Table II. The items have not been prioritized. This report describes the panel findings and the recommended development plan to achieve the required capabilities on the necessary time scales. Note that requirements for other areas of space missions were not included in the considerations. The recommendations are restricted to issues of relevance to the specific missions and science objectives of the Astrotech 21 mission set described earlier in this Proceedings.

Table 1. Astrotech 21 Missions Requiring Advances in Cryocooler Technology

Mission Instrument	Detector Technology (µm)	Wavelength Range (K)	Detector Temperature	Cooling Load	Heat Sink (years)	Mission Life	Technology Freeze Date	Pacing Cooler Technology
HST	IR	0.1-2.5	80	0.5 W	LEO	5	1994	No vibration
LTT	CCD	0.12-2.5	100	1 W	Moon	10	1995	Moon surface, life
NGST	10^4x10^4	0.1-10	10-30	1 W	EO/Mn	15	2004	No vibration
Imag. Int.	10^3x10^3	0.1-10	10-30	1 W	EO/Mn	10	2007	No vibration
SIRTF/IRS	Ge:Ga BIB	36-200	1.3	60 mW	HEO	6	1994	SFHe Vent/Plug
SIRTF/MIPS	Bolometer	100-700	0.1	10 µW	2 K	6	1994	Subkelvin ADR
SMIM	Submm	250-700	2-5	15 mW	HEO	2-4	1996	See SIRTF
SMIM	Bolometer	100-900	0.1-0.3	10 µW	2 K	2-4	1996	See SIRTF
LDR	Submm	30-3000	2-5	100-300 mW	EO/Mn	10-15	2006	5 K, heat load, life
LDR	Bolometer	30-3000	0.3	100 µW	2 K	10-15	2006	Subkelvin
SMMI	SIS	100-800	2-5	20 mW	EO/Mn	10	2006	5 K, long life
SMMI	Bolometer	150-300	0.1	10 mW	2 K	10	2006	Subkelvin
NGOVLBI	Submm	10-220 GHz	5-20	100 mW	EO	10	2000	5 K, long life
AXAF	X-ray	0.09-10 keV	0.1	10 µW	2 K	15	1995	Subkelvin ADR
NAE	Ge	Gamma-ray	80	1 W	LEO	2-4	1994	No vibration
GRSO	Ge	Gamma-ray	80	200 W	TBD	15	2004	No vibration, life

LONG-LIFE VIBRATION-FREE REFRIGERATORS

A. Technology Assessment

Long-life precision pointing space telescope type missions with measurements in the near to mid IR range require vibration-free coolers with ~ 1 W of cooling capacity in the 65 to 80 K temperature range for use with 2.5 µm detectors, and with ~ 20 mW of capacity in the 10 to 20 K range for use with 10 µm detectors. The critical issues are the requirements for no vibration and long life. The requirement for no vibration is expected to exclude present Stirling cooler technologies being developed for Earth Observing System (Eos) missions. Similarly, typical lifetimes of 10 - 15 years also render the use of stored cryogens inappropriate (not cost effective). Thus new approaches will be needed to meet the mission requirements.

B. Development Plan

The panel recommends that NASA develop and qualify one or two vibration-free coolers in the two key temperature ranges (10 to 20 K, and 65 to 80 K), for use on space-telescope type missions. Candidate technologies include sorption refrigerators (Fig. 2), and high-speed turbo-Brayton systems. Both of these technologies have demonstrated technical feasibility in recent lab breadboard tests, but must be carried to the point of engineering model construction and life testing before they can be proposed for flight applications. These technologies are ready for engineering model development, but remain unfunded at this time. An appropriate development schedule is shown in Table III.

MECHANICAL REFRIGERATORS FOR 2 TO 5 K

A. Technical Assessment

Long-life IR and submm missions require significant (> 100 mW) cooling capacity in the 2 to 5 K temperature range for periods of up to 15 years. This type of mission considerably exceeds (by more than a factor of 10) the cooling capacity being developed for SIRTF (see Figs. 3 to 5), and is probably unrealistic (not cost effective) for a stored cryogen system.

