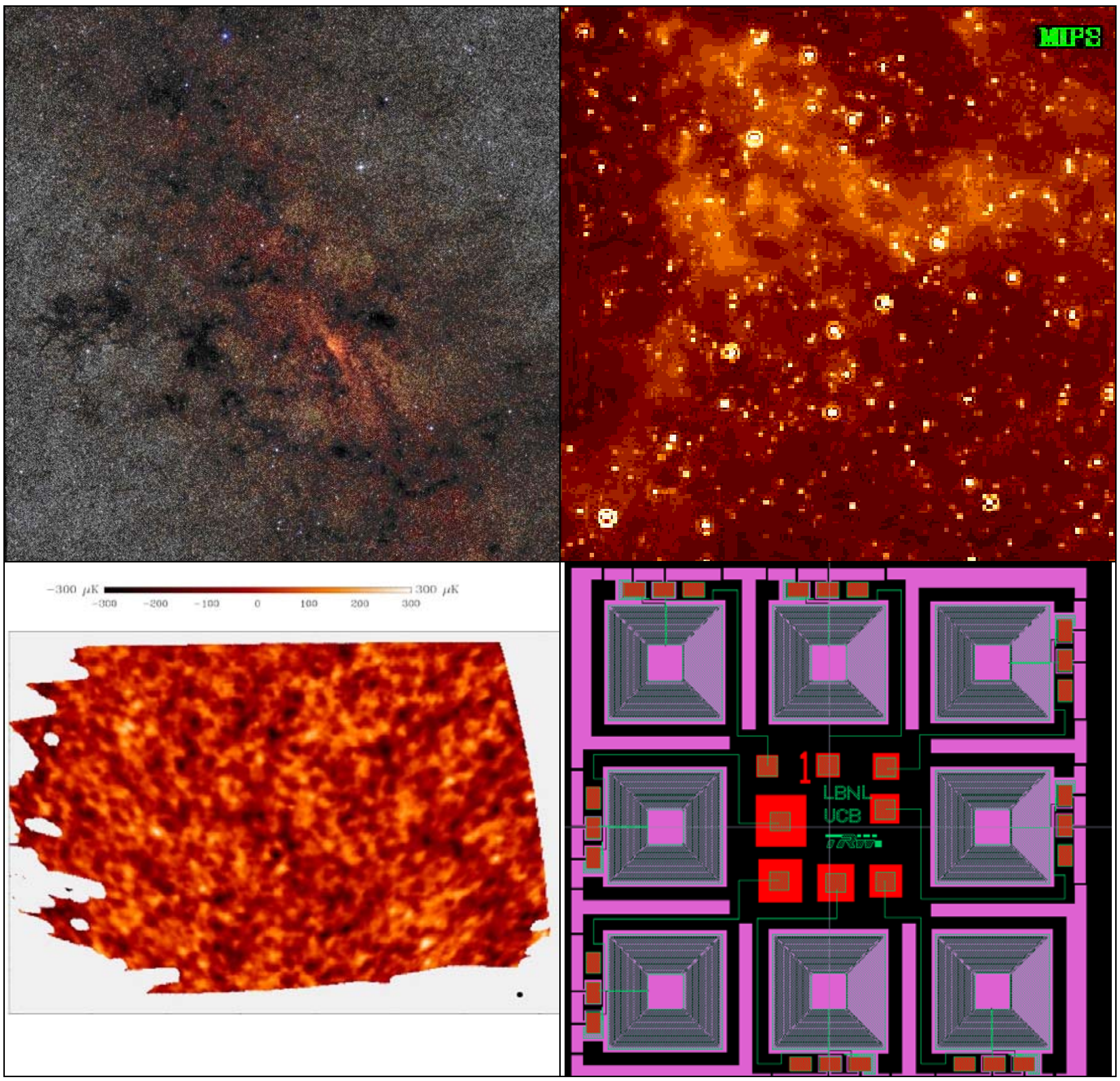
Detector Needs for Long Wavelength Astrophysics



A Report by the Infrared, Submillimeter, and Millimeter Detector Working Group

June 2002

Infrared, Submillimeter, Millimeter Detector Working Group

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Front Cover Figure Captions: (Upper Left) Simulated map of the sky observed with 1024-pixel 70 μm camera on the Multiband Imaging Photometer for SIRTF [C. Engelbracht]; (Upper Right) Galactic Center region observed with the 2MASS Survey; (Lower Left) Cosmic Microwave Background temperature fluctuations observed with the BOOMERANG instrument [A. Lange]; (Lower Right) Eight-channel superconducting frequency domain multiplexer for Transition Edge Bolometers. The chip is 1 x 1 cm in size. [A. Lee].

Executive Summary

Observations at infrared, submillimeter, and millimeter wavelengths will be essential for addressing many of the key questions in astrophysics. Because of the very wide wavelength coverage, a variety of detector types will be required to satisfy these needs. To enable and to take full advantage of the opportunities presented by the future mission concepts under consideration, a significant and diverse effort in developing detector technologies will be needed.

The Infrared, Submillimeter, and Millimeter Detector Working Group (ISMDWG) finds that the development of very large (10^3 – 10^4 pixels) arrays of direct detectors for far-infrared to millimeter wavelengths to be the most important need. Several technologies should be explored, including impurity band photoconductors and TES bolometers, with the emphasis on producing complete systems.

As detector systems become larger, more complex, and more expensive, the available mechanisms for supporting development from proof of concept to flight worthy technology are limited. We encourage NASA to develop the resources to support this type of engineering. As part of this finding, we stress the importance of maintaining key infrastructure elements in the research community.

For coherent systems, the greatest need is improvement in sensitivity between 1 – 3 THz (λ = 300 – 100 μm). Additionally, development in other system components such as local oscillators will be needed. The development of arrays of coherent receivers will greatly increase mapping speed.

Readout technology is an essential element in both photon and bolometer systems. The continued development of SQUID (Superconducting Quantum Interference Device) amplifiers and multiplexers will be key to the production of very large format bolometer arrays. Cryogenic silicon integrated circuit readout technology is crucial to photoconductive infrared and submillimeter detectors, and maintenance of the design and fabrication capabilities is important.

Si:Sb Blocked Impurity Band detectors are a unique NASA developed technology, and they provide the highest performance in the 28-40 μm wavelength range. Continued maintenance of this capability is critical to science in this wavelength band.

Surplus detectors from major missions should be made available on a competed basis to the scientific community for use in other NASA flight programs, SOFIA instruments, ground-based instrumentation, and laboratory testing. We also endorse an examination of the spares philosophy on major missions with the goal of maximum scientific return throughout OSS.

Maintaining technology requires the continued support of NASA, industrial, and university laboratories. Support of key detector technologies requires consistent management oversight that looks at the long-term goals to insure continuity of effort. Continuity and stability of funding is essential to insuring the availability of detectors for future missions.

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I Introduction

a) Charge of the Working Group

The Infrared, Submillimeter, and Millimeter Detector Working Group (ISMDWG) was chartered by the Astronomy and Physics Division of NASA's Office of Space Science (OSS) to produce a roadmap of sensor developments needed to attain the scientific goals of missions defined in the roadmaps for the Astronomical Search for Origins (ASO) and Structure and Evolution of the Universe (SEU) Themes.

The charge of the ISMDWG includes:

1. Enumeration of the requirements for IR, Sub-mm, and millimeter wave detectors associated with the goals of the Theme roadmaps and the Decadal Survey.
2. Evaluation of the compatibility of existing detector technology with the foreseen missions.
3. Assessment of the current capabilities for design, fabrication, and testing of IR, Sub-mm, and millimeter detectors and associated readout technologies in the U.S. and abroad.
4. Assessment of the current state of IR, Sub-mm, and millimeter detector technology research and development.

On the basis of this assessment of the current state of IR/Sub-mm detector technology, the ISMDWG should outline a Research Roadmap for detector development in the near term and the long term based on NASA OSS mission needs. The immediate application of this report is to provide input to the strategic planning activities for the Origins and SEU Themes. Additionally, the report will be made available to the scientific community to guide investigators to NASA's strategic needs.

The ISMDWG is chaired by Erick Young (University of Arizona). Because of the breath of technologies encompassed under the charter, the Working Group is organized into three subgroups:

1. 1 – 40 μm Detectors: Craig McCreight (Ames Research Center, Subgroup Chair), Terry Herter (Cornell), and Ian McLean (UCLA);
2. Long Wavelength Direct Detectors: Paul Richards (UC Berkeley, Subgroup Chair), Andrew Lange (Caltech), Harvey Moseley (Goddard Space Flight Center), and Erick Young (University of Arizona);
3. Coherent Detectors: Charles Lawrence (JPL, Subgroup Chair), John Carlstrom (Chicago), William Danchi (Goddard Space Flight Center), and Jonas Zmuidzinas (Caltech)

Additional members of the Working Group are Jay Frogel (NASA Headquarters), Eric Smith (NASA Headquarters), and Guy Stringfellow (University of Colorado).

Significant input to the Working Group came from two workshops held in early 2002. The *Second Workshop on New Concepts for Far-IR Submillimeter Space Astronomy* was held at the University of Maryland on March 7-8, 2002. It focused on the science goals, mission concepts, and enabling technologies for space observatories that will operate between 20-800 µm. The *Far-IR, Sub-MM, and MM Detector Technology Workshop* was held in Monterey California on April 1-3, 2002. It highlighted both direct and coherent detector technology for space missions. Additional input from the community came in the form of town hall meetings held in conjunction with the AAS Meeting at Washington, DC in January 2002 and the Monterey Detector Technology Workshop, as well as site visits to GSFC, JPL, and a number of detector vendors.

b) NASA Strategic Planning Process

In the Office of Space Science, the strategic planning process fulfills a number of different purposes. Most importantly, the planning process allows the OSS to develop a consensus on the long range goals of the organization and to focus investments in technology and research for future missions. It provides a guide to the science community in presenting research requests to NASA. Finally, the plan provides the scientific and technical justification for augmentation requests. The Strategic Plans are developed with input from a number of sources, as is depicted in Figure 1-1. Most important is the flow down from fundamental questions identified by the scientific community, with the most prominent input being the National Academy Decadal Survey.

Additionally, the Committee on the Physics of the Universe has recently released a report on the scientific opportunities at the interface between physics and astronomy. The Astronomy and Physics Division of the OSS is preparing roadmaps for both the SEU and ASO Themes under the sponsorship of the SEU and the Origins Subcommittees. These plans feed into the development of the overall strategic plan for the Space Science Enterprise (SSE). The goal of the roadmapping effort is to produce a plan that addresses the 10 to 20 year timescale.

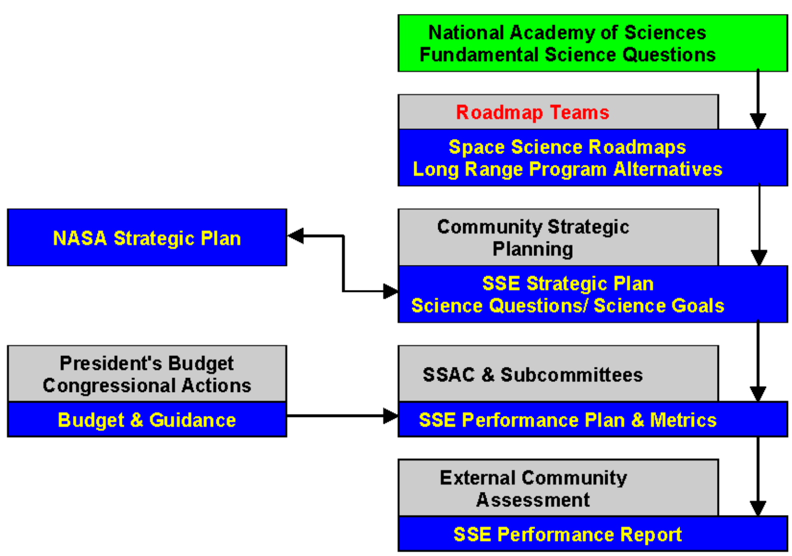

Figure 1-1. The OSS Strategic Planning Process

c) General Considerations

The charge of the Working Group covers a phenomenal four decades of wavelengths from 1 μm to 10 mm. No single detector technology is suitable for the entire range, and diverse physical detection mechanisms are required. Based on the technologies involved, it proved to be natural to divide the landscape into three subgroups.

In the 1 – 40 μm range, large format, hybrid detector arrays are available utilizing a number of detector materials including InSb, HgCdTe, and doped silicon. Generally, the technology involves a two-dimensional pixel array of photon detectors that is attached to a matching silicon readout integrated circuit. This hybrid technology is generally well advanced, and high performance detector arrays are available in formats as large as 2048 x 2048 pixels.

Beyond 40 μm, both photon and thermal detectors are used. Photon detectors directly convert incoming light directly into electronic carriers that are then measured. The most prevalent long wavelength photon detectors use doped germanium in the photoconductive mode. Recent work on other materials systems such as extrinsic germanium or GaAs impurity band conduction detectors has shown promise. Thermal detectors, in contrast, convert the photon energy into heat that raises the temperature of the sensing element. Some form of thermometer is then required to measure this temperature rise. Detectors of exquisite sensitivity have been built using advanced technologies such as semiconducting thermistors or superconducting Transition Edge Sensors (TES). For both long wavelength photon and thermal detectors, the construction of large arrays of detectors is a major challenge.

Coherent detector systems amplify the incoming photon stream, preserving both phase and amplitude information. Consequently, coherent detectors are subject to a quantum mechanical noise limit [see Section III-b]. The signals are often downconverted in frequency prior to detection, and they have proven particularly useful in applications that require very high spectral resolution. The main technical challenges in coherent detectors are the need to improve sensitivities at higher frequencies, the need for improved local oscillators, and the desire for large arrays of receivers.

An absolutely key point about the detector technologies beyond ~30 μm is the minimal commercial or military support for development. Historically, it has been astronomers who have been responsible for the advances in the technology. Without the support of NASA, particularly in the steps to take a technology from "promising" to "useful", much of this wavelength range would be unreachable. Even at wavelengths shorter than 30 μm, where an industrial base has been established for IR astronomical detector technology, this base is very fragile. Without sustained support, this base may disappear, and high performance detectors will no longer be available.

Clearly the emphasis of the Decadal Report and the Roadmaps is on the large, "strategic" space missions. Other important opportunities exist. The long lifetime of the Stratospheric Observatory for Infrared Astronomy (SOFIA) will allow the airborne observatory to take great advantage of advances in detector technology. It is also important to remember that the development of new detector technologies often enables highly productive, smaller space investigations.

II Science Motivation

For a number of fundamental reasons, observations at infrared, submillimeter, and millimeter wavelengths are essential to the understanding of diverse astrophysical phenomena. In this section we describe three representative investigations that sample the range of infrared, submillimeter, and millimeter science. The three areas, the cosmic microwave background, the formation and evolution of galaxies, and the formation of stars, address some of the most important questions in contemporary astrophysics. For this report, these examples also serve the important role of helping to identify the key measurement capabilities that will be needed. How these measurement capabilities translate into specific detector requirements will be summarized in Section III and discussed in detail in Section IV.

