N92-22617

Report of the Direct Infrared Sensors Panel

Craig McCreight, Panel Chair
NASA Ames Research Center

Members of the Direct Infrared Sensors Panel:
R. Bharat, *Rockwell International*
R. Capps, *Jet Propulsion Laboratory*
W. Forrest, *University of Rochester*
A. Hoffman, *Hughes Santa Barbara Research Center*
C. McCreight, *NASA Ames Research Center*
R. McMurray, *NASA Ames Research Center*
H. Moseley, *NASA Goddard Space Flight Center*
M. Reine, *Loral Infrared Imaging Systems*
P. Richards, *University of California, Berkeley*
D. Smith, *Los Alamos National Laboratory*
E. Young, *University of Arizona*

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

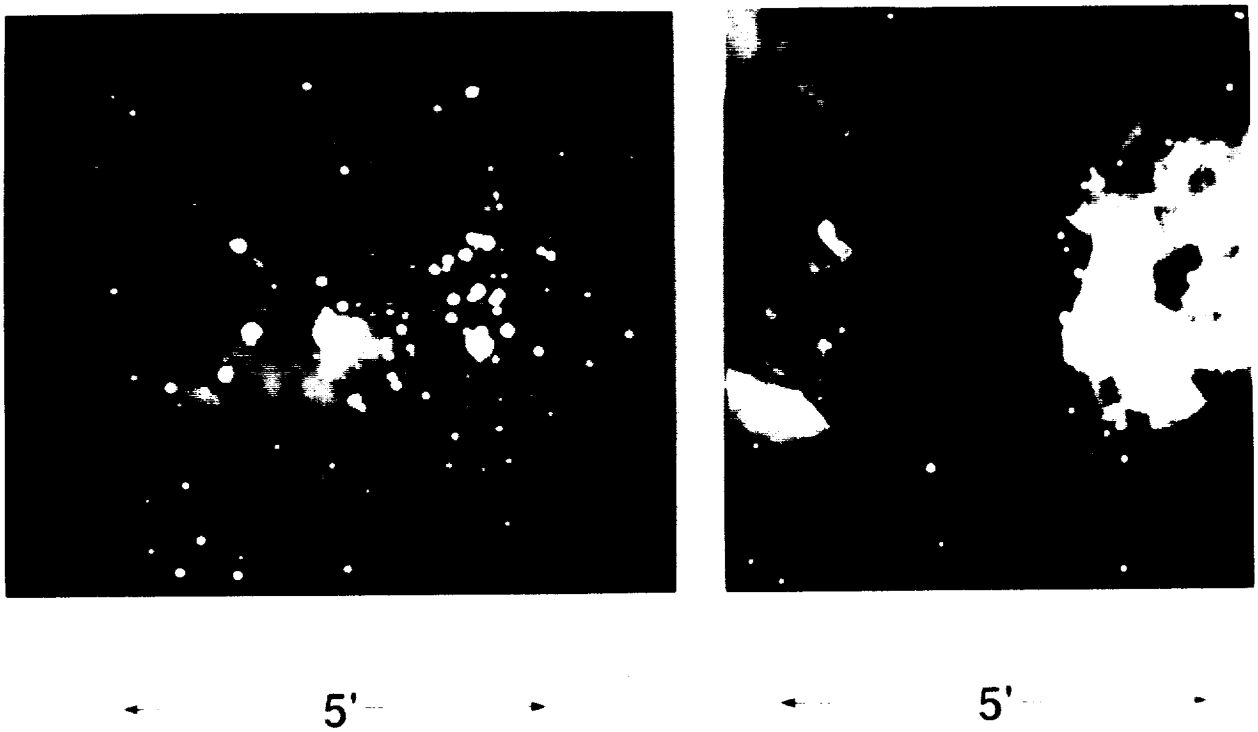

Figure 1. Infrared (left) and visible (right) images of star-forming region NGC 2024. Dust clouds which obscure much of the detail in the visible image are transparent to longer wavelength radiation. This comparison illustrates the wealth of information which will become available with the development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

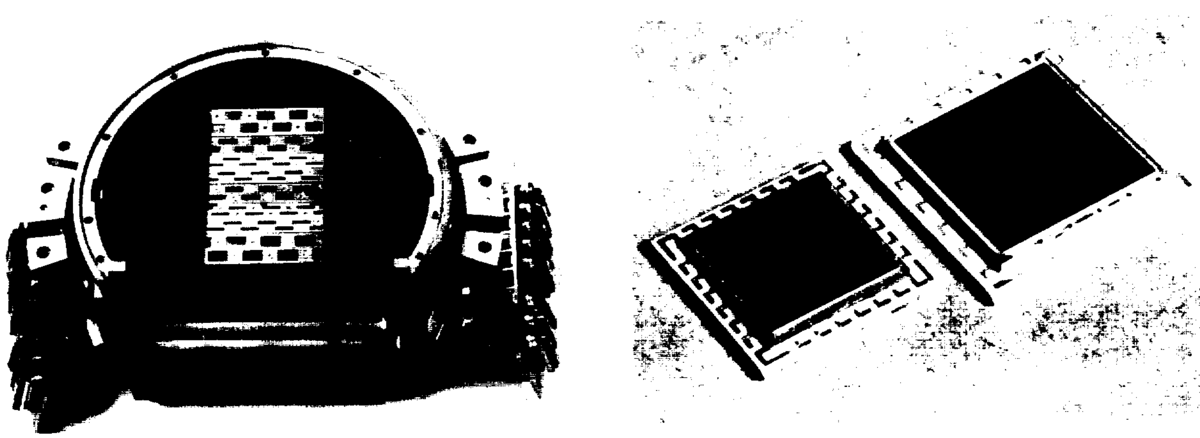

Figure 2.
Left: Array of discrete detectors used in the IRAS mission. Right: State-of-the-art IR array demonstrating recent advances in two-dimensional array technology.

(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 Launch Date	IRAS 1983	N/A	SIRTF / IRS, IRAC ~ 2000	Imag. Int. / NGST ~ 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 Spectral Range (μm)	~ 10% & 24% 8-15 & 15-30	~ 40% 5 - 28	~ 40% 5 - 40	~ 70 % 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 Launch Date	IRAS 1983	N/A	SIRTF / IRS & MIPS ~ 2000	LDR ~ 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 Spectral Range (μm)	7% & 5% 40 - 120	≥ 10% 40 - 200	≥ 10% 40 - 200	> 40 % 40 - 250
NEP (W/√Hz)	1×10^{16} & 6×10^{1}	$\sim 2 \times 10^{-18}$ (in 1 sec)	$\leq 2 \times 10^{-18}$ (in 1 sec)	$\leq 2 \times 10^{-19}$ (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 ($W/\sqrt{Hz}$)	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 ($\lambda < 30\ \mu m$), 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
1-5μm 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 Monolithic arrays Non-Si readouts	Si maturity No thermal mismatch Some radiation hardness	Onset of freeze-out Processing maturity Maturity	MB
30-120 μm Ge:x PC 3x32	> 30 μm Ge:x arrays	Stacked Si MOS, cascode or source-follower circuits Planar Si readouts for Ge BIB	Si maturity, SIRTF heritage Packaging simplicity	Requires very low operating temperature Requires very low operating temperature	LB, MB, SMMM
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.) Si bolometer arrays	SQUID amplifier advancements AXAF heritage	Still at idea stage FET coupling	LB, MB, SMMM

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 ($\leq$1 nv/$\sqrt{\text{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.