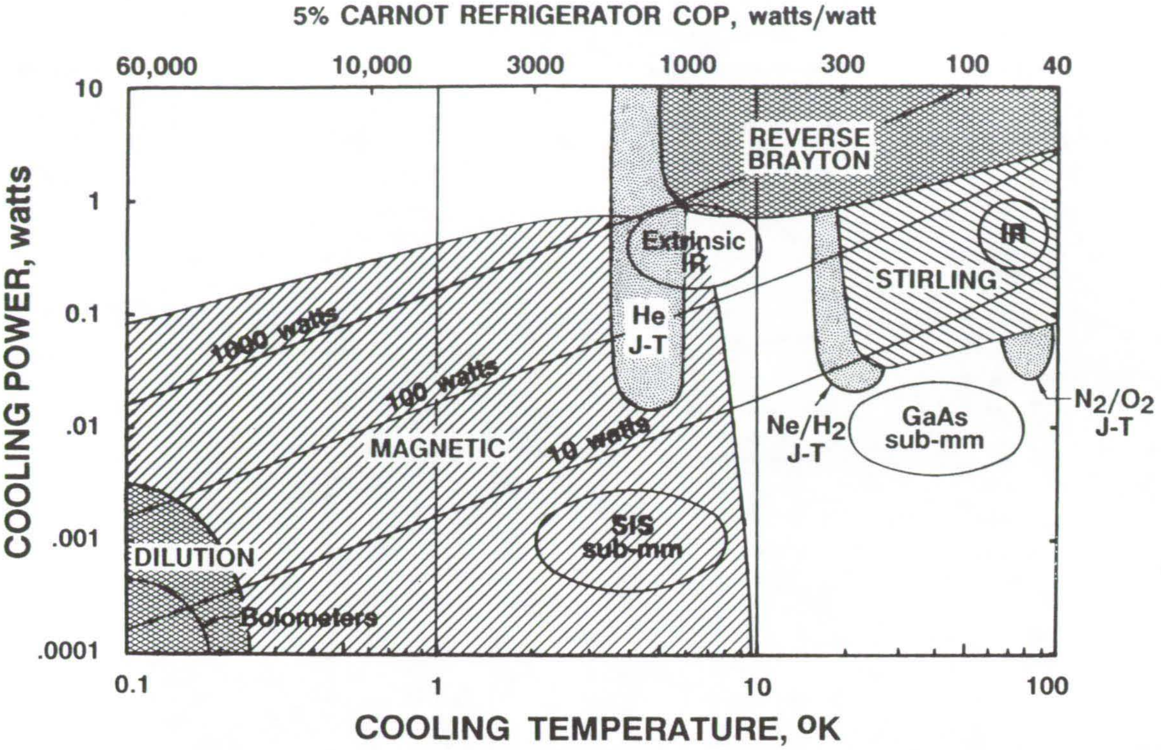

Figure 1. A compilation of the primary operating regions for various cryocooler technologies in terms of the cooling temperature and cooling power ranges they can each be expected to offer. Included for comparison are the operating ranges required for various detector types.

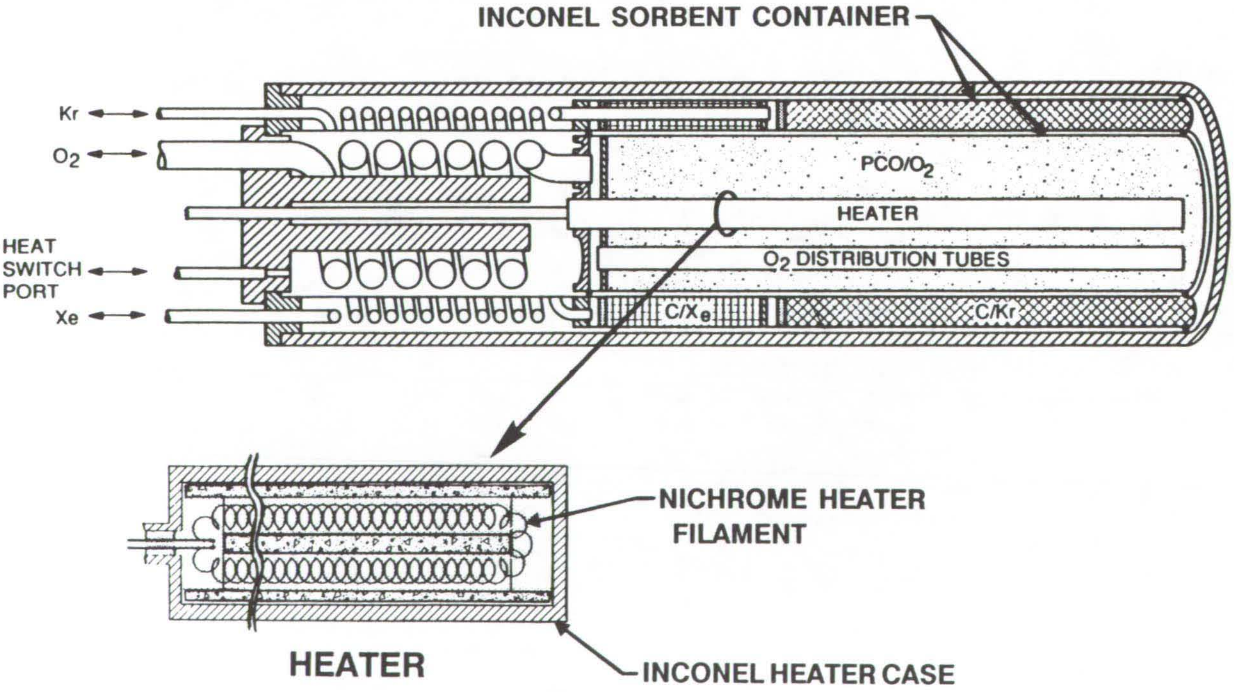

Figure 2. Schematic diagram of a concentric sorption compressor, a candidate for vibration-free cooling at 65 K.