The astronomical community has devoted significant thought to prioritizing future investments in observing capabilities, and we follow the lead set by the Decadal Survey (2001), the Committee on Physics of the Universe (2002), as well as the Origins and SEU Roadmaps in identifying specific mission concepts. Some of these missions concepts such as the Single Aperture Far Infrared telescope (SAFIR, also known as the Filled Aperture Infrared telescope, FAIR) and the Cosmic Microwave Background Polarization mission (CMBPol) have been identified in the OSS Strategic Plan as potential missions beyond 2007, but they are not yet part of the approved NASA program. The IRDWG has, nevertheless, found it useful to use these concepts to help define the directions that astronomy will be going at these wavelengths, understanding that details of the implementations will certainly change as the mission ideas develop.

a) CMB Science and Mission

The Cosmic Microwave Background radiation (CMB) is the oldest electromagnetic radiation in the universe. Observations of the CMB give a detailed picture of the universe 300,000 years after the Big Bang, and they are one of the pillars of Big Bang cosmology. The smoothness of this radiation supports the idea of an inflationary expansion of the universe at an early epoch. The black body spectrum measured by the Far Infrared Absolute Spectrometer (FIRAS) on the Cosmic Background Explorer (COBE) constrains energy release in the universe back to about two months after the Big Bang. Angular fluctuations in the CMB provide an ancient record of the interaction between matter and radiation in the early universe. The COBE Diffuse Microwave Radiometer (DMR) first measured the primordial temperature fluctuations remaining after inflation at a level of 30 μK. Recent ground and balloon based measurements of the small-scale temperature anisotropy have confirmed the 30 year old prediction that acoustic waves modify these fluctuations and play an important role in the formation of structure. The observed angular power spectrum of these fluctuations provides constraints on the contents of the universe, and it shows that the universe is flat. These results are consistent with the picture that ordinary baryonic matter makes up only ~5% of the universe and that dark matter is ~25% and dark energy ~70%. Figure 2-1 (Hu and Dodelson, 2002) shows the results for a theoretical calculation of the temperature and polarization spectra for plausible cosmological parameters. The anticipated **statistical** uncertainties for Planck are also shown. The Microwave Anisotropy Probe (MAP) and Planck will test these results with exquisite precision, provide accurate values of nearly all important cosmological parameters, and begin the exploration of the polarization anisotropy of the CMB.

Observations of the polarization characteristics of the CMB have the potential to provide a vision of the universe near the instant of its birth. Some mechanisms for polarization, such as scattering from density fluctuations, produce so-called E-mode polarization, which has no curl-like component. E-mode polarization will be measured over limited sky regions by ground based and balloon borne experiments, and it will be statistically characterized over the entire sky by MAP, and especially the Planck mission. Gravitational waves created in the earliest phase of an inflationary universe imprint a different and distinctive polarization pattern on the CMB radiation. The polarization field arising from tensor gravitational waves has a curl-like component and is called B-mode polarization. The detection of B-mode polarization would be a great triumph for inflationary cosmology, providing us a picture of physical processes in the universe 10^{-34} seconds after the Big Bang. Since the inflationary models are dependent on the details of particle physics, this measurement would allow us to probe particle physics at the Grand Unified Theory (GUT) energy scale, which is unreachable by any conceivable Earth-bound accelerator. Its absence would still constrain the energy for inflation or support

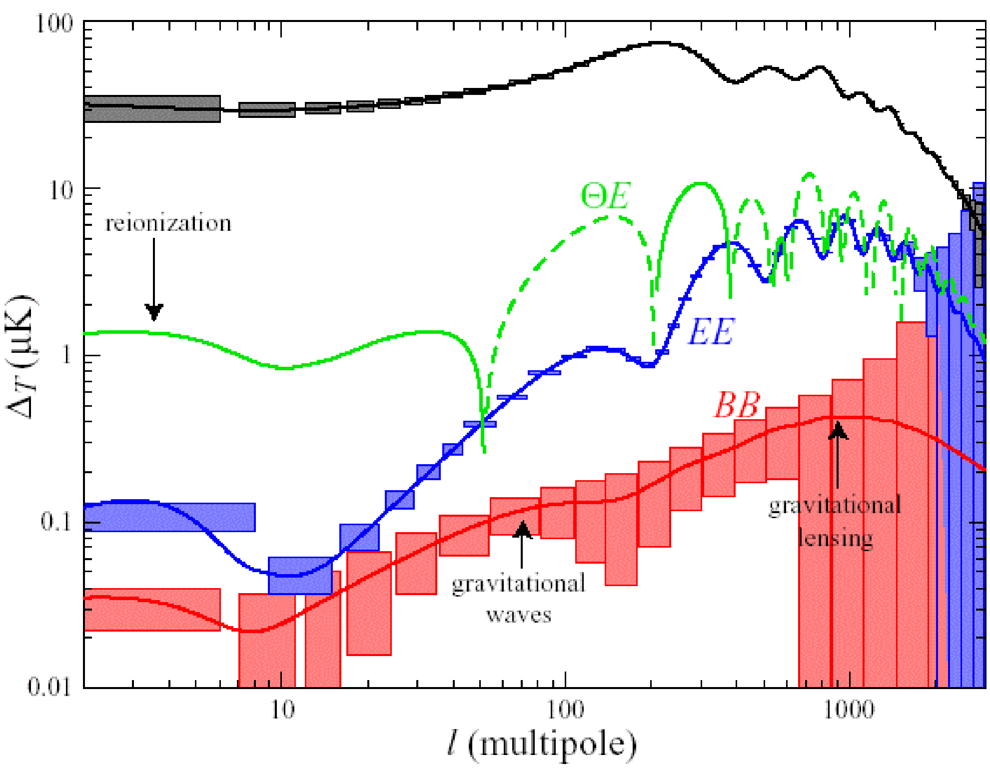

Figure 2-1 Temperature (black), E-mode polarization (blue) and B-mode polarization (red) spectra for $\Omega_{tot} = 1$, $\Omega_\Lambda = 2/3$, $\Omega_b h^2 = 0.02$, $\Omega_m h^2 = 0.16$, $n = 1$, $z_{ri} = 7$, $E_i = 2.2 \times 10^{16}$ GeV. Dashed lines represent negative crosscorrelation and boxes represent the statistical errors of the Planck satellite. From Hu and Dodelson (2002).

alternative Big Bang models. The measurement of CMB polarization with the goal of detecting the signature of inflation has been strongly endorsed by the Committee on Physics of the Universe (2002).

A deep probe of the polarization of the CMB will yield additional important results. Weak lensing by the intervening matter influences both the E and B-mode polarization fields. Lensing dominates the B-mode field for multipoles > 100. Correlation of the E and B-mode fields can provide an accurate map of the mass distribution in the early universe out to multipoles of ~ 1000, which extends the range of estimates based on temperature alone by an order of magnitude.

The CMB community is developing a mission concept that has the objective of measuring the B-mode polarization predicted from GUT-level inflation. The detector requirements for such a mission can be estimated from the predicted signal strength which, assuming reasonable cosmological parameters, is thought to be ~ 300 times smaller than the temperature anisotropy. Additionally, many measurement issues including angular scale, sky coverage, subtraction of polarized foregrounds, multipole-space coverage, and especially control of systematic errors will need to be considered in the mission development. A noise floor at least two orders of magnitude below that for Planck may be required. Since fundamental limits restrict improvements in individual detectors to factors of 2, or 3, the square of the remaining factor must be obtained from some combination of the number of detectors and the observing time. The need for high performance polarimetry with arrays of $> 10^3$ detectors in each of many wavelength bands is inescapable.

Table 2-1 Detector Needs for CMB Investigation

Science Investigation	Measurement Capability	Detector Requirements
Physics at GUT Energies	CMB B-Mode Polarization	Arrays of $>10^3$ Detectors in a High Performance Polarimeter

b) Formation and Evolution of Galaxies

Understanding the formation and evolution of galaxies is a key goal for astrophysics and cosmology. It has only recently become widely recognized that far-IR and submillimeter observations will be essential for this task. The first clue that this might be the case was given by the Infrared Astronomical Satellite (IRAS), which detected numerous infrared-luminous galaxies in the local universe. Figure 2-2 shows the spectrum of a local star-burst galaxy Arp 220. IRAS showed that over 90% of the energy in this galaxy is emitted at far-IR wavelengths by warm dust, with a spectrum peaking at ~60 μm. This behavior is not unusual: most of the energy of nearby galaxies undergoing active star formation emerges in the far-infrared part spectrum.

COBE showed that the far-IR/sub-mm bands are of cosmological importance, through the detection of a Far-IR Background (FIRB). This background is thought to be the unresolved emission from numerous high-redshift galaxies with spectra similar to Arp 220. At high redshifts, the 60 μm peak seen in Arp 220 would be shifted to submillimeter wavelengths (see Fig. 2-2). The energy of the FIRB is substantial, equal to that contained in the optical/near-IR band. The ISOPHOT instrument on the Infrared Space Observatory (ISO) and the Submillimetre Common-User Bolometer Array (SCUBA) instrument operating on the James Clerk Maxwell Telescope (JCMT) have detected the most luminous of the galaxies contributing to the COBE FIRB; however, these sources only account for a small fraction of the FIRB.

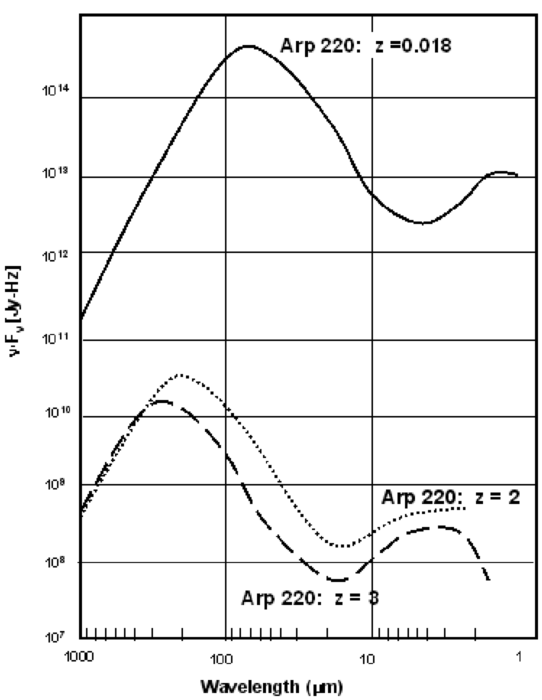

Figure 2-2. Spectral Energy Distribution (SED) of galaxy Arp 220 (solid curve) and the SED redshifted to z = 2 and 3. More than 90% of the energy emerges at far-infrared and submillimeter wavelengths.

Resolving and determining the nature of the FIRB is essential to understanding how galaxies form and evolve. Observations with the Space Infrared Telescope Facility (SIRTF) will make a significant impact in this area, but this investigation will ultimately require far-infrared and submillimeter measurements with much greater sensitivity and angular resolution than will be available with any combination of SIRTF, SOFIA, and ground-based telescopes. The luminosities of these dusty, distant galaxies cannot be determined using any other method.

Beyond simply measuring luminosities, new observing capabilities will be needed to study the far-infrared and submillimeter structure and evolution of these

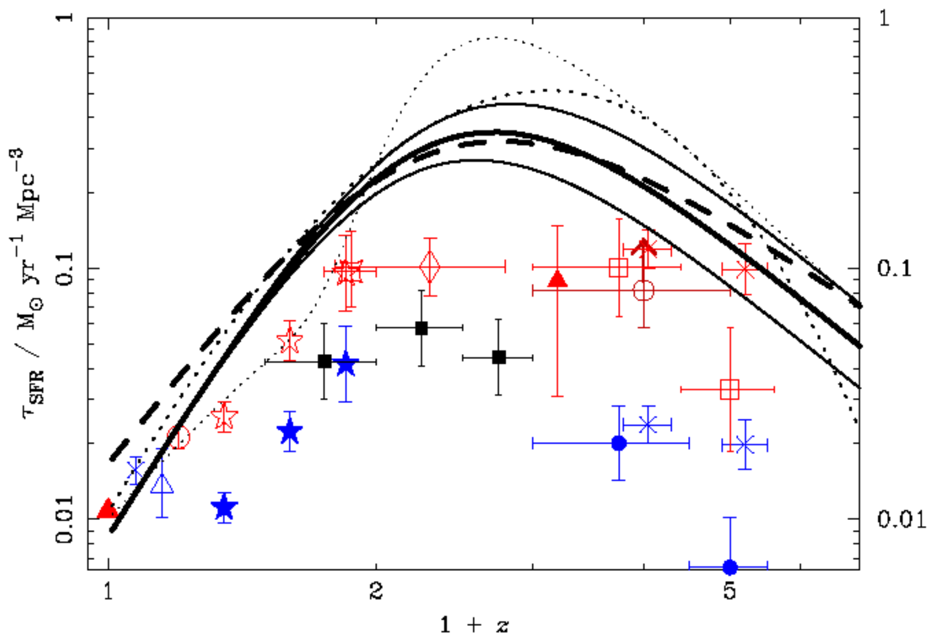

Figure 2-3: Estimated history of star formation rate per unit commoving volume in the universe (from Blain *et al* 2002). The individual points represent various optical and near-infrared measurements, and the single up-pointing arrow represents current submm estimates. The thick solid and dashed curves represent best fits of a simple luminosity evolution model and a hierarchical model of luminous merging galaxies to the far-infrared and submillimeter data. Further details of the plot can be found in Blain *et al.* (2002).

galaxies. What are the roles of star formation and active nuclei in the creation of this luminosity? How do these roles change with time?

Progress has been made both observationally and theoretically in understanding the star formation rate in galaxies. However, there is still significant difficulty in reconciling the estimates for the star formation rate given by ultraviolet, visible, infrared, and submillimeter observations. For instance, Figure 2-3 (Blain *et al.* 2002) shows estimates of the star formation rate of the universe as a function of redshift determined at a variety of wavelengths. There is a dramatic increase in the star formation rate at redshifts greater than ~0.4. However, these data do not yet constrain the redshift at which the star formation rate begins to decline; for instance, z~5 is not ruled out. The interpretation of the optical and near infrared data suffers from large and uncertain corrections for dust extinction. The existing submillimeter data are difficult to interpret, since the number of objects is small, and few redshifts are known. Furthermore, it is not yet clear what the connection is, if any, between the high redshift star-forming galaxies seen in the optical and near infrared and those seen in the submillimeter.

It is clear that much more detailed information will be required in order to fully understand early galaxy formation and evolution, and the nature of the far-infrared background. Some of the key observations will include:

1. Large, sensitive, high angular resolution, multi-band far-IR/sub-mm surveys to fully resolve the FIRB.
2. Complete far-IR spectral energy distributions to determine the luminosity, and to obtain estimates of the dust temperature and emissivity law.
3. Measurements of spectroscopic redshifts from infrared and submillimeter lines.
4. Determination of the physical properties of galaxies from detailed multi-line spectroscopy.
5. Determination of the galaxy luminosity function as a function of redshift by combining broadband photometry with spectroscopic redshifts.
6. Detailed photometric and spectroscopic measurements of nearby galaxies, to firmly establish the connection between far-IR/sub-mm measurements and the physical properties of galaxies, and to provide templates for high-redshift objects.

Many of these goals are within reach of a 10-m class, cold, far-infrared/submillimeter space telescope, such as the concept endorsed in the Decadal Survey. Ultimately, high angular resolution imaging will be necessary to resolve the structures of early galaxies, as suggested by numerical modeling and HST imaging. Interferometry is the leading approach to attaining the needed resolution in the far-infrared/submillimeter bands, as suggested in the Decadal Survey.