Table II. Technology Areas Recommended for Development

Technology Area	Requirements	Missions	Freeze Date
Long-life, vibration-free refrigerator	10 - 20 K,	HST, NAE	'94
	65-80 K.	Imag. Int, GRSO	'04
2-5 K mechanical refrigerators	10-20 mW @ 2K,	SMILS	'96
	50-100 mW at 4-5 K,	NGOVLBI	'00
	< 1 kW input power.	LDR, SMMI	'06
Flight testing of emerging prototypes	65 K Stirling, Subkelvin ADR, Others, as required.	Relevant to all missions	
R&D of backup technologies	Lower parasitic heat loads, alternate subkelvin concepts, alternate vibration-free concepts	Relevant to all missions	

Table III. Long-Life Vibration-Free Refrigerators

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Develop new approaches including sorption and turbo-Brayton	lab breadboard tests demonstrated feasibility	engineering model and life testing	91 - 93	Moderate
Qualify best option(s)		Space qualified model:		
		for HST & NAE	93-94	Large
		for NGST & GRSO	95 - 00	Large

B. Development Plan

It is recommended that one or two long-life low-vibration mechanical refrigerators be developed and qualified to provide 2 to 5 K cooling for future LDR-type applications that are beyond the reach of launch-vehicle limited SFHe Dewars such as used on SIRTF. A ball park target of less than 1 kW input power and 10 - 20 mW of cooling at 2 K together with 50 to 100 mW of additional cooling at 4 - 5 K was identified as about right. This distribution of cooling should be carefully reviewed in light of the thermodynamic inefficiency and immaturity of hardware for providing mechanical cooling at 2 K; the capacity at 2 K should be selected to just meet those science objectives requiring this temperature. Because of the vastly improved efficiency of providing cooling above the liquefaction point of He at 4 K, the science community should strive to meet as many objectives as possible using temperatures in the 4 to 5 K range or higher.

A variety of candidate technologies exist for providing 4 to 5 K mechanical cooling (Fig. 6). These include: three-stage turbo-Brayton systems, closed-cycle He Joule-Thomson (J-T) refrigerators with upper stages, 4 K Stirling plus upper stages, and magnetic refrigerators with upper stages. Two-stage Stirling, pulse tube, and turbo-Brayton systems are candidate upper-stage technologies. Of these technologies for attaining 4 - 5 K, the three-stage turbo-Brayton is the most mature, having reached the prototype stage under DoD/SDIO funding. Because of the diversity of technical approaches, a multiple-path development approach is recommended, with down selection occurring after the definition of a preferred configuration. The proposed development schedule is summarized in Table IV.

Significant (x 10) expansion of superfluid He Dewar size and life performance beyond that for SIRTF was judged not to be a cost effective approach to meeting these most demanding Astrotech 21 missions. However, the SFHe technology is the logical choice for the smaller SIRTF-size missions.

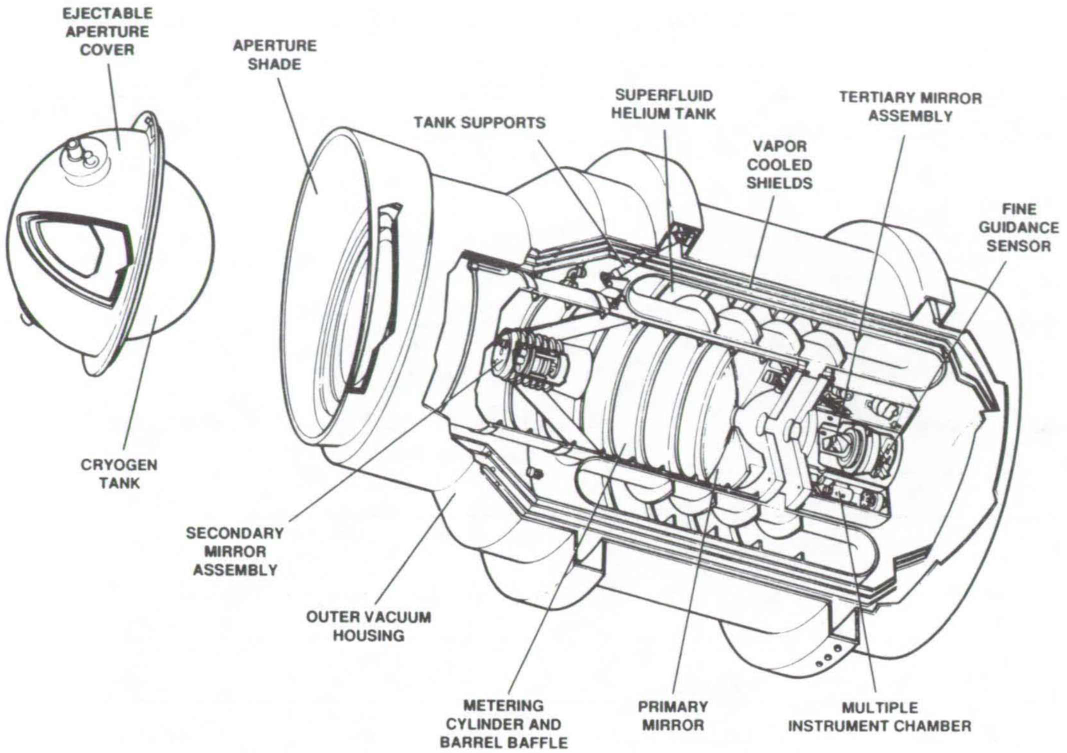

Figure 3. Schematic cut-away view of the plans for the SIRTF telescope displaying the cryogenic Dewar assembly.

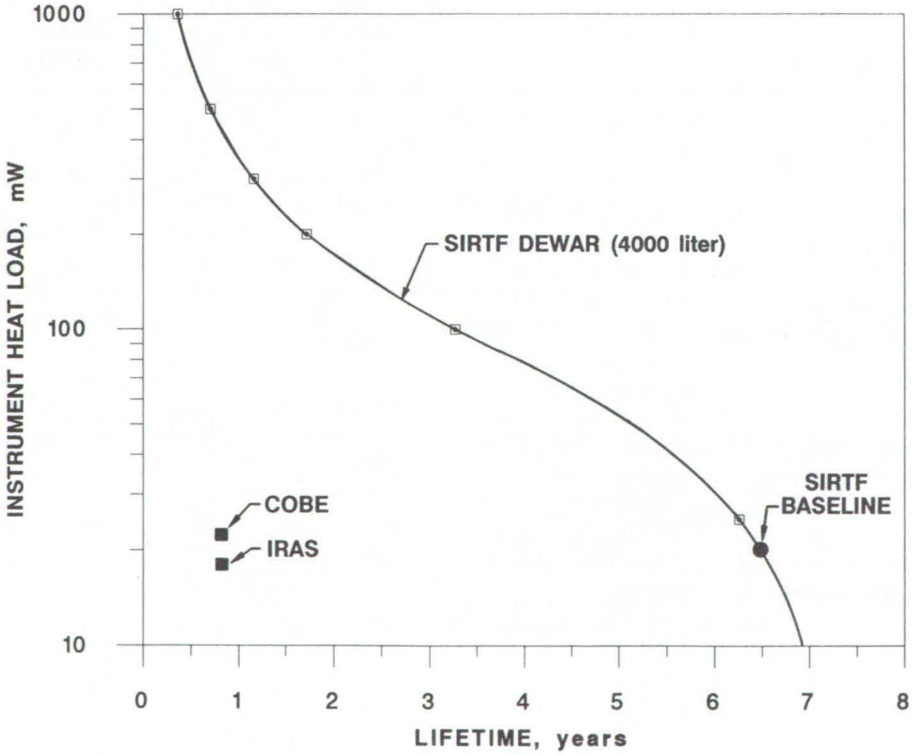

Figure 4. Plot of the instrument heat load that can be accommodated as a function of mission lifetime, assuming a 4,000 liter cryogen Dewar, as is planned for SIRTF.

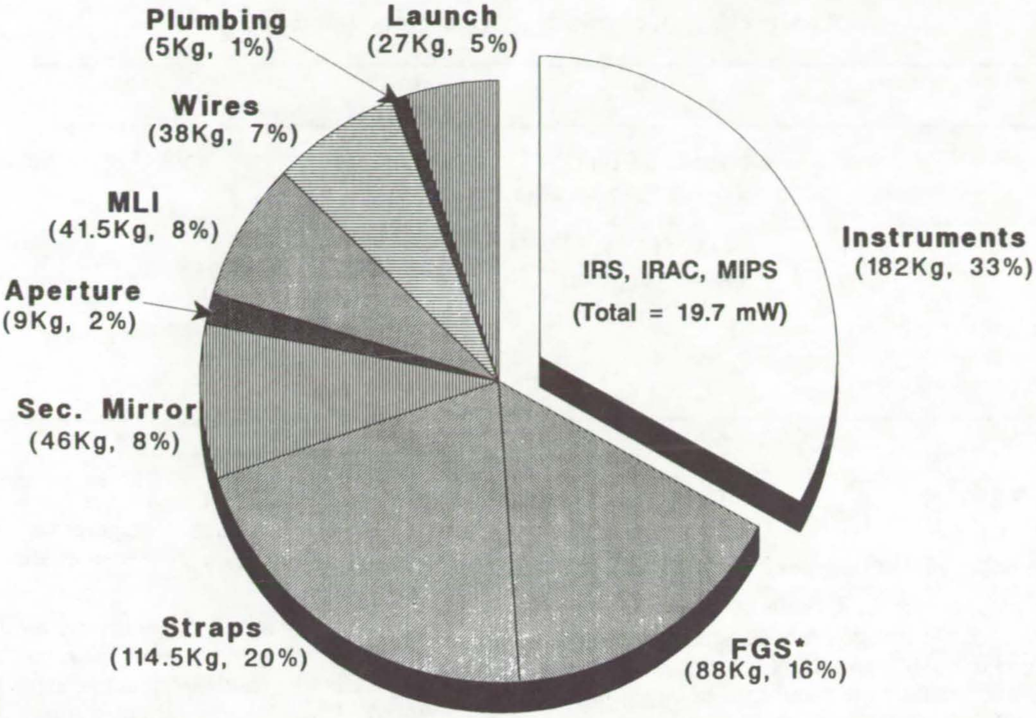

Figure 5. Breakdown of the heat load budget for a SIRTF-like mission displaying the relative contributions of different system components. FGS refers to the fine guidance system, and MLI to the multilayer insulation.