Table 2-2 Detector Requirements for Extragalactic Investigations

Science Investigation	Measurement Capability	Detector Requirements
Measurement of FIRB/ Galaxy Luminosity Function	Wide-Field, Deep FIR Surveys	10^4 element Direct Detector Arrays NEP 10^{-18} $WHz^{-1/2}$
Redshifts of Galaxies	Spectroscopy R=1000	10^4 elements/octave Detector Arrays with Response beyond 300 μm NEP 10^{-20} $WHz^{-1/2}$
Constituents and Energetics of Nearby Galaxies	High Resolution Spectroscopy $R > 10^4$	10^4 element direct detector arrays NEP 10^{-21} W $Hz^{-1/2}$ or Coherent Spectrometers

c) Formation of Stars and Planets

Although the general outlines of the star formation process are known, many of the most important aspects remain elusive. What initiates the core collapse? How are binary stars formed? What is the detailed role of disks to outflows from protostars? What determines the mass of a star? What processes determine when, where and how planets form, and with what masses? Far-infrared and submillimeter observations are critical for the study of star and planet formation for three fundamental reasons. First, since star formation regions are cold, they radiate predominantly at long wavelengths. To understand the physical processes acting during star formation, we must observe the dominant form of radiated energy. Second, the process of conversion of interstellar clouds into stars invariably occurs in regions of high dust extinction. Stars are born in cold interstellar cloud cores that are so optically thick they are sometimes undetectable even in the mid-infrared. Far-infrared and submillimeter photons can penetrate this dust and allow the study of the underlying objects and processes. Third, the dominant atomic and molecular spectral lines that provide cooling in these clouds are at infrared and submillimeter wavelengths. Additionally, the chemical evolution of star forming regions is best explored at these wavelengths where the spectra show an amazing richness of features (see, for example, Figure 2-5). These spectral signatures have great diagnostic potential for unraveling the physical, dynamical and chemical evolution of clouds.

Key to addressing these questions will be the improved angular resolution promised by future large missions at wavelengths inaccessible from the ground. While SIRTF and Herschel will be yield substantial information on the long-wavelength emission from these regions, neither facility will have the angular resolution to explore the key physical scales of the star formation process. A new generation of far-infrared and submillimeter missions will improve on the situation. A far-infrared 10-m telescope, for example, provides a resolution of ~1 arcsec at 50μm (~ 100 AU for the nearest star forming regions), so imaging could probe the density and temperature structure of these ~1000 AU collapsing cores on critical physical scales (Figure 2-4). This angular resolution will begin to allow the investigation of fragmentation and binary star formation. High-resolution far-infrared and submillimeter spectroscopy with a large FIR telescope would enable study of the dynamical collapse of dense cores on these angular scales, providing a velocity resolution better than 1 km/s.

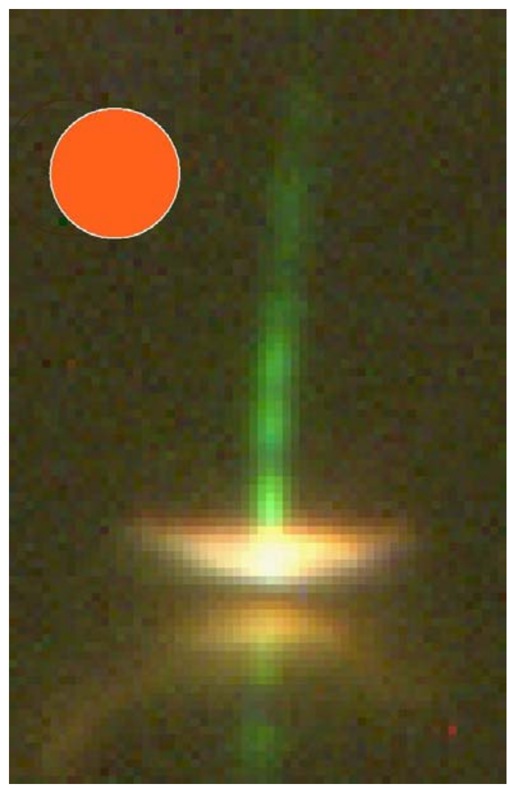

Figure 2-4. HH-30 disk and jet observed with HST/WFPC-2. The circle indicates the resolution attainable at 50 μm with a 10-m FIR telescope. (C. Burrows, K. Stapelfeldt, the WFPC2 Science Team, and NASA).

In addition to observing structures associated with disks, an understanding of the star formation process will need studies of entire star formation complexes. The regions of interest range from a few arcminutes to nearly a degree across, and maps in both continuum emission from the dust as well as maps in important emission lines will be needed to assess the physical conditions in the clouds. The requirement for efficient mapping at high resolution requires that facilities be equipped with very large format arrays of far-infrared and submillimeter detectors. Spectroscopic investigations of star forming regions will also greatly benefit from large detector arrays. With SOFIA, for example, large format far infrared arrays would be needed for the construction of a cross dispersed echelle spectrograph that would give spatially resolved spectra of extended structures.

Ultimately, very high angular resolution observations will be crucial to confirming theories outlining how stars form and interact with their surrounding disk environment, and in understanding exactly what factors control whether and how planets form. Resolutions of 0.1 to 1 AU are required to probe circumstellar disk structure in the regions of terrestrial planet formation, searching for disk gaps and measuring the sharp thermal and compositional gradients that are predicted as a consequence of planet growth. Core accretion and outflow processes can be studied, and the structure near the interface between the central star and disk can be probed. These resolutions will be attainable with a 1 to 10 km baseline interferometer at 50μm for the nearest star formation regions.

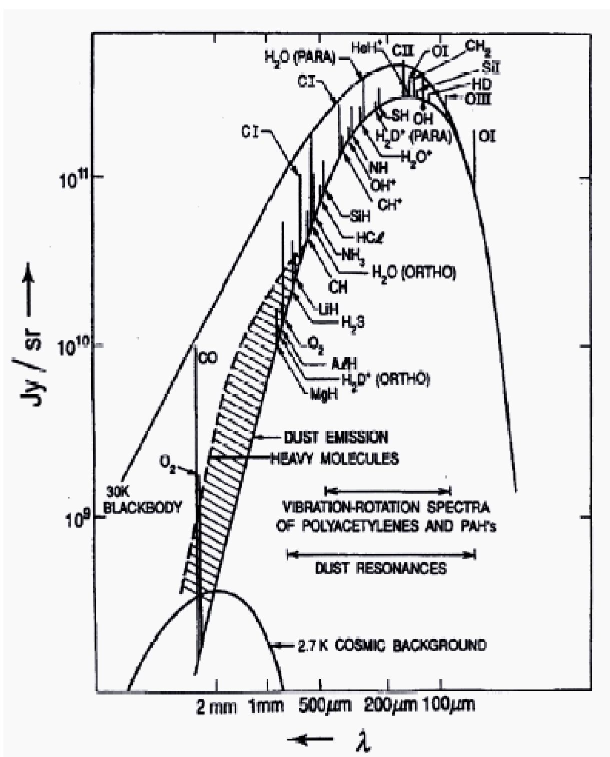

Figure. 2-5 Predicted submillimeter spectrum of a protostellar cloud. Phillips and Keene (1992)

Spectroscopy in the far-infrared and submillimeter is key to understanding both the energy balance and the kinematics of clouds. Figure 2-5 shows the predicted spectrum from a protostellar cloud, illustrating the wealth of spectral lines. In addition to the richness of spectral lines at these wavelengths, it is important to note that the continuum emission also peaks in the far-infrared.

Key velocity scales for the study of star forming regions range between 0.1 km/s to hundreds of km/s, necessitating spectral resolutions in excess of 10^6 to measure the associated Doppler shifts. Knowledge of the kinematics of the clouds will demand observations with heterodyne systems. High spectral resolution spectroscopy of star forming regions with heterodyne systems has revealed complex dynamical structure.

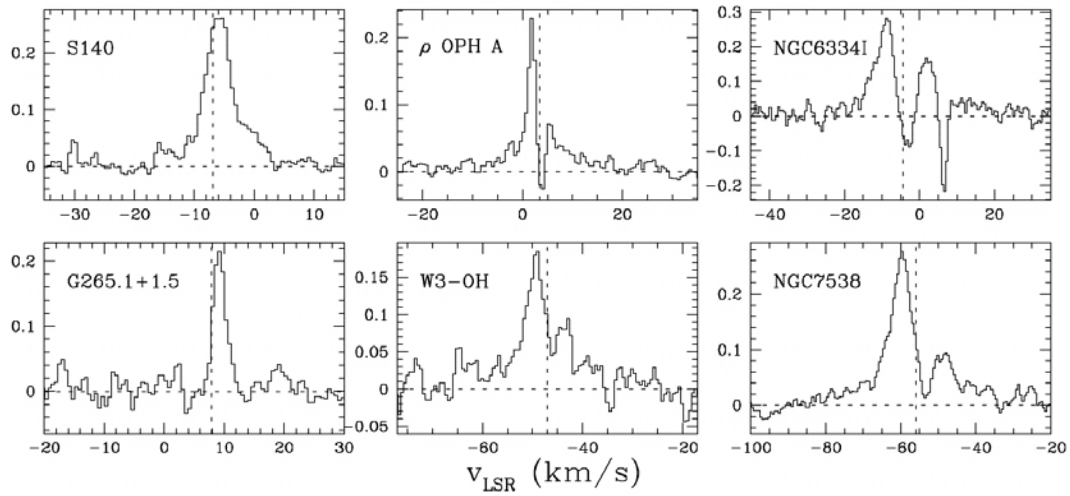

Figure 2-6 SWAS spectra of the 557 GHz transition of ortho-H_2O in various star formation regions showing the wide variety of line shapes. Ashby et al (2000).

Figure 2-6 shows spectra that were taken with SWAS that illustrate the richness of the kinematic information available with these types of observations. By combining the high angular resolution with the kinematic information possible with heterodyne receivers, it will be possible to produce detailed dynamical models of representative systems.

The technical challenges for future detector development for spectroscopy are twofold. First, high performance systems need to be pushed to beyond 1 THz since many of the lines occur at $\lambda < 300$ μm. Second, exploration of the structure of these regions will require mapping over extended regions, and arrays of heterodyne receivers will be required for observing efficiency.

Table 2-3. Detector Needs for Star Formation Investigations

Science Investigation	Measurement Capability	Detector Requirements
Census of Star Formation Regions/ Structure of Young Stellar Objects (YSO's)	High Resolution Continuum Mapping	10^4 element Detector Arrays at Far Infrared and Submillimeter wavelengths
Cloud and YSO Kinematics and Energy Balance	High resolution Spectroscopy $R>10^6$	Arrays of Coherent Receivers and/or Arrays of Direct Detectors

III. Detector Overview

In this section we describe fundamental limits to detector performance, summarize the current state of the art, and present our findings for the developments in detectors and detector systems needed to answer the key science questions identified in the NASA Strategic Plans and the National Academy of Sciences reports.

a) Fundamental limits on performance

The fundamental lower limit on noise in astronomical observations is set by the statistical fluctuations of photon rate from the region of sky being observed. These are typically photons from a background, which may be dominated by the integrated emission from unresolved sources (e.g., the X-ray and far-infrared backgrounds), or which may be diffuse emission (e.g., the Cosmic Microwave Background and the zodiacal light). Figure 3-1 shows the flux (λF_λ) of these natural backgrounds from infrared to millimeter wavelengths. These backgrounds are dominated by scattered sunlight and zodiacal thermal emission shortward of 100 μm, by Galactic and extragalactic dust emission from 100–400μm, and by the Cosmic Microwave Background at wavelengths longer than 400μm.

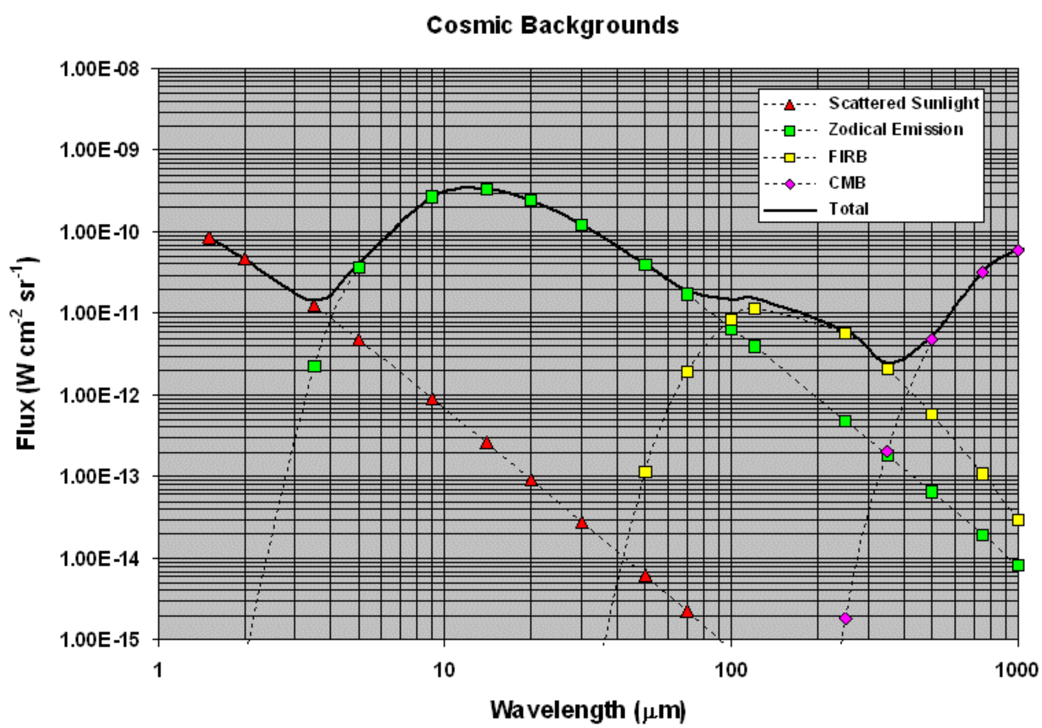

Figure 3-1. Astronomical background levels from infrared to millimeter wavelengths.

Ideally, the noise generated by detectors, instruments, optics, etc. is small compared to this background noise. This condition is referred to as the Background-Limited Infrared Photodetection limit, or BLIP limit. Reaching the background limit in the infrared, submillimeter, and millimeter spectral region, invariably requires cooling optics to reduce thermal emission and cooling detectors to limit fundamental noise sources. Figure 3-2 shows the detector Noise Equivalent Powers (NEP) required for a possible version of SAFIR to be BLIP limited. We assume a single mode detector ($A\Omega = \lambda^2$), where A is the telescope area and Ω is the pixel field of view on the sky. Two scenarios are computed, broadband imaging with a spectral resolution of $R = \lambda/\Delta\lambda = 4$, and moderate resolution spectroscopy with a spectral resolution of 1000. For other resolutions R and optical efficiencies τ, the NEP scales as $(\tau/R)^{1/2}$.