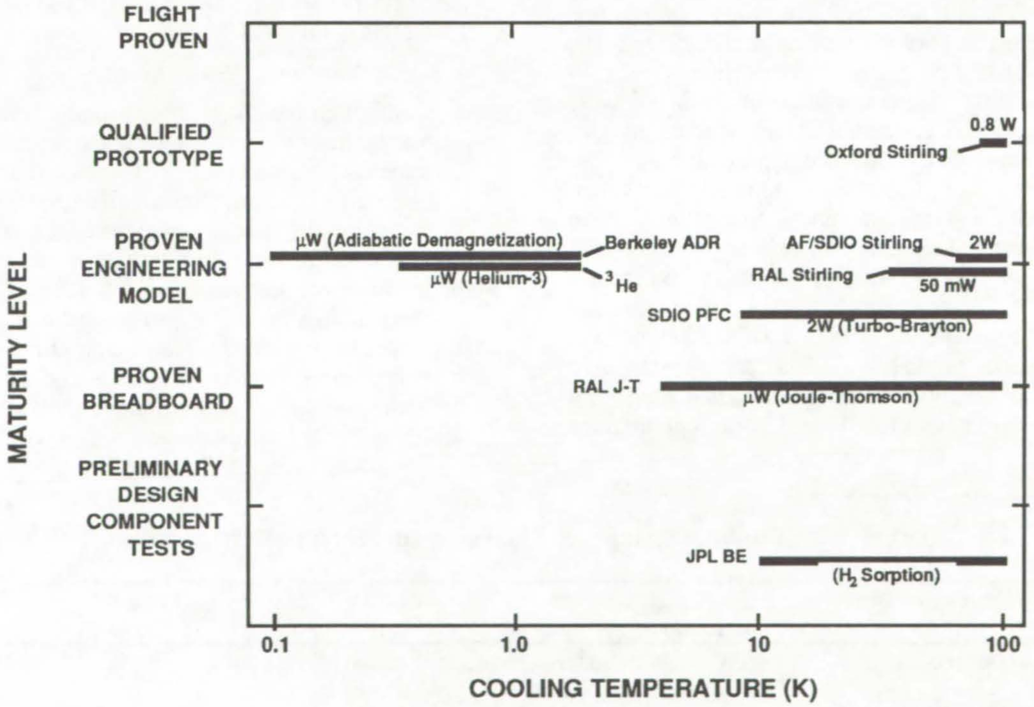

Figure 6. Maturity level of various mechanical cryocooler technologies versus their temperature range of operation.

Table IV. Mechanical Refrigerators for 2 - 5 K

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Explore multiple approaches	Prototype turbo-Brayton 2.5 W at 8.5 K 9 W at 25 K 80 W at 70 K ~ 3 kW input power	Feasibility for 2 - 5 K operation long life, low vibration	93 - 96	Several small
Develop best option(s)		10-20 mW at 2 K 50-100 mW at 4-5 K long life, low vibration	96 - 00	Large

FLIGHT TESTING OF EMERGING PROTOTYPE REFRIGERATORS

A. Technology Assessment

Because of the extreme challenges in achieving long-life mechanical refrigerators, a significant need was identified to qualify and flight test critical cooler technologies before they are committed to large high-visibility astrophysics missions that demand very low risk of failure.

B. Development Plan

To this end, it is recommended that a program of advanced development and flight testing be supported to help bridge the technology maturity gap between present cooler research activities and the demands of flight programs. As this time, 65 K low-vibration Stirling refrigerators and subkelvin adiabatic demagnetization refrigerators (ADR) are technologies in this category. The former are required for a number of missions, including the gamma-ray missions, which need low-vibration, high-capacity coolers in the 65 K temperature range. These applications will logically be met by the class of low-vibration Stirling (Fig. 7) and turbo-Brayton coolers currently under development for Eos and DOD, but not yet flight qualified. Subkelvin ADR systems are required for long-life subkelvin applications associated with the use of bolometers for IR and X-ray applications which need ~ 10 μW of cooling at 0.1 K with heat sinking at 2 K. Such refrigerators are under development (Fig. 8), but also need qualification and flight testing.

Other refrigerator technologies, as they reach this stage of development, would also greatly benefit from a pathfinder qualification and debugging phase in a low-risk (Class D) experiment setting. The panel recommends that this program be maintained at a moderate level throughout the development of new cooler capabilities required for Astrotech 21 missions, as indicated in Table V.

R&D OF PROMISING BACKUP TECHNOLOGIES

A. Technology Assessment

Although the above three program elements are necessary to achieve technology readiness for the Astrotech 21 mission set, it is not certain that they will be sufficient, and the parallel development of other promising backup technologies is strongly advised to mitigate against failure of one or more of the baseline technologies, and/or to take advantage of enabling improvements in current technologies. This is particularly relevant for large, high-visibility missions, such as many of these for astrophysics research, for which it is desirable to reduce the risk of failure to a very low level.

Table V. Flight Testing of Emerging Prototype Refrigerators

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Flight test experiments	New research-grade cooler technologies	Qualification and flight testing as Class D experiments	93 - 03	Moderate

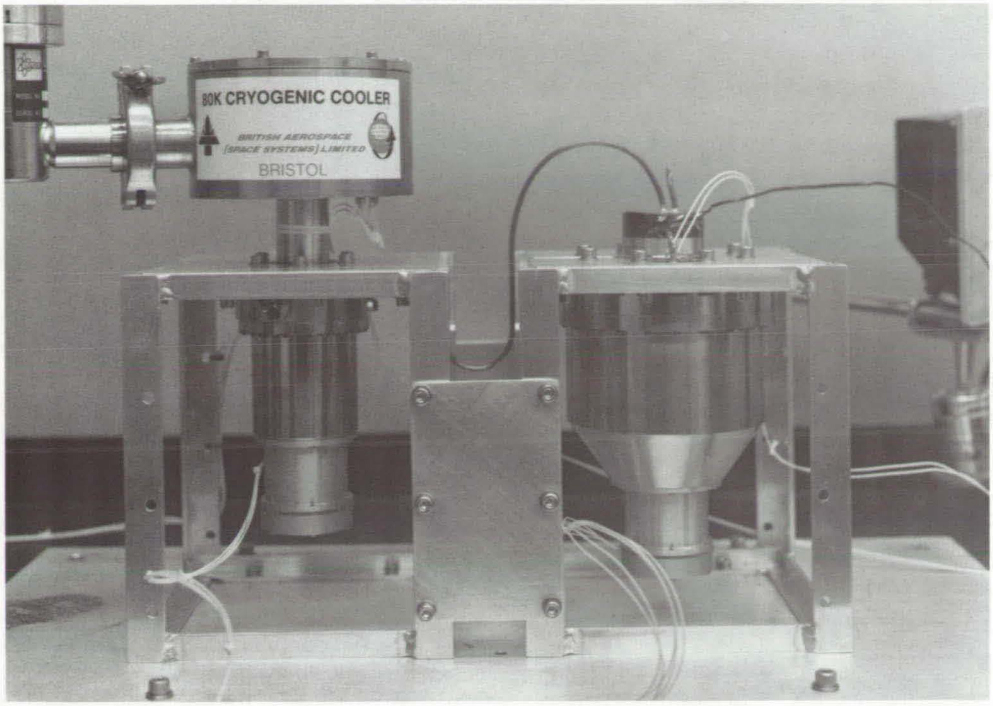

Figure 7. Photograph of 80 K Stirling Cooler developed by British Aerospace from a prototype constructed at Oxford University. This cooler is currently being evaluated by JPL for Earth Observing Systems application.

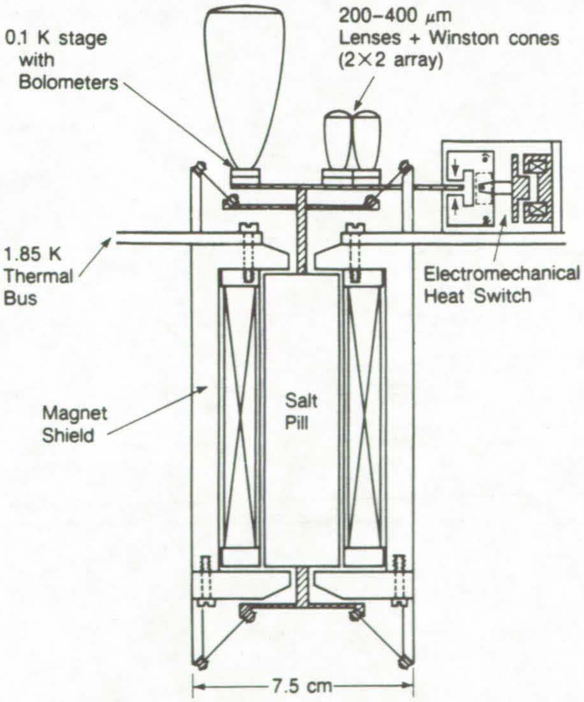

Figure 8. Schematic of prototype adiabatic demagnetization refrigerator (ADR) planned to provide subkelvin cooling for SIRTF bolometers.

B. Development Plan

With this concern in mind, the panel recommends that a program be initiated to support a number of promising backup technologies at relatively low levels. Example backup technologies that are of interest for the Astrotech 21 mission set include:

- Technologies that would significantly reduce parasitic heat loads into SFHe Dewars.
- Alternate refrigerator concepts for subkelvin cooling such as dilution and ^{3}He-^{4}He Stirling technologies.
- Alternate vibration-free cooling concepts such as lower-temperature (80-100 K) thermoelectric coolers (TEC).
- Alternate low-vibration upper-stage coolers such as pulse-tube refrigerators.

This plan is summarized in Table VI.

SUMMARY

The Sensor Cooler Technology Panel identified four major areas in which technology development must be supported in order to meet the system performance requirements for the Astrotech 21 mission set science objectives. These are, in short:

- Long-life vibration-free refrigerators
- Mechanical refrigerators for 2-5 K
- Flight testing of emerging prototype refrigerators

A development strategy and schedule were recommended for each of the four areas.

Discussions between the cooler panel and other workshop panels also brought to light additional issues which should be considered by space scientists and detector instrument designers to optimize the total system performance. There are natural break points in operating temperature for space cooler technologies, such that the arbitrary selection of a sensor temperature just below one of these points can result in significant increases in cooler power requirements and in technical complexity, with concomitant increases in demands on the mission budget and in the risk of in-flight failure. An important break point for the Astrotech 21 mission set is at around 4 K, the liquefaction temperature of He. In addition, large cooling loads can be just as demanding of cooler technology as operating temperature requirements. Consequently, there are situations where it may be worthwhile sacrificing some small amount of signal to noise, and allowing the amplifier and/or readout electronics to operate at a different (higher) temperature than required for the sensors themselves, thereby reducing the heat load at the lowest temperatures. Similarly, efforts to improve thermal isolation technology, as recommended by the Sensor Readout Electronics Panel, are also supported by this panel.