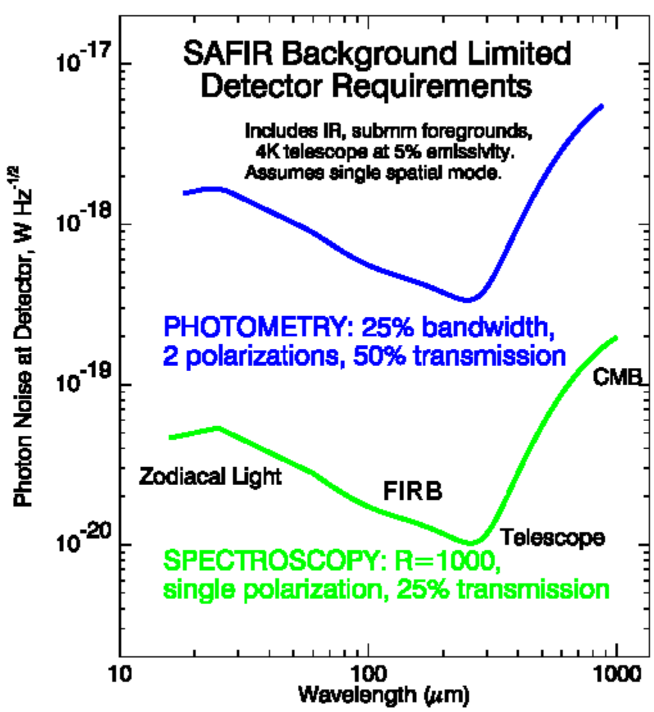

Figure 3-2. Detector NEP's required for background-limited performance for a possible version of SAFIR.

Astronomical measurements are also subject to confusion. If the density of discrete sources on the sky is such that multiple sources lie within a single resolution element, fluctuations in the integrated emission from these unresolved sources from pixel to pixel on the sky add uncertainty to the measurements of brighter sources that stand out from the background. The "confusion limit" depends on angular resolution, wavelength, and to a certain extent on sky position. For example, at its longest wavelength of 160 μm, SIRTF will reach the confusion limit in as little as 40 seconds even in regions of low background. If it turns out that the far-infrared background is entirely due to sources that become resolved with future facilities, then the infrared background limit would be a resolution-dependent confusion limit, and inferences from Figure 3-2 would have to be interpreted accordingly. A discussion of the various limits can be found in Rieke et al. (1995).

In addition to the basic sensitivity requirements, useful astronomical sensors should exhibit good photometric behavior. Freedom from non-linear effects, predictable behavior, and stable performance in an ionizing radiation environment are all important for space astronomical detectors.

Detectors that respond only to the intensity of the electromagnetic field are called "direct" or "incoherent" detectors. Examples of direct detectors are photon detectors and bolometers. Systems with photon number gain while preserving both phase and amplitude of the field prior to detection are called "coherent" detectors. Examples of coherent detectors include heterodyne and High Electron Mobility Transistor (HEMT) amplifier systems. Since amplitude and phase are non-commuting quantities in quantum mechanics, there is a limit to the precision with which they can be measured simultaneously. This results in a fundamental noise floor that affects coherent, but not direct detectors. This "quantum noise limit", expressed as a noise temperature, is given by $h\nu/k_B$, where h is Planck's constant, ν is the frequency, and k_B is Boltzmann's constant. Numerically, the quantum limit is 0.05ν K/GHz, or 50ν K/THz. Equivalently, the quantum limit can be thought of as the photon shot noise from a background of one photon per second per unit bandwidth.

The mean photon occupation number n_0, defined as the number of photons per spatial mode per second per hertz of bandwidth, is useful in characterizing the photon background. The quantum noise floor for a coherent detector corresponds to $n_0 \approx 1$. Thus for low backgrounds, i.e., $n_0 \ll 1$, BLIP-limited direct detection is lower noise by a factor $\approx n_0^{1/2}$. For high backgrounds, i.e., $n_0 \gg 1$, noise in both types of detector is limited by background photon noise, and both types have comparable sensitivity. Figure 3-3 shows that the quantum limit is not important for ground-based or airborne submillimeter

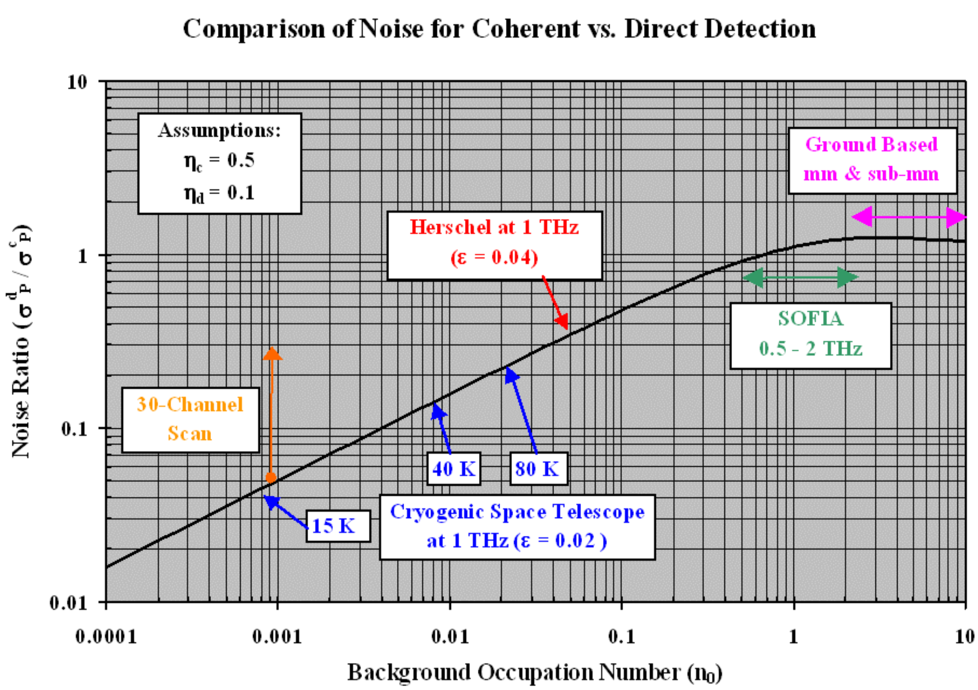

Figure 3-3 Noise of an ideal direct detector σ^d_P with system efficiency η^d=0.1 divided by the noise of an ideal coherent detector σ^c_P with a system efficiency of η^c=0.5. The vertical arrow shows the sensitivity penalty associated with a 30-channel sequential spectral scan. The indicated temperatures refer to the cryogenic space telescope temperatures.

telescopes where the background is dominated by hot thermal emission of the optics or the atmosphere, but is a serious issue at frequencies beyond 1 THz for a cold telescope in space, where direct detectors enjoy a large advantage. As a result, direct detection should be used for imaging instruments and low-to-medium resolution spectroscopy on low-background space telescopes. Note, however, that the CMB itself contributes $n_0>1$ below about 50GHz (λ = 6 mm); thus at these frequencies, coherent receivers can be competitive for observation of the CMB.

The situation for high-resolution spectroscopy is subtler. While grating spectrometers with array detectors are the systems of choice for moderate resolutions, they cannot provide the highest resolutions at long wavelengths. The difficulty with grating spectrometers is that for a resolution R, the linear size must be of order $R\lambda$. Achieving $R = 10^6$ at λ = 200 μm would require a cold grating 200 meters long! Other classes of spectrometer, such as Fabry–Perot spectrometers, solve this size problem by folding the optical path, and resolutions approaching $R = 10^6$ are achievable. The cost is reduced sensitivity because of the need to scan through the spectrum. Fig. 3-3 shows the penalty for a scan of 30 spectral elements, which is sufficient to give a modest amount of information about the line shape. In practice, system factors combine to strongly favor coherent heterodyne detection for high-resolution spectroscopy for frequencies below 1.5–2THz (λ >200 - 150 μm). In addition, coherent detection is competitive at low frequencies where quantum noise is not an issue.

b) Detector Arrays

Astronomy has greatly benefited from the advances in semiconductor technology over the past few decades. Following the original observation by Moore (1965) that the complexity of integrated circuits was doubling on a yearly basis, the industry has maintained an exponential rate of growth for more than 40 years. The array sizes available to astronomy have shown a similar growth. Figure 3-4 shows the increase in formats over the years. The advantages of large format arrays have been well documented, and they include greatly increased efficiency, sensitivity, ability to accurately assess backgrounds, high precision photometry, and high precision positional information. Clearly, however, the longest wavelengths have yet to realize the full potential of large array formats.

The time required to measure a given section of sky to a specified noise level scales as $\text{Sensitivity}^2 / N_{pixels}$. The squared dependence gives a high priority to improvements in detector sensitivity. However, the detection sensitivity for astronomical sources will eventually be limited by background photon noise or confusion. In that case, increasing the number of pixels becomes the highest priority of detector development. For broadband imaging applications, the raw sensitivity of existing long wavelength direct detectors is adequate to approach background or confusion limits. Large gains in observing capability will need to come primarily from increasing array sizes. Optical arrays are now in use with tens of millions of pixels. In contrast, the largest far-infrared array is the 32x32 SIRTF photoconductor array. The situation is the same across the entire wavelength range that we are considering. To answer the fundamental science questions discussed in Section II, significantly larger far infrared and submillimeter arrays will be needed. Since the angular resolution of future missions will likely be an order of magnitude better than SIRTF, much larger arrays will be needed to cover useful

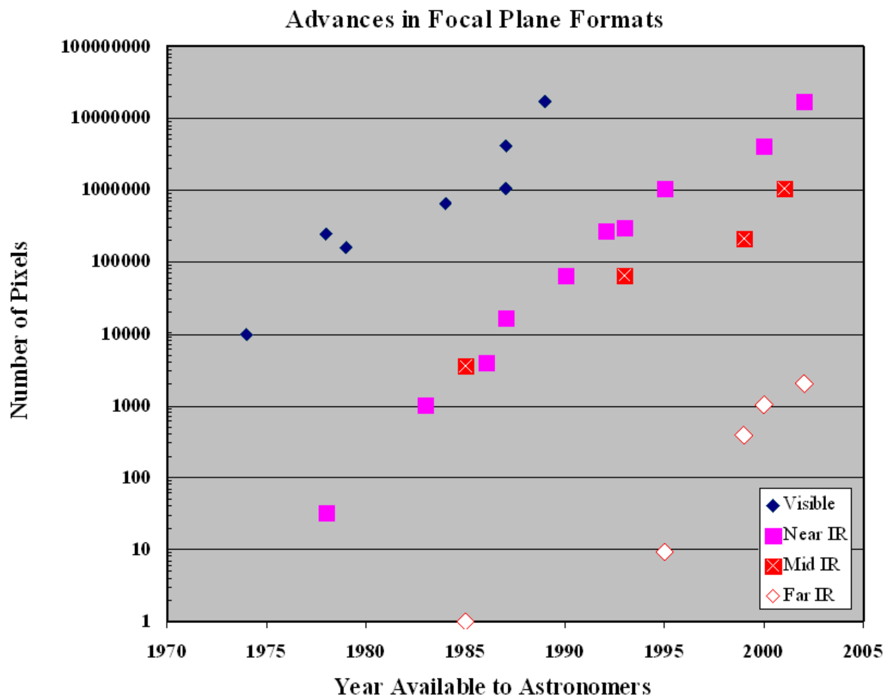

Figure 3-4. Growth of Detector Array Sizes with Time.

areas of sky. This consideration is also important for wide-field stellar interferometry, such as for the astrophysics program for the Terrestrial Planet Finder (TPF). Increasing array size is a dominant theme in our findings.

c) The State of the Art

We summarize here the current state of the art in the three detector categories. Details are provided in Section IV. The necessary technology development is determined by the difference between what is required to achieve the science goals of Section II and the current state of the art.

Direct Detectors λ<40 microns

- Near-IR (λ = 1-5 μm) hybrid arrays have been produced in InSb and HgCdTe in 2024 x 2048 formats, with plans to tile into 4096 x 4096 arrays for Next Generation Space Telescope. Characterization of these arrays has started.
- Thermal-IR (λ = 5-30 μm) hybrid arrays have been produced with Si:As Impurity Band Conduction (IBC) detectors in 1024 x 1024 formats; first generation devices have been tested.
- Pixel-level sensitivities match, or improve upon levels achieved in smaller formats. Performance for space IR imaging is at or near background limits. Spectrometers remain detector noise limited for *R* higher than a few times 10^3.

- Extrinsic silicon (especially Si:Sb) technology has only limited support outside of NASA and is therefore vulnerable. The associated silicon readout technology for temperatures below 20 K is not firmly established.
- Industry is a key partner in this wavelength range, and astronomy-relevant technologies need to be sustained to assure they are available.

Direct Detectors λ > 40 micron

- No military or commercial technology is available for long wavelength direct detectors.
- Flight Ge:Ga photoconductor arrays for SIRTF have 1024 pixels at 70μm, and 40 pixels at 160 μm, with MOS multiplexers.
- Work on IBC detectors from Ge or GaAs may improve pixel performance and extend lithographed photon detector arrays to ~ 400 μm, but significant effort will be needed to demonstrate useful performance for even a single pixel.
- Concepts for longer wavelength superconducting photon detectors have been demonstrated and ideas exist for multiplexers.
- Semiconducting bolometer arrays up to several hundred pixels are in use or under development, but it will be difficult to scale JFET amplifier technology to larger arrays. Larger arrays using MOSFET readouts are under development for the Herschel mission.
- Superconducting TES bolometers with SQUID amplifiers have demonstrated excellent test results from individual pixels. Lithographed arrays of both absorber-coupled bolometers and antenna-coupled bolometers with integrated filters are being fabricated. Output multiplexing has been demonstrated.

Coherent Detectors

- Mixers operate at nearly the quantum noise limit for frequencies below ~500 GHz (λ = 600 μm) but performance degrades to 20 - 40 times the quantum limit above 1 THz (λ = 300 μm).
- A number of local oscillator (LO) technologies are in use, including frequency multipliers, lasers, and vacuum tube devices.
- Only small mixer arrays have been built.
- The best present amplifier performance is roughly 3 times the quantum limit below 10 GHz (λ = 30 mm) and 6 times the limit at 100 GHz (λ = 3 mm). The highest amplifier frequency is above 200 GHz (λ = 1.5 mm).
- Amplifier arrays of 10 - 20 elements have been built

d) Detector Development Needs

To identify the areas where detector development is needed, the accompanying Table restates the required measurement capabilities from the example science programs in Section II, and compares them to the existing state of the art. In several areas, the gap is large, and a formidable amount of development will be needed to realize the promise of the future missions. Additionally, the ISMDWG has identified a number of infrastructure issues that will need to be addressed to insure the success of the detector development program. Most important of these issues is the need for sustained support to bridge the gap between proofs of concepts and flight-ready systems. Details of the detector systems are discussed in Chapter IV, while key infrastructure issues are detailed in Chapter V.

Table 3-1 Examples of Needed Capabilities

Science Investigation	Measurement Capability	Current State of the Art	Required Detectors
Physics at GUT Energies	CMB B-Mode Polarization	Single element polarization-sensitive bolometer or HEMT amplifiers	Arrays of $>10^3$ detectors in a high performance polarimeter
Measurement of FIRB/ Galaxy LF	Deep FIR Surveys	~400 element bolometer arrays NEP 10^{-18} W Hz$^{-1/2}$	10^4 element Direct Detector Arrays NEP 10^{-18} W Hz$^{-1/2}$
Redshifts of Galaxies	Line Spectroscopy R=1000	~1000 element photoconductor arrays NEP 10^{-18} W Hz$^{-1/2}$	10^4 element direct detector arrays with Response beyond 300 μm NEP 10^{-20} W Hz$^{-1/2}$
Constituents and Energetics of Nearby Galaxies	High Resolution Spectroscopy $R > 10^4$	~1000 element photoconductor arrays NEP 10^{-18} W Hz$^{-1/2}$	10^4 element direct detector arrays NEP 10^{-21} W Hz$^{-1/2}$ or Coherent Spectrometers
Star Formation in Local Universe	High Resolution Spectroscopy $R > 10^5$	20x Quantum Limit at 1 THz Single channel coherent systems.	Array heterodyne systems near quantum limit for ν up to 3 THz
Census of Star Formation Regions; YSO Structure	Mapping in Lines and Continuum	~10^3 element arrays	10^4 Element Direct Detector Arrays
Cloud and YSO Kinematics	Dynamical studies	20x Quantum Limit at 1 THz Single channel coherent systems.	Array heterodyne systems near quantum limit for ν up to 3 THz

e) Principal Findings

Far-infrared and Submillimeter Arrays

As its most important conclusion, the ISMDWG finds that an aggressive effort to develop the largest possible format far-infrared and submillimeter detector arrays would be the most significant benefit to the NASA Space Science Program in the area of infrared, submillimeter, and millimeter detectors. Arrays of 10^3-10^4 pixels will be needed for SOFIA and the important future mission concepts. For spectroscopy, sensitivity improvements of two orders of magnitude are needed. It is essential that complete prototype systems be fabricated. Because of the wide range of applications for these arrays, it is likely that a variety of technologies will be needed to satisfy the different requirements.

We strongly support the development of large format bolometer arrays, in particular TES systems. These will likely be an essential element of the far-infrared to millimeter wave-length astronomy program. In particular, the development of complete ***systems***, including sensors, readouts, cryogenic systems, and electronics, will be needed to meet the ambitious science goals of NASA.

We encourage continued work toward very large photoconductor arrays. In particular, the realization of Impurity Band Conduction detectors that operate at far-infrared and submillimeter wavelengths should be pursued. Promising new material systems such as GaAs should be explored. Readouts for far-infrared photoconductors need continued development.

Support for Infrastructure and Intermediate Technology Readiness Level (TRL) Detector Development

Mechanisms, such as the SARA Program, exist within NASA to support low-TRL developments, while mission funding is available for the final development to bring technologies to full flight status. As systems become more complex and expensive, the methods to support the work to take promising concepts to mid-TRL prototypes are very limited. The ISMDWG strongly encourages NASA to develop the resources to support this type of engineering, as a complement to the existing SARA program, which should retain its role of supporting innovative low-TRL research.

As part of this finding, we encourage NASA to explore methods for supporting key infrastructure elements in the research community. There is limited commercial or military interest for most of the technologies discussed in this report, so NASA will have to assume responsibility for the bulk of the development effort. Often, the work involves specialized facilities or equipment, and there are currently very few ways to provide the needed support. In particular, the push to large array formats will likely require substantial new investments in equipment and facilities.

Improvements in Coherent Systems

For coherent systems the most important goal is to continue the push toward better sensitivity. Between frequencies of 1 - 3 THz (λ = 300 - 100 μm), the attained sensitivity is well below that set by the quantum limit, and significant improvements are possible.

For submillimeter heterodyne receivers, a priority is continued local oscillator development, where higher frequencies, wider tuning bandwidths, and more output power are all important. The development of arrays of coherent receivers will provide significant improvements in mapping speed.

Readout Technology

Multiplexing is the key issue for achieving large format arrays.

For TES bolometers, superconducting SQUID readouts provide low-noise, low-power amplification. Multiplexed SQUID readouts will be essential for the construction of very large format bolometer arrays for a CMB polarization mission, and we strongly endorse continued development of this technology.

For photoconductive detectors, maintenance of the design and fabrication capabilities for large format silicon readout integrated circuits is of vital importance throughout the wavelength range covered by this report. Relative to the costs of integrated circuit development, the available OSS funding is limited, and the success of producing high performance cryogenic ($T < 20$ K) readouts has been spotty. The ISMDWG urges OSS to develop resources to insure the availability of this technology in the future.

Maintenance of Si:Sb Detector Capability

Si:Sb Blocked Impurity Band detectors are a unique NASA-developed technology. These detectors provide the highest performance detectors in the key 28-40 μm wavelength range. We note that the continued maintenance of this capability is critical to astronomical research in this wavelength band.

Distribution of Surplus Flight Detectors

Surplus detectors from major missions should be made available on a competed basis to the scientific community for use in other NASA flight programs, SOFIA instruments, ground-based instrumentation, and laboratory testing. We also endorse an examination of the spares philosophy with the goal of maximum scientific return throughout OSS.

IV Detailed Detector Discussion

a) 1 – 40 μm Detector Arrays

The previous decade has seen a dramatic increase in the available sensitivity and format of various types of multiplexed IR detector arrays within the wavelength range 1 – 40 μm. These hybrid arrays have been developed and optimized for space astronomy, and, with appropriate modifications, for higher background ground-based astronomical applications. They have been successfully used in a wide range of scientific applications, ranging from relatively broadband imaging to high-resolution spectroscopy. They have been used for detailed studies of a wide range of objects and physical processes, ranging from extrasolar giant planets, brown dwarfs, proto-planetary disks and star formation, to obscured active galactic nuclei, primeval galaxies and the origins of the first stars and galaxies. Dust-enshrouded regions, substellar mass temperature ranges, molecular bands, and the UV-optical emission of high-redshift sources are all accessible from space platforms at these wavelengths.

In this wavelength range, a useful technological base for IR arrays has been established, building upon previous military and industrial investments and the commercially driven silicon Complimentary Metal-Oxide (CMOS) circuit processing industry. In this class of detector, an infrared active semiconductor material is photolithographically delineated into pixels with individual electrical contacts. Industrial suppliers have developed successful approaches for the design and fabrication of both the infrared-sensitive semiconductor materials, and the separately optimized silicon CMOS multiplexing readouts to which the detector substrates are indium bump-bonded. (See Figure 4-1) During an observation, photo-generated charge is collected on the transistor gate bumped directly below each detector element. Upon readout, each pixel's stored charge is directly accessed, sensed by an output transistor, and then reset, all in a very low-noise, efficient process. The resulting two-dimensional infrared hybrid arrays provide high quantum efficiency and background-limited noise performance for imaging. Astronomical hybrid arrays up to 4 million pixels in size, with read noise well below 10 electrons, have been produced in this fashion.

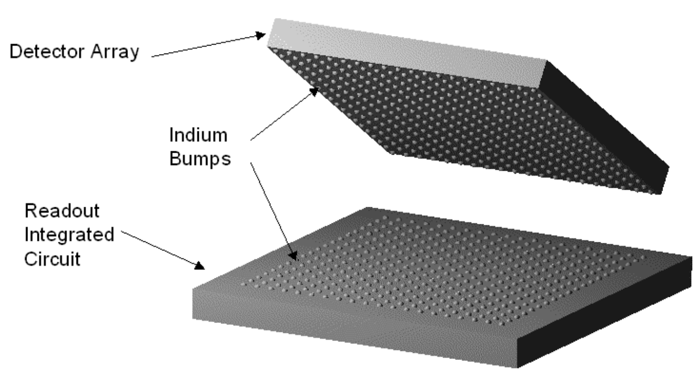

Figure 4-1. Indium bump bonding of an infrared detector array to a silicon readout integrated circuit is the principal architecture for detectors in the 1 - 40 μm range.

This technology field is relatively mature, although areas for improvement have been identified, and further advancements and optimizations are warranted. While a useful industrial base has been established, one must remember that the total astronomical market remains relatively small, and that industrial participation and progress is dependent upon sustained funding.

The common astronomical hybrid detector arrays in this region can be grouped by wavelength depending on the energy gap of the infrared active detector material. At the shortest wavelengths (1 - ~5 µm), photovoltaic (PV) detector arrays are used. These diode detectors are made from intrinsic semiconductors, are typically operated with a modest back bias, and have inherently high absorption efficiency. The most sensitive detector choice for applications between 5 and ~40 µm is extrinsic silicon. In this technology, an appropriate impurity is introduced (doped) into the silicon lattice, so that a relatively small (long-wavelength) energy gap results to create mobile carriers. Whether the detector substrate is made of intrinsic or extrinsic semiconductor, they are bonded with indium bumps to a silicon CMOS multiplexer (or 'readout') to form a hybrid structure.

Photovoltaic IR Detector Arrays

At the shortest IR wavelengths, 1 to about 5 µm, PV detectors have been fabricated from intrinsic semiconductor materials such as indium antimonide (InSb, with 5.3 µm cutoff) and mercury cadmium telluride ($Hg_{(1-x)}Cd_xTe$, with variable cutoff).

InSb arrays with excellent sensitivity have been developed for SIRTF (256 x 256 format) and the Japanese Astro-F (412 x 512 format). A major development program is underway for the Next Generation Space Telescope (NGST). Data indicate that the NGST read noise requirement of <9 electrons read noise (multiply sampled) will be achieved at 30 K. Material purity and processing technologies have steadily improved. The physical dimensions of the detector-grade substrates have increased to about 75 mm, large enough to accommodate 2048 x 2048 arrays of 25 µm pixels. Ground-based InSb arrays are commercially available in 1024 x 1024 formats, and developmental 2048 x 2048 hybrids for ground-based applications have been produced and successfully tested. NGST is sponsoring the development and demonstration of 2048 x 2048 low-background arrays that meet the requirements of this mission. These candidate arrays will be 'tiled' together into 4096 x 4096 mosaics and optimized for operation at 30 K.

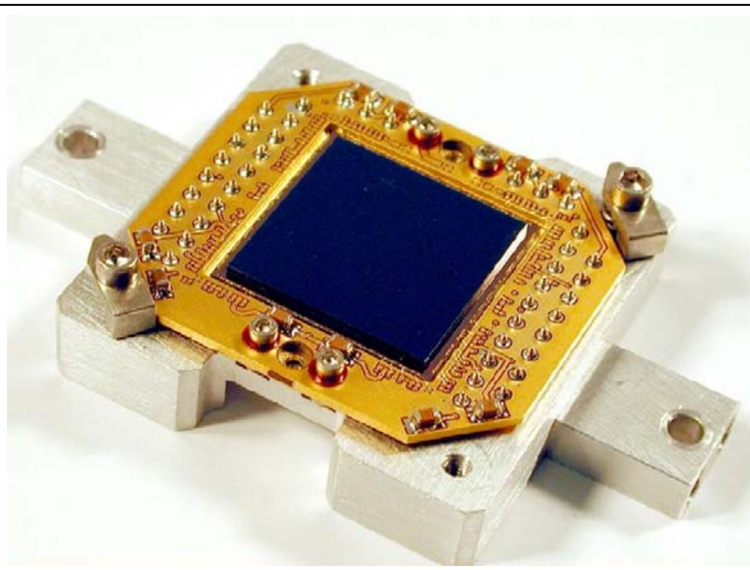

Figure 4-2. WFC3 Infrared Focal Plane Array. The detector is a 1024x1024 HgCdTe array with a 1.7 µm cutoff.

HgCdTe arrays have been developed for scientific use in a range of alloy compositions (and hence, of cutoff wavelengths and operating temperatures). The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) arrays were developed for HST nearly a decade ago, with 2.5 µm-cutoff material in a 256 x 256 format. Steady progress has been made, and substantially larger arrays with this cutoff are now available for ground-based applications. As with InSb, larger detector substrates have been produced to accommodate 2048 x 2048 formats. These arrays have pixel sizes near 18 µm. For space applications, both 1.7 µm-cutoff arrays for Wide Field Camera 3 (WFC3) and 5 µm-cutoff arrays for NGST are under development, the latter in 2048 x 2048 format. Figure 4-2 shows the 1024 x 1024 pixel infrared focal plane array for WFC3 that will be installed on HST in 2004. The 5 µm-cutoff arrays being developed for NGST, like other modern devices of this type, are produced by molecular beam epitaxy. Test data indicate excellent sensitivity, with correlated double sampled noise of ~15 electrons at 35 K; the noise requirements for NGST appear to be achievable. Like the competing InSb candidate for NGST, HgCdTe detectors will be implemented in tiled array modules of 4096 x 4096 pixels, which are baselined for operation at 37 K.

These PV detectors utilize silicon CMOS readouts produced at commercial foundries. Because the required operating temperatures are above the carrier freeze out at ~20 K, the readout circuits can be implemented with reasonably conventional design rules and processing steps. Close cooperation between designers within the detector houses, and their counterparts at the silicon foundries, is important in developing low-noise, low-power readouts appropriate for astronomical applications. The overall sensitivity of recent intrinsic arrays is very good, with quantum efficiencies approaching unity, and read noise, after multiple sampling, well below 10 electrons rms.

Impurity Band Conduction (IBC)* IR Detector Arrays

For longer wavelengths, extrinsic silicon is used as the detector material. Modern extrinsic silicon detectors are now produced with a very thin, very highly-doped detector layer, in the IBC (also called BIB) configuration. Figure 4-3 depicts the representative structure of an n-type IBC detector. The energy band diagram shows the heavily doped IR absorbing layer with the associated impurity band and the low-doped blocking layer that prevents the dark current from reaching the electrical contacts. The IBC / BIB detectors have demonstrated clear advantages in radiation hardness and photometric operation, and they offer a modest extension in wavelength coverage compared to the earlier bulk photoconductors. The arsenic-doped silicon IBC (Si:As, ~28 µm cutoff) was the first, and is the clearly the most mature, example of this class. This material provides useful spectral coverage down to ~5 µm. It was incorporated in formats of both 128 x 128 and 256 x 256 on SIRTF, with operating temperatures around 6 K. Quantum efficiencies above 60%, and multiply sampled read noise at or below 10 electrons, have been achieved. A prototype NGST Si:As IBC array with a 1024 x 1024 format has been produced and tested. The sensitivity is similar to that achieved in smaller formats. A relatively new variant of this detector material, antimony-doped silicon (Si:Sb IBC), was developed for the Infrared Spectrograph on SIRTF, and useful response has been

* The terms Impurity Band Conduction (IBC), and the trademarked name Blocked Impurity Band (BIB), are equivalent.

achieved out to ~38 µm. These SIRTF arrays, in 128 x 128 format, will operate at 4 – 5 K, with somewhat lower quantum efficiency and higher noise. A higher-background version of these Si:Sb arrays, in 256 x 256 format, will fly in the FORCAST instrument on SOFIA. These IBC devices exhibit excellent photometric behavior, in many respects acting like PV detectors.