Table VI. R&D of Promising Backup Technologies

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Approaches to reduce parasitic heat load into SFHe Dewars	Concepts	Feasibility	93 - 98	Small
Subkelvin coolers such as dilution and ^{3}He-^{4}He Stirling technologies	Concepts	Feasibility	93 - 98	Small
Vibration-free approaches such as thermoelectric coolers	Concepts	Feasibility	93 - 98	Small
Low-vibration upper-stage coolers such as pulse-tube	Concepts	Feasibility	93 - 98	Small

APPENDIX A. SENSOR TECHNOLOGY WORKSHOP PANELS AND CHAIRS

X-Ray and Gamma-Ray Sensors Panel

Chair: A. Szymkowiak, *NASA Goddard Space Flight Center*

S. Collins, *Jet Propulsion Laboratory*

J. Kurfess, *Naval Research Laboratory*

W. Mahoney, *Jet Propulsion Laboratory*

D. McCammon, *University of Wisconsin - Madison*

R. Pehl, *Lawrence Berkeley Laboratory*

G. Ricker, *Massachusetts Institute of Technology*

Direct Infrared Sensors Panel

Chair: C. McCreight, *NASA Ames Research Center*

R. Bharat, *Rockwell International Science Center*

R. Capps, *Jet Propulsion Laboratory*

W. Forrest, *University of Rochester*

A. Hoffman, *Hughes SBRC*

H. Moseley, *NASA Goddard Space Flight Center*

R. McMurray, *NASA Ames Research Center*

M. Reine, *Loral Infrared and Imaging Systems*

P. Richards, *University of California, Berkeley*

D. Smith, *Los Alamos National Laboratory*

E. Young, *University of Arizona*

Sensor Readout Electronics Panel

Chair: E. Fossum, *Jet Propulsion Laboratory*

J. Carson, *Irvine Sensors*

W. Kleinhans, *Valley Oak Semiconductor*

W. Kosonocky, *New Jersey Institute of Technology*

L. Kozlowski, *Rockwell International Science Center*

A. Pecsalski, *Honeywell SRC*

A. Silver, *TRW*

A. Spieler, *Lawrence Berkeley Laboratory*

J. Woolaway, *Amber Engineering*

Ultraviolet and Visible Sensors Panel

Chair: J.G. Timothy, *Stanford University*

M. Blouke, *Tektronix, Inc.*

R. Bredthauer, *LORAL (Ford)*

R. Kimble, *NASA Goddard Space Flight Center*

T.-H. Lee, *Eastman Kodak Corporation*

M. Lesser, *Steward Observatory, University of Arizona*

O. Siegmund, *University of California, Berkeley*

G. Weckler, *EG&G Solid-State Products Group*

Heterodyne Submm-Wave Sensors Panel

Chair: R. Wilson, *AT&T Bell Laboratories, Crawford Hill*

G. Chin, *NASA Goddard Space Flight Center*

T. Crowe, *University of Virginia*

M. Feldman, *University of Rochester*

M. Frerking, *Jet Propulsion Laboratory*

E. Kolberg, *California Institute of Technology*

H. LeDuc, *Jet Propulsion Laboratory*

T. Phillips, *California Institute of Technology*

F. Ulaby, *University of Michigan Center for Space Terahertz Technology*

W. Wilson, *Jet Propulsion Laboratory*

J. Zmuidzinas, *California Institute of Technology*

Sensor Cooler Technology Panel

Chair: R. Ross, *Jet Propulsion Laboratory*

S. Castles, *NASA Goddard Space Flight Center*

N. Gautier, *California Institute of Technology*

P. Kittel, *NASA Ames Research Center*

J. Ludwigsen, *Nichols Research (SDIO)*

APPENDIX B. ACRONYMS AND ABBREVIATIONS

The following tables are provided of all the acronyms and abbreviations utilized in the text of this Proceedings.

Space missions and instruments are listed in Table I, all other acronyms and abbreviations in Table II.

TABLE I. SPACE MISSIONS AND INSTRUMENTS

ACT	Advanced Compton Telescope (balloon instrument)
AIM	Astrometric Interferometer Mission
AXAF	Advanced X-Ray Astrophysics Facility
COBE	Cosmic Background Explorer
EGRET	Energetic Gamma-Ray Experiment Telescope (GRO instrument)
EUVE	Extreme Ultraviolet Explorer
FUSE	Far Ultraviolet Spectroscopic Explorer
GP-B	Gravity Probe-B
GRO	Gamma Ray Observatory
GRSO	Gamma-Ray Spectroscopy Observatory
HEAO	High Energy Astronomy Observatory
HST	Hubble Space Telescope
HXIF	Hard X-Ray Imaging Facility
Imag. Int.	Imaging Optical Interferometer
IPC	Imaging Proportional Counter (HEAO II instrument)
IRAC	Infrared Array Camera (SIRTF instrument)
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrograph (SIRTF instrument)
LAGOS	Laser Gravity-Wave Observatory in Space
LDR	Large Deployable Deflector
LTT	Lunar Transit Telescope
MIPS	Multiband Imaging Photometer for SIRTF (SIRTF instrument)
NAE	Nuclear Astrophysics Experiment
NGIR	Next Generation Infrared Mission
NICMOS	Near Infrared Camera & Multi-Object Spectrometer (HST II instrument)
NIMS	Near Infrared Mapping Spectrometer (Galileo instrument)
NGOVLBI	Next Generation Orbiting Very Long Baseline Interferometer
NGST	Next Generation Space Telescope
ORI	Orbital Replacement Instrument (HST refurbishment instrument)
OVLBI	Orbiting Very Long Baseline Interferometry
Radioastron	Soviet OVLBI mission
SIRTF	Space Infrared Telescope Facility
SMMI	Submillimeter Interferometer
SMIM	Submillimeter Intermediate Mission
SOFIA	Stratospheric Observatory for Infrared Astronomy
STIS	Space Telescope Imaging Spectrograph (HST II instrument)
SWAS	Submillimeter Wave Astronomy Satellite
VHTF	Very High Throughput Facility
VSOP	Japanese OVLBI mission
WF/PC	Wide-Field and Planetary Camera (HST instrument)
XST	X-Ray Schmidt Telescope