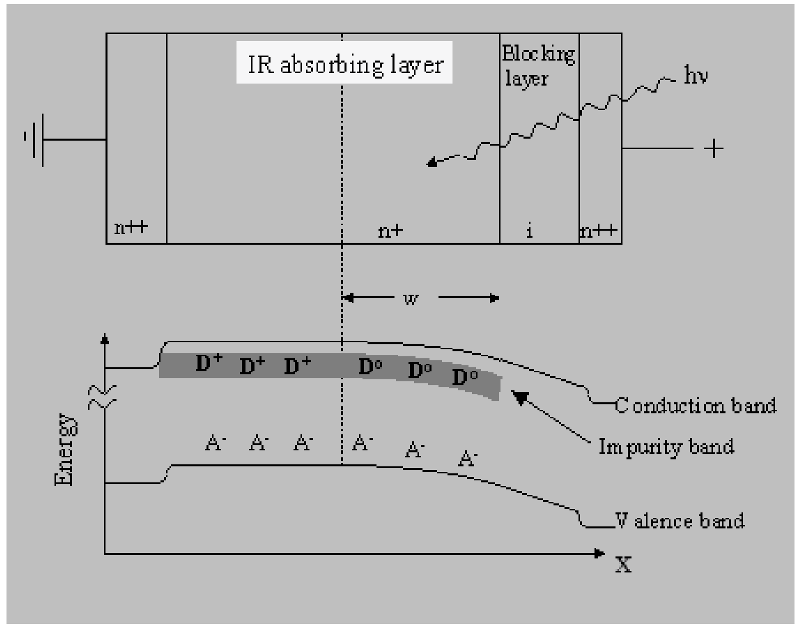

Figure 4.3 (a) Representative Structure of n-Type IBC Detector; (b) Band diagram of the detector. (Haller and Beeman 2002).

Since temperatures of 4 - 8 K are needed to suppress dark current, specialized low-temperature readouts are required. The silicon multiplexers must be specially designed and processed, to allow low noise operation at sub-freezeout temperatures. This is a difficult challenge, both because of the low-temperature device physics, and because of the ongoing problem of identifying silicon foundries willing to depart from their normal processing schedules. There are numerous examples of such 'deep-cryo' custom foundries failing, or moving on to other interests. Years are often required to (try to) re-establish a lost capability, with serious consequences in the development of readouts in both the 5 – 40 µm range, and also for the 50 – 200+ µm far-infrared, which requires even lower temperatures.

Promising Directions

Array Formats

The continued development of ever larger formats can be expected with adequate support. Formats of 4096 x 4096 pixels appear to be feasible today. Extending formats beyond the NGST objectives should be done with activities that are aligned to future Origins and SEU goals.

Detector Materials

Refinements in modern material growth techniques, in particular those using molecular beam epitaxy, are resulting in improvements in $Hg_{(1-x)}Cd_xTe$. It should be possible to extend the high quantum efficiency and moderate operating temperatures of this material system to significantly longer wavelengths.

Readout technology

Both the format and functionality of readout integrated circuits can be improved. Examples include on-chip clock generation, reference pixels, star tracking circuitry, and A/D conversion capability. For mid-IR and longer wavelengths, effort is needed to improve the custom deep-cryogenic CMOS readouts required to achieve low noise at temperatures below 20 K. The challenge will be to identify ways to take advantage of the increasingly powerful capabilities of the silicon processing industry while adapting to the foundries' commercial emphasis on high-speed digital devices. The potential benefit to NASA would be sophisticated sensor systems that have simple (and low cost) interfaces at the system level.

Developmental technologies

NASA should continue to monitor the status of developments in advanced bandgap-engineered devices such as Quantum Well Infrared Photoconductors (QWIP's), strained-layer superlattice devices, and quantum dots or wires, which may offer improvements in producibility and higher operating temperature. Some of these technologies promise 'multi-color' detection (simultaneous detection of photons in 2 or more wavelength bands within the same detector), which may have applicability in specific scientific investigations. NASA should also monitor advanced energy resolving / photon counting technologies such as the Superconducting Tunnel Junctions (STJ) and Transition Edge Sensors (TES), that may be emerging at very near-IR wavelengths. These technologies should be supported when technological progress appears encouraging, and the characteristics of the devices align well with future OSS mission requirements.

Development Findings

Si:Sb BIB Technology

Si:Sb technology is unique to NASA. It has proven to be useful for application in SIRTF and SOFIA, but is not fully developed. This technology that will be lost unless it is sustained by NASA

Array Formats

Future NASA missions will require improved large format arrays, with excellent sensitivity (high quantum efficiency, low noise, low dark current, and good photometric performance). It is desirable to develop more highly integrated, on-chip array electronics, so that the interface would involve only a few noise-immune digital (or optical) lines. It is also desirable to achieve array technologies that operate at higher temperatures without degrading sensitivity. For future large space missions, simplified cryogenic systems or passively-cooled approaches may be essential. Silicon readout electronics will continue to be critical in achieving these large-format arrays. The challenging aspects of deep-cryogenic silicon CMOS processing for multiplexing readouts are essentially unique to NASA; the techniques and know-how need to be supported and sustained by NASA. It is important to note that many of these readout considerations also apply to long-wavelength photon detectors.

b) Long Wavelength Direct Detectors

Direct detectors for wavelengths from 40 µm to several mm are used to measure many different astronomical phenomena including thermal radiation from dust in our galaxy, redshifted dust emission from the earliest galaxies, and the CMB. These sources comprise >80% of the radiant energy in the universe. Because there is no commercial or military interest, these detectors are built by and for astronomers. Progress in receiver sensitivity has been remarkable. The speed with which a given region of the sky can be mapped has increased by a factor 10^{18} in 40 years, corresponding to a doubling of speed every 12 months. Sensitivities of individual detectors are approaching the fundamental limits set by photon noise. As shown in Figure 3-2, these correspond to NEP ~ 10^{-18} $WHz^{-1/2}$ for photometry, which can be achieved, and ~10^{-20} $WHz^{-1/2}$ for spectroscopy, which remains difficult. However, the science goals discussed in Section II will require arrays of long wavelengths direct detectors in formats that do not now exist.

There are many requirements for useful arrays of direct detectors. These include sensitivity at the photon noise limit for the particular application, insensitivity to cosmic rays, wide dynamic range, simple time response, low power dissipation, moderate cryogenic requirements, etc. System requirements such as output multiplexing and practical ambient electronics are also critical. Existing long wavelength arrays are either limited to a few hundreds of detectors or fall short of the above requirements in important ways. There is much room for improvement. Fortunately, developments now envisioned or now in progress promise to enable the arrays required for future missions. However a sustained effort by NASA will be required to produce flight-ready hardware.

There are three main types of long wavelength direct detector. In a photon detector, the absorbed photon creates one or two electronic excitations that are measured before they are thermalized. Examples include photovoltaic, photoconductive, and blocked-impurity-band (BIB) devices made from semiconductors. There are also quasiparticle photon detectors made from superconductors. Photon detectors have a long wavelength cut-off set by the excitation energy (energy gap) and an operating temperature requirement set by the noise from the thermally excited dark current. In thermal detectors, such as bolometers with semiconductor or superconducting Transition Edge Sensor (TES) thermometers, the electronic excitation by the absorbed photon is thermalized before it is measured. There is no fundamental long wavelength cut-off, and the operating temperature requirement is set by the need to reduce thermal fluctuation noise. The required temperatures are typically lower than for photon detectors. A third distinct type of receiver, used as a direct detector at millimeter wavelengths, consists of a High Electron Mobility Transistor (HEMT) amplifier followed by a diode direct detector. This approach is subject to the quantum noise limit and is described in Section IVc.

Photon Detectors

Photoconductive detectors of Ge:Ga have been widely used for astronomy, for example, on IRAS, COBE, IRTS, ISO, and the Kuiper Airborne Observatory. Ge:Ga arrays have been developed for the Multiband Imaging Photometer for SIRTF (MIPS) instrument, and detectors are being developed for spectroscopy with the Photoconductor Array Camera and Spectrometer (PACS) instrument on Herschel. The MIPS has two Ge:Ga arrays. One array has 1024 unstressed detectors covering 50-100 μm. The other array has 40 detectors, which have been stressed to reduce the excitation energy, for a 160 μm band. They operate at temperatures of 1.5 K, have detective quantum efficiencies of 15-20%, and use custom (but commercially produced) cryogenic CMOS charge-integrating amplifiers and multiplexers. The SIRTF arrays are the result of a long development process and are a major achievement. The 70μm array (Figure 4-4) is the only 1024-element far-infrared direct detector system. There is, however, room for improvement. Higher quantum efficiencies would yield significant benefits. Conventional germanium photoconductors have low absorption coefficients, require large volumes, and thus have significant cosmic ray sensitivity. They also have complicated time responses that affect calibration, observing strategies and data analysis in low background applications. Recent theoretical insight suggests that there may be an opportunity to eliminate some of the nonlinear behavior. Compared to the hybrid detector arrays found at shorter wavelengths, these arrays are complex and require hand assembly of monolithic elements. In particular, in the case of stressed detectors, the need to apply a uniaxial stress to extend the long wavelength cutoff adds significant mechanical complexity.

At shorter wavelengths, silicon photoconductors have been replaced by IBC (or BIB) devices that have a number of well-known advantages. These include high quantum efficiency, low cosmic ray cross-section, simple time response, extended wavelength coverage, and array fabrication by optical lithography. A modest NASA program to produce longer wavelength IBC detectors from Ge has made steady progress. However, methods for producing the required epitaxial

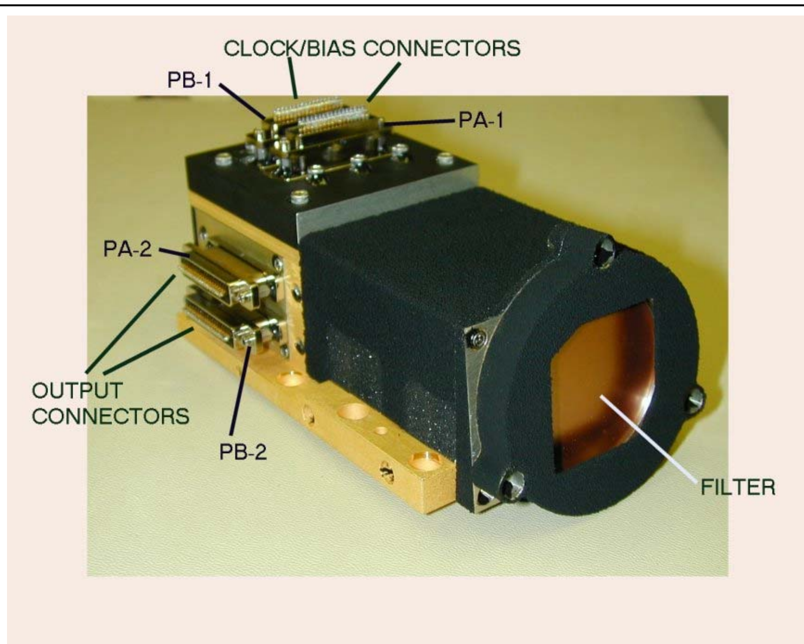

Figure 4-4. The SIRTF/ MIPS Ge:Ga Array. The array is 32x32 format and covers the wavelength range 50 - 110 μm.

low-doped blocking layer remain problematic. Recent successes in producing low-doped epitaxial blocking layers suitable for GaAs IBC detectors suggests that it may be possible to extend IBC photon detector performance to arrays at wavelengths as long as 400μm. Satisfactory detector pixels are anticipated, but have not yet been produced. If successful, however, the potential payoff will be very large, promising many of the benefits currently enjoyed at shorter wavelengths including operating temperatures higher than required by thermal detectors and the applicability of silicon multiplexer technology. MOSFET amplifiers and multiplexers that operate at these low temperatures exist, but their use at longer wavelengths will require additional optimization. Additionally, the maintenance of the foundry production capabilities remains an issue.

An entirely different type of photon detector is being developed which use the very small excitation energy in a superconductor. In these devices, photons are absorbed in a cold superconducting film where the electrons are bound into Cooper pairs. Each incident photon breaks a pair and creates two single excited electrons, or quasiparticles. The readout is designed to be sensitive to quasiparticles, but not to the pairs. Individual pixels of two different devices show promising performance and multiplexing schemes have been suggested. However, it is too early to judge whether these approaches will extend photon detection to mm wavelengths.

Thermal Detectors

Well-developed semiconductor bolometer technologies exist to produce arrays of tens to hundreds of pixels that are operated at temperatures of 100 to 300 mK. They are typically fabricated by lithography on membranes of Si or SiN and use thermistors of ion-implanted silicon or neutron-transmutation-doped Ge. Thermistor impedances of ~ 10^7 Ω match well to JFET amplifiers operated at ~ 100K. An AC bias is used when low frequency noise must be minimized. The photons are absorbed by metal films that can be continuous or patterned in a mesh. The patterning can be designed to minimize the cosmic ray cross section, to select the spectral band, to provide polarization sensitivity, or to control the throughput. Bolometer architectures include pop-up structures or two-layer bump bonded structures for close-packed arrays and spider web or other bolometers for horn-coupled arrays. Bolometers are used from 40 to 2000μm in many experiments including NASA pathfinder ground based instruments, and balloon experiments such as BOOMERANG, MAXIMA and BAM. Figure 4-5 shows a spider web bolometer from the BOOMERANG experiment. This type of detector is being used on space experiments such as the High Frequency Instrument (HFI) on Planck and SPIRE on

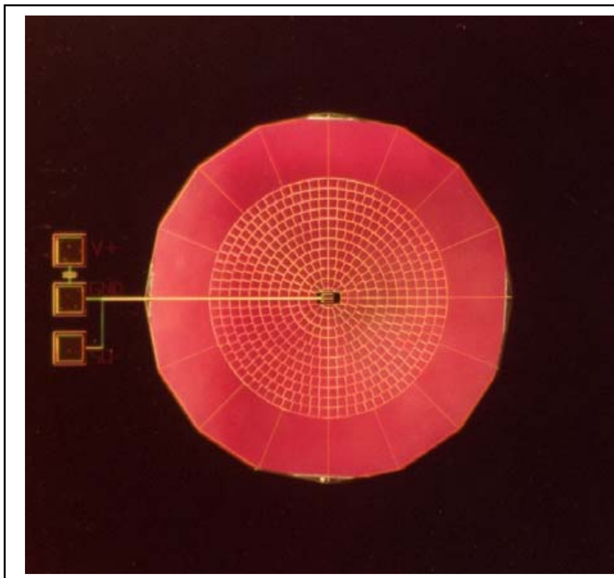

Figure 4-5. BOOMERANG Spider Web bolometer.

Figure 4-6. HAWC engineering prototype array for the SHARC II instrument. The array is a 12x32 (384 pixel) format

Herschel. An alternative approach to bolometer construction involves producing filled arrays in a "pop-up" configuration, where the absorber is deposited on a dielectric film that is subsequently folded. Arrays of this type are being developed for the HAWC and SAFIRE instruments on SOFIA. An example of this technology is shown in Figure 4-6.

The current generation of bolometers gives excellent performance in many applications. Quantum efficiencies can be high, and the time-domain response is simple and calibration is straightforward. However, the operating temperatures are lower than for photon detectors, necessitating the use of sub-Kelvin (0.3 to 0.1 K) refrigerators. The interface between the cold bolometers and the JFET amplifiers, which must operate at 100 K, can cause electrical, thermal and microphonic problems. Moreover, the JFET amplifiers generate significant heat and have small noise margins. For these reasons, arrays of semiconductor bolometers have been limited to several hundred pixels.

As an alternative to JFET amplifiers, large format arrays of 32 x 64 ion-implanted silicon bolometers are being developed for photometry in the PACS instrument on Herschel. The approach for this high background application is to use very high impedance ($>10^{10}$ Ω) thermistors that are bump bonded to MOSFET amplifiers and multiplexers. Performance is currently limited by the noise in the MOSFET amplifiers to the NEP $\sim10^{-16}$ $\mathrm{WHz}^{-1/2}$ regime, but this technology allows the construction of very large arrays suitable for higher background applications.

A new approach to thermal detectors uses the voltage-biased superconducting Transition Edge Sensor (TES) and Superconducting Quantum Interference Device (SQUID) readout amplifier. These devices can be made entirely by thin film deposition and optical lithography. The negative electrothermal feedback reduces the response time, improves the linearity, and isolates the bolometer responsivity from changes in infrared loading or heat sink temperature. The benefit in linearity comes at the cost of sudden saturation. There is also some suppression of Johnson noise. The SQUID amplifiers operate at bolometer temperatures, dissipate very little power and have significant noise margin. These bolometers are being produced with architectures that could be scaled to the large format horn-coupled and filled arrays required for many new missions.

In addition, there is work on bolometers that are coupled to the optics by planar lithographed antennas and superconducting microstrip transmission lines. In this implementation, the absorbing element is a resistive termination to the line, which can be very small. At low operating temperatures (~ 100 mK) such terminations can be deposited directly on the dielectric substrate. The weakness of the coupling between electrons and phonons provides adequate thermal isolation between the (hot) electrons and the substrate without the use of membranes or legs. In antenna-coupled bolometers, the signal is propagated in a superconducting microstrip transmission line. These lines can branch to form diplexers, and can incorporate high performance microstrip bandpass filters for frequencies up to ~700 GHz ($\lambda \sim 430$ μm). It should even be possible to make a low-resolution spectrometer with this technology. This feature may prove important for obtaining photometric redshift information at long wavelengths and for doing direct detection spatial interferometry. However, this development is at an early stage. The performance of superconducting antennas, transmission lines and diplexers, has been demonstrated in other contexts, but their use in bolometer systems has not been fully demonstrated.

Large format arrays of antenna-coupled TES bolometers or possibly superconducting photon detectors are very attractive candidates for a CMB polarization mission. Broadband antennas with RF diplexing and/or interleaved antennas can make efficient use of the focal plane. Antennas are inherently polarization sensitive, and the excellent gain stability provided by the feedback in TES bolometers facilitates polarization differencing. Such detectors are necessary for the high frequency bands of a CMB polarization mission and would be sufficient for all bands. However, much work remains to be done on the bolometers themselves and, especially, on the design of a high performance bolometric polarimeter.

Large format arrays of TES bolometers must have output multiplexing to avoid very large numbers of leads leaving the cryostat. Lines of 30-50 detectors can be multiplexed before amplification using superconducting thin film technology. A time-domain multiplexer that uses a SQUID for each bolometer to switch the outputs sequentially through a single SQUID amplifier has been fabricated and successfully demonstrated. Progress is being made on a frequency-domain multiplexer which combines the signals from a row of bolometers, each of which is biased at a different frequency. The signals are then amplified by a single SQUID and recovered with ambient temperature lock-in amplifiers. The success of TES bolometer arrays ultimately depends on the success of one or both of these multiplexer technologies.

Individual devices with a variety of architectures have been fabricated by lithography and tested successfully. Fabrication of large format arrays is in progress. However, very little work has been done on system architectures. Fortunately, the basic building blocks of the type of system that will be needed for space submillimeter and millimeter missions are common both to ground-based long-wavelength systems and to TES X-ray calorimeters on missions such as Constellation X. The NASA long wavelength infrared program can benefit greatly from these developments if and only if it makes a sustained investment in demonstrating the unique aspects of the systems architectures that will be necessary for infrared and mm-wave applications. In particular, scaling to $10^3 - 10^4$ pixels will require substantial development beyond the proof-of-principle stage to insure flight-ready status.

Summary

Photoconductors

Semiconducting photon detector arrays of 1024 pixels exist for wavelengths out to 120 μm. These arrays use CMOS readout multiplexing technology that has been adapted from shorter wavelengths. Expansion to larger formats while retaining the system level advantages that are present with this technology is important. Development of Ge or GaAs IBC detectors, which could improve pixel performance and extend large format photon detector array technology to several hundred μm will be of particular importance. Readout issues such as compatibility with very long wavelength detectors and the manufacturing infrastructure should be addressed.

TES Bolometers

The new TES bolometer technology has a number of useful operational characteristics, and should be producible in large format arrays. It is compatible with time domain or frequency domain multiplexing to SQUID amplifiers. The expectation is that this technology will enable large format detector arrays with very good performance over a wide range of wavelengths. The development of SQUID multiplexers will be critical to the success of TES bolometers. Support should be sought to improve the maturity of promising bolometer technologies and to develop the system architectures required for very large arrays on future missions.

Semiconducting Bolometers

Semiconducting bolometric detectors with individual JFET amplifiers perform well, and arrays of up to several hundred pixels are under development or in use for many missions. However, this JFET technology is difficult to scale to large format arrays for space missions. Large format bolometer arrays mated to MOSFET readouts are being developed for Herschel, and we recommend that NASA monitor developments in this area.

Research and Analysis Program and System Demonstrations

The long wavelength direct detector community is very creative, and novel devices can be expected from it. The SARA program plays an essential role in enabling new developments such as the superconducting photon detectors. Promising new devices should be developed as their predicted performance warrants. Many of the detectors being developed are entirely new and have not yet been demonstrated in astronomical instrument systems. In addition, several of the mission applications will have very demanding performance specifications. As a result, it will be crucial to gain experience with prototype ground-based, balloon-borne, and airborne instruments using these technologies. The ISMDWG is concerned that present grant sizes may be inadequate to develop the complex, very large array systems that will be needed in the future, and we encourage exploration of new funding mechanisms.

c) Technologies For Coherent Detection

A coherent receiver system (Fig. 4-7) usually consists of a local oscillator (LO), which produces a monochromatic signal at frequency ν_{LO}; a "mixer", which is a nonlinear device that down-converts the signal collected by the telescope at frequency ν_s to a lower microwave frequency $\nu_{IF} = |\nu_s - \nu_{LO}|$, known as the intermediate frequency (IF); a series of IF amplifiers; and finally a "backend" spectrometer which produces a spectrum of the IF signal. This IF spectrum is a replica of the spectrum of the telescope signal. The mixer usually determines the sensitivity of the system. At submillimeter and far-infrared wavelengths, the mixer is usually a superconducting device. Alternatively, at centimeter and millimeter wavelengths, low-noise amplifiers may be used prior to downconversion using standard semiconductor diode mixers. For continuum radiometers, such as those used for CMB observations, the down-conversion step may be omitted, in which case the amplified signal is filtered and detected, usually with a diode detector. In all cases, the system has a large photon number gain, and is therefore subject to the quantum limit.

Mixers

Dramatic advances have been made in submillimeter and far-infrared mixers over the past decade. Semiconductor Schottky-diode mixers have been replaced by Superconductor-Insulator-Superconductor (SIS) tunnel junction and superconducting Hot Electron Bolometer (HEB) mixers. These devices use metallic low-T_c superconductors and generally operate at 1.5 - 4 K. Alternative devices are also being investigated, such

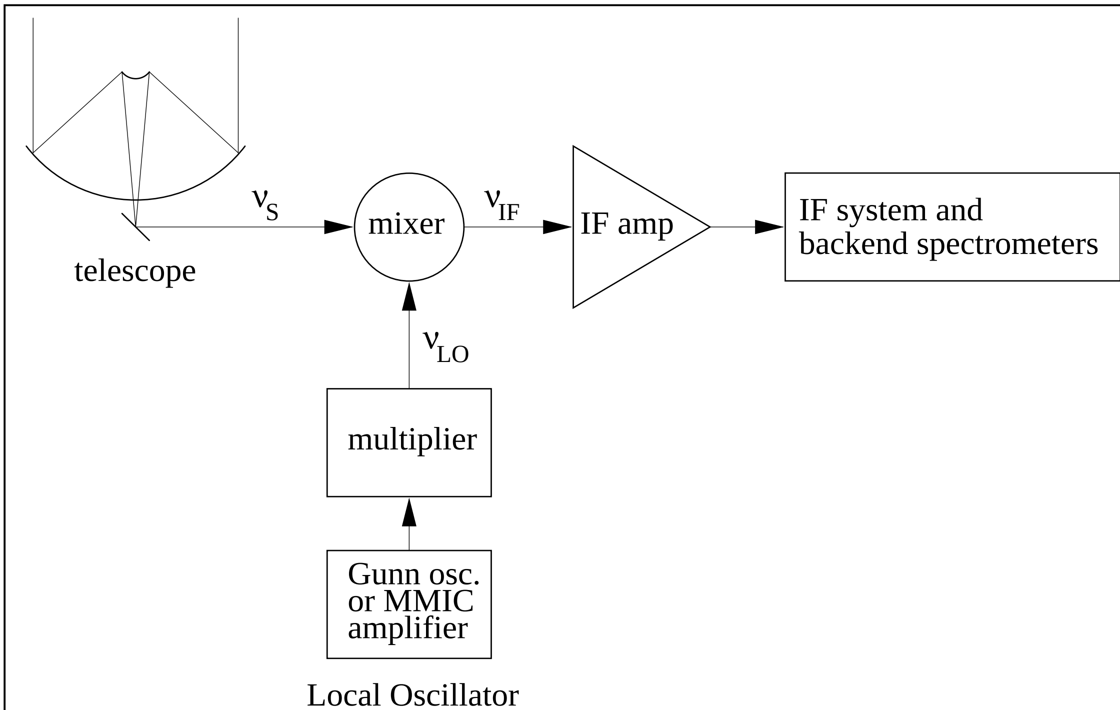

Figure 4-7. Block diagram of a heterodyne spectrometer. The telescope signal is combined with a local oscillator in a mixer, to yield the intermediate frequency

as those using semiconductor quantum wells. These may offer advantages such as higher temperature operation, but competitive devices have not yet been demonstrated. SIS mixers have achieved sensitivities within a factor of 2 of the quantum limit at millimeter wavelengths. However, mixer performance above 1 THz (λ=300 μm) degrades to typically 40 times the quantum limit. It is not yet clear whether current device concepts will allow the quantum limit to be approached at these higher frequencies, or whether new ideas will be needed.

SIS Mixers

At frequencies below 1.2 THz (λ > 250 μm) superconducting tunnel junction (Superconductor-Insulator-Superconductor or SIS) mixers offer the best performance. These devices behave essentially as photodiodes; photon-assisted tunneling produces one electron of current per photon absorbed. The tunnel junction itself is usually made using niobium (T_c = 9.2 K) or higher T_c niobium alloys such as NbN or NbTiN, along with a very thin (10—20 Å) tunnel barrier, usually aluminum oxide or aluminum nitride (AlN). It is nontrivial to fabricate high quality tunnel junctions, and only certain materials combinations have proved successful. The submillimeter signal is coupled to the SIS junction from a waveguide probe or planar antenna using a thin-film transmission line circuit. The theory of SIS mixers is quite well developed and is used extensively for detailed design. One of the main challenges for high-frequency SIS mixer design is dealing with the large parallel-plate capacitance of the SIS junction. It is necessary to fabricate an inductive tuning circuit along with the tunnel junction. This approach is very effective for millimeter-wavelength mixers, and noise within a factor of a few of the quantum limit has been achieved. At higher frequencies, especially over 1 THz (λ = 300 μm), the losses in the tuning circuit become important and cause the mixer performance to deteriorate. Nevertheless, good performance has been obtained up to 1.2 THz (λ = 250 μm) for the HIFI instrument for the Herschel Space Observatory, with noise within a factor of 20 of the quantum limit. The upper frequency limit for SIS mixers given current technology is around 1.5-1.6 THz (λ =200-188 μm).

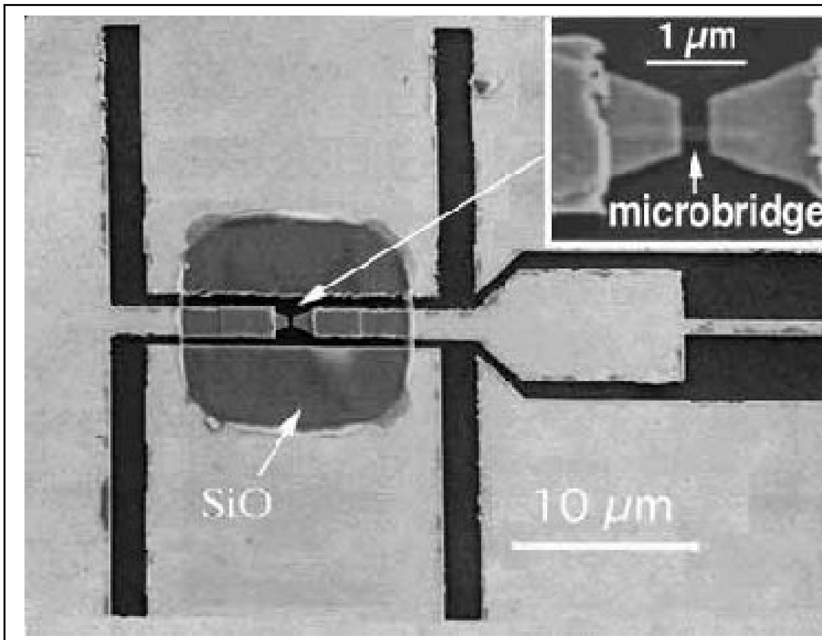

Figure 4-8 Microbridge HEB mixer designed to operate at frequencies as high as 2.5 THz. (JPL).

HEB Mixers

Hot Electron Bolometer (HEB) mixers use a small, thin superconducting film operating at the transition temperature, coupled to a waveguide probe or planar antenna. Changes in the submillimeter power deposited in the HEB cause changes in the resistance, much like the TES readouts for direct-detection bolometers. A major issue for HEB mixers is achieving a thermal time constant that is fast enough to yield a useful IF output bandwidth of a few GHz. Two methods are used: (1) phonon cooling, using ultra-thin NbN or NbTiN films; (2) diffusion cooling, using sub-micron Nb, Ta, NbAu, or Al devices coupled to normal-metal cooling “pads” or electrodes. Competitive sensitivities have been demonstrated for both types of devices. Phonon-cooled devices perhaps enjoy a modest sensitivity advantage, while diffusion-cooled devices may have broader IF bandwidths. In contrast to SIS mixers, HEB devices do not have an identifiable high frequency limit, and have been demonstrated well into the far-infrared, at frequencies exceeding 2.5 THz ($\lambda \sim 120$ μm). Typical performance levels are a factor of 40 over the quantum limit, or roughly 1 K/GHz for the double-sideband noise temperature. The detailed physics of HEB mixers is not thoroughly understood yet, although significant progress is being made.

Local Oscillators

Superconducting mixers typically require microwatt LO powers, which is roughly 3-4 orders of magnitude lower than their semiconductor (Schottky diode) predecessors. As a result, a broader range of LO sources can be used. The technologies being used or investigated include diode multipliers, lasers and optoelectronics, and “vacuum tube” oscillators such as klystrons, including novel nano-fabricated versions.

Frequency Multipliers

Multipliers use semiconductor (Schottky varactor) diodes to generate successive harmonics of a powerful millimeter-wavelength signal. Several multipliers may be cascaded to obtain high multiplication factors, e.g. x12 or x16. Dramatic advances in this area have been made over the past few years, particularly as a result of the developments for HIFI/Herschel. These advances have come through a combination of sophisticated electromagnetic modeling, a better understanding of the device physics, and vastly improved device and waveguide fabrication techniques. One major advance has been the development of millimeter-wave InP HEMT power amplifiers which drive the first stage multiplier. These amplifiers replace Gunn oscillators, and allow broadband operation with purely electronic tuning. Another major advance is the development of integrated diode multipliers, which eliminate the delicate whisker contacts used previously. These diode devices are mounted in waveguide blocks, with a waveguide horn output on the final stage. This all solid-state approach offers continuous tuning, high reliability, and relatively straightforward system integration. On the other hand, this approach becomes increasingly difficult at higher frequencies. At present, useful power from all-solid-state sources has been demonstrated to ~1.5 THz ($\lambda = 200$ μm).

Lasers and Optoelectronic Approaches

Optically-pumped far-infrared gas lasers can generate > 1 mW power levels and have been used in receiver systems, particularly for pumping Schottky-diode mixers, but are not continuously tunable and have numerous drawbacks for space applications. Semiconductor “quantum-cascade” lasers have recently been demonstrated at 4.4 THz

(70 μm), which need only DC current to produce a far-infrared output. So far only pulsed (not CW) operation has been demonstrated. Alternative approaches are being proposed, in which a far-infrared semiconductor laser is pumped using another laser, such as near-infrared diode lasers. Photomixer LO's are another approach for generating submillimeter radiation using optical or near-infrared diode lasers. The photomixer is essentially a very fast detector, and generates the submillimeter beat frequency between two optical or near-IR diode lasers. A very appealing aspect of this approach is the possibility of generating frequencies over a very wide tuning bandwidth. While substantial (mW) power levels have been demonstrated at millimeter wavelengths, the output power of photomixers drops very rapidly with frequency. Nonetheless, microwatt power levels useful for pumping HEB mixers may be feasible up to 2-3 THz (λ = 150 - 100 μm).

Vacuum-tube devices

Scaled versions of traditional microwave oscillators such as klystrons and backward-wave oscillators have been pushed to frequencies exceeding 1 THz (λ = 300 μm). While these devices are continuously tunable, they are often bulky, power hungry, require water cooling, and have limited operating lifetimes, and therefore have limited applicability for space missions. However, interest in these devices has resurfaced recently, due to novel micro- and nano-fabrication techniques that may mitigate some of the problems.

Amplifiers

Low-noise amplifiers are useful for microwave and millimeter-wave detection, particularly for CMB studies. Substantial performance gains have been achieved through the development of cryogenic InP-based HEMT devices and integrated circuits. HEMT amplifiers are also used as the IF amplifiers which follow superconducting mixers in sub-mm heterodyne systems. HEMT's may also find an important role in direct detection systems, and are being proposed as preamplifiers for several novel superconducting detector concepts.

Low-noise Millimeter Amplifiers

Over the last decade, two developments in transistor technology have produced significant reductions in noise and dissipated power and have enabled operation at frequencies above 200 GHz (λ = 150 μm). The first development was High Electron Mobility Transistors (HEMT's) based on indium phosphide substrates. This development was funded initially by the DOD, and is supported by substantial commercial demand. The second development was Monolithic Microwave Integrated Circuit (MMIC) technology, also supported by large military and commercial demand.

InP amplifiers have achieved excellent noise performance. Cooling from room temperature to 20 K lowers noise by roughly an order of magnitude, and noise of three times the quantum limit at 8 GHz (λ = 38 mm) and six times the quantum limit at 100 GHz (λ = 3 mm), with nearly uniform performance over bandwidths of 20-30% has been realized. Noise and power dissipation are roughly a factor of three lower than in GaAs devices. Compared to SIS mixers and bolometers, which require temperatures from several K to tenths of a K, InP amplifiers have modest cooling requirements. However, the typical power dissipation is several milliwatts per amplifier, which becomes an important issue for large arrays.

At frequencies above ~40 GHz (λ = 7.5 mm), the performance of MMIC amplifiers is clearly superior to that of amplifiers built from discrete transistors. MMIC amplifiers also can be assembled much more quickly, and are very reproducible.

The largest millimeter arrays built to date involve several tens of radiometers (i.e., "pixels"). If this technology is used on a CMB polarization mission, much larger arrays of up to 10^3 elements would be required. This scale should be achievable with the development of advanced packaging and manufacturing techniques.

Improvements of amplifier noise by a factor of two are expected with devices based on InSb materials. Currently under development by the DoD, InSb devices also offer the prospect of higher frequency operation and lower power dissipation. Noise of three times the quantum limit or lower should be achievable through 100 GHz (λ=3 mm) over the next few years.

IF Amplifiers

HIFI/Herschel, along with many other projects, has chosen an IF band of 4-8 GHz. Amplifier performance in this band is truly impressive, with noise temperatures of ~2 K, as low as 3 times the quantum limit. However, broader IF bandwidths are desirable. An amplifier that operates between 4-12 GHz has been demonstrated, and a 6-18 GHz cryogenic MMIC amplifier is under development.

Spectrometer Backends

A wide variety of technologies are available for backend spectrometers. The major parameters of interest are bandwidth, spectral resolution, power dissipation, and in some cases, cost. Digital correlators can provide very high spectral resolution (<< 1 MHz), can have bandwidths of 1-2 GHz per unit, can have numerous operating modes with varying resolutions and bandwidths, and are straightforward to mass-produce. This technology continues to advance rapidly, due to the large investments being made by the semi-conductor industry. However, the power dissipation remains relatively high. Acousto-optic spectrometers (AOS), such as those being developed for HIFI/Herschel, use substantially less power and can provide ~1 MHz resolution with four 1 GHz bands in a single unit. This technology is relatively mature, and only evolutionary improvements may be expected. Very wide contiguous bandwidths (4 GHz) with moderate spectral resolution (~30 MHz) can be provided with analog correlators, which have relatively low power dissipation. It appears possible to extend this technology to much wider band-widths. An alternative technique for wide band (10-20 GHz) spectroscopy has been proposed, involving optical modulation of a visible or near-IR laser.

Development Priorities

Improvements in Sensitivity

The most important goal is to continue the push toward better sensitivity. Sensitivities within a factor of a few of the quantum limit have been achieved below ~500 GHz (λ = 600 μm), but there remains much room for improvement throughout the radio to far-infrared spectrum. The need is particularly acute at frequencies between 1-3 THz (λ=300 - 100 μm), and also at millimeter wavelengths for CMB work. Modern design tools, improved understanding of the device physics, better fabrication techniques, and new materials, or better knowledge of materials parameters, will all play important roles. However, in some cases better engineering may not be the answer, and novel device concepts may be needed.

Local Oscillators

For submillimeter heterodyne receivers, the second priority is continued local oscillator development. Higher frequencies, wider tuning bandwidths, and more output power are all important. Diode multipliers are the best solution at this point, but may be overtaken by new technologies, especially at the higher frequencies.

Array Technology

Array receivers allow fast mapping. For CMB measurements, large array receivers are the second priority for development, since LO's are not needed. For submillimeter spectroscopy, array receivers are a third priority.

Other issues

Backend spectrometers should be developed in parallel with the receiver front ends. The goals here include broad bandwidths, low power, low mass, high spectral resolution, and stable operation.

Power dissipation is obviously a key issue for large arrays of HEMT amplifiers; a substantial reduction in the dissipated power would be a big benefit.

Increasing the IF and RF bandwidth of heterodyne receivers is important, since this reduces system complexity and increases the speed of line surveys. Another area to investigate is the integration of the final LO stages with the mixer, which would simplify system integration.

V. Keys to Success

There are three major drivers for detector development: 1) support of planned major NASA missions such as SOFIA and NGST, 2) maintenance and advancement of technology for competed missions in the Small Explorer (SMEX) and Medium-Class Explorer (MIDEX) programs, and 3) development of new technologies that could open up new opportunities for science either through competed missions or future strategic missions. Each of these efforts has different requirements for implementation.

Major Missions

Major missions require early development of key detector technologies to keep them off the critical path. A good example of the benefit of this approach is SIRTF, where the program obtained focal planes that met or exceeded the original requirements through concentrated efforts on detectors for each instrument. This was possible because of adequate funding by the project and an intimate knowledge of the system requirements on the part of the instrument teams. NGST is proceeding in a similar fashion but with the project overseeing the technology development. *For major missions, a coordinated, focused early detector development program overseen by the project and/or instrument teams is essential.*

Competed Missions

Both the Explorer and Discovery programs allow for focused missions to target specific, compelling science questions. Competed missions make efficient use of existing detector technology, typically leveraging developments made by large missions. These programs do not have the budget or schedule for significant detector development. Examples of competed missions that leveraged technology from SIRTF and NGST include the Wide-field Infrared Explorer (WIRE), a SMEX mission, and two MIDEX missions recently accepted for Phase A study, the Next Generation Sky Survey (NGSS) and the AstroBiology Explorer (ABE). *NASA must maintain and enhance detectors that have been developed for specific missions since this technology is the linchpin that enables the Explorer and Discovery lines to succeed with new, exciting science.*

Maintaining Existing Capabilities

There is already evidence of the disappearance of capabilities with the completion of the SIRTF focal planes, and such a problem is expected once NGST has completed its detector procurement. The cost of maintaining a core group and doing a “development cycle” in an industrial vendor type environment (either corporate or at a government lab) ranges from $400 K/year to more than $1 M/year depending on the vendor and the scope of the effort. This amount is significantly more than a typical ROSS award, but can be highly leveraged due to other programs. *It is very important to provide a mechanism for competitively funding proposals that maintain or advance key capabilities that are justified by potential science missions.*

Program Management

Maintaining technology requires the continued support of industrial and university laboratories. The difficulty that arises is determining which technologies should be maintained, especially given limited resources. Although peer review is necessary to select amongst competing proposals, it does not have a long-term corporate memory and cannot provide vision for the program. The ISMDWG believes that a detector "czar" is needed to see that the overall program is balanced and sustained. *Support of key detector technologies requires consistent management oversight that looks at the long-term goals to insure continuity of support.*

SOFIA

An important source of support for the infrared, submillimeter, and millimeter detector community is the SOFIA project. During operations, SOFIA management hopes to spend significant resources on detector development through peer reviewed grants. With its decades-long lifetime coupled with the ability to quickly change instruments, SOFIA will be an ideal testbed for advanced detector concepts. Because these detectors will potentially benefit future space flight missions, there is clear synergy between the SOFIA detector efforts and other NASA programs. *The ISMDWG is encouraged by the expression of support for detector development by the SOFIA project. We also endorse application or leveraging of other NASA technology funding to SOFIA detector needs.*

Surplus Detectors

Most major missions produce a surplus of detectors during their development stage. These residual assets can help maintain a knowledge base of this technology in the community and can provide an opportunity for innovative scientific use. They could be used to accomplish exciting science in SMEX and MIDEX missions or ground based instruments. This mechanism is not to be used as a substitute for ongoing detector development, but rather is a way to take full advantage of the technological investment from flight programs. Making residual detectors available to the community can act as a bridge between major missions, and it can keep some of the infrastructure and expertise available for competed missions. *Surplus detectors from major missions should be made available on a competed basis to the scientific community for use in the other NASA programs, ground based instrumentation, and laboratory testing, and would represent an extremely effective use of these government investments.*

Mid-TRL Development

It is clear that sustained investment in future infrared, submillimeter, and millimeter detector development will be required to assure that the expert teams remain intact, at NASA, in industry, at universities, and within the user community. NASA should consider instituting and managing a detector development program which takes a long-term, strategic view of needs as system develop through the Technology Readiness Levels (TRL) (see Appendix B). Low TRL development properly occurs through the Space Astrophysics Research and Analysis (SARA) program, while support for detailed engineering development is available through flight projects. However, mid-TRL (pre-mission) funding is much more difficult to obtain, particularly when there is little commercial or military interest. Bridging this gap is essential if promising technologies are ever to become candidates for flight. The problem becomes more serious as systems increase in complexity, and the needed amount of support exceeds the typical SARA levels. *Alternate funding mechanisms that can support the extension of promising technologies to mid-TRL's would benefit NASA Space Science efforts*.

Detector Fabrication Infrastructure

Most of the detector technologies described in this report are of interest only to NASA, and do not have significant commercial or military support. This is especially true for emerging technologies, such as the superconducting detectors. As a result, there are limited opportunities for leveraging costs, and NASA must largely assume responsibility for the entire detector development effort, including the support of the detector fabrication infrastructure. *In particular, new investments in equipment and facilities are likely to be needed to support the development of large format arrays. Such support is beyond the scope of the present SARA program.*

System-level Demonstrations

Many of the detectors being developed are entirely new and have not yet been demonstrated in astronomical instrument systems. In addition, several of the mission applications such as CMB polarization and submillimeter direct-detection spectroscopy will have very demanding performance specifications. As a result, it will be crucial to gain experience with prototype ground-based, balloon-borne, and airborne instruments using these new technologies. *We encourage NASA to maintain and enhance opportunities to conduct these system-level demonstrations.*

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Appendix A. Acronyms

2MASS	Two-Micron All Sky Survey
ABE	AstroBiology Explorer
A/D	Analog to Digital
AOS	Acousto-Optic Spectrometer
ASO	Astronomical Search for Origins
BAM	Balloon Anisotropy Measurement
BIB	Blocked Impurity Band
BLIP	Background Limited Infrared Photodetection
BOOMERANG	Bolometric Observations Of Millimetric Extragalactic Radiation ANd Geophysics
CDS	Correlated Double Sample
CMB	Cosmic Microwave Background
CMBPol	Cosmic Microwave Background Polarization Mission
CMOS	Complimentary Metal Oxide Semiconductor
COBE	Cosmic Background Explorer
CW	Carrier Wave
DoD	Department of Defense
DMR	Diffuse Microwave Radiometer (on COBE)
DQE	Detective Quantum Efficiency
FET	Field Effect Transistor
FIR	Far-Infrared (40 - ~200 μm)
FIRAS	Far Infrared Absolute Spectrometer (on COBE)
FIRB	Far Infrared Background
GUT	Grand Unified Theory
HAWC	High-resolution Airborne Widebandwidth Camera
HEB	Hot Electron Bolometer
HEMT	High Electron Mobility Transistor
HIFI	Heterodyne Instrument for the Far-Infrared (on Herschel)
HFI	High Frequency Instrument (on Planck)
HST	Hubble Space Telescope
IBC	Impurity Band Conduction

IF	Intermediate Frequency
IRAC	Infrared Array Camera (on SIRTF)
IRAS	Infrared Astronomical Satellite
IRS	Infrared Spectrograph (on SIRTF)
IRTS	Infrared Telescope in Space
ISMDWG	Infrared, Submillimeter, and Millimeter Detector Working Group
ISO	Infrared Space Observatory
ISOCAM	ISO Camera
ISOPHOT	ISO Photo-polarimeter
JCMT	James Clerk Maxwell Telescope
JFET	Junction Field Effect Transistor
KAO	Kuiper Airborne Observatory
LO	Local Oscillator
MAXIMA	Millimeter Anisotropy eXperiment IMaging Array
MIDEX	Medium-class Explorer
MIPS	Multiband Imaging Photometer for SIRTF
MIR	Mid-Infrared (5 - 40 μm)
MMIC	