APPENDIX B. ACRONYMS AND ABBREVIATIONS (Continued)

TABLE II. OTHER ACRONYMS AND ABBREVIATIONS

1/f noise	Fundamental noise with inverse frequency dependence
1D	One dimensional (array)
2D	Two dimensional (array)
3D	Three dimensional (2D spatial array+ energy resolution)
A/D	Analog-to-digital converter
ADR	Adiabatic demagnetization refrigerator
AGN	Active galactic nuclei
AOS	Acousto-optic spectrometer
AT	Advanced technology
BAe	British Aerospace
BIB	Blocked impurity band (same as IBC)
BLIP	Background-limited performance
BW	Bandwidth
BWO	Backward-wave oscillator
CCD	Charge-coupled device
CHIGFET	Complementary heterojunction insulated-gate FET
CID	Charge-injection device
COP	Coefficient of performance
CSTI	Civil Space Technology Initiative (NASA)
CTE	Charge transfer efficiency (CCD readout)
CTIA	Capacitive trans-impedance amplifier
D*	Detectivity
DoD	Department of Defense (US)
demo.	Demonstration
e^-	electron
E	Energy
$E/\Delta E$	Energy resolution
EMI	Electromagnetic interference
E res.	Energy resolution
EO	Earth orbit
EO/Mn	Earth orbit or Moon
EUV	Extreme ultraviolet
f	frequency
FET	Field-effect transistor
FGS	Fine guidance system
FPA	Focal-plane array
h	Planck's constant
HEMT	High-electron-mobility transistor
HIP	Heterojunction internal photoemission
HQ	Headquarters
HTS	High-temperature superconductor
hν/k	Quantum limit for mixer sensitivity
IBC	Impurity band conduction (same as BIB)
IF	Intermediate frequency (mixer output signal)
IR	Infrared
JFET	Junction field-effect transistor
J-T	Joule-Thomson (refrigerator)
k	Thousand, or Boltzmann constant
kTC noise	Noise associated with reset through capacitor, C
LB	Low background
LHe	Liquid helium
LN2	Liquid nitrogen
LO	Local oscillator
LWIR	Long-wavelength infrared
M	Million
MAMA	Multi-anode microchannel array
MB	Moderate background
MCP	Microchannel plate
MLI	Multilayer insulation
MODIL	Manufacturing Operations, Development and Integration Laboratory (SDIO)
MOS	Metal-oxide-semiconductor
MUX	Multiplexer

APPENDIX B. ACRONYMS AND ABBREVIATIONS (Continued)

TABLE II. OTHER ACRONYMS AND ABBREVIATIONS (Continued)

NEP	Noise-equivalent power
OAET	Office of Aeronautics, Exploration and Technology (NASA Headquarters)
PMT	Photomultiplier tube
preamp.	preamplifier
osc.	Oscillator
OSSA	Office of Space Science and Applications (NASA HQ)
PC	Photoconductive
PMOS	P-type metal-oxide-semiconductor
PMT	Photomultiplier tube
pos. res.	Position resolution
PC	Photoconductive
PV	Photovoltaic
QE	Quantum efficiency
QW	Quantum well
QWIP	Quantum-well infrared photodetector
req.	Requirement
res.	Resolution
Rm. T	Room temperature
SBD	Schottky barrier device
SBRC	Santa Barbara Research Center (Hughes)
SDI	(Or SDIO) Strategic Defense Initiative Organization
semicond.	Semiconductor
SFHe	Superfluid helium
SIN	Superconductor-insulator-normal metal
SIS	Superconductcor-insulator-superconductor
SQUID	Superconducting quantum interference device
SSPM	Solid-state photomultiplier
STIS	Space Telescope Imaging Spectrograph (HST instrument)
submm	Submillimeter
supercond.	Superconductor
SWIR	Short-wavelength infrared
T_c	Critical temperature (superconducting transition temperature)
TEC	Thermoelectric cooler
TIA	Trans-impedance amplifier
UV	Ultraviolet
u-v plane	telescope pupil (aperture) plane
VLBI	Very long baseline interferometer
VLSI	Very large scale integrated circuits
VLWIR	Very long wavelength infrared

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16. Abstract In 1989, the Astrophysics Division of the Office of Space Science & Applications initiated the planning of a technology development program, Astrotech 21, to develop the technological base for the Astrophysics missions developed in the period 1995-2015. 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 & Technology Requirements; and Integrated Technology Planning. Traceability of technology plans & recommendations to missions requirements and impacts was emphasized. However, "breakthrough technologies", whose ultimate applications cannot be anticipated, were also considered. Proceedings documents are published for each workshop. A summary report has also been prepared which synthesizes the results of the planning effort. The Sensor Systems 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 electromagnetic radiation sensor 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 sensor technology. Program plans and recommendations were prepared in four areas: X-Ray and Gamma Ray Sensors, Ultraviolet and Visible Sensors, Direct Infrared Sensors, and Heterodyne Submillimeter-Wave Sensors.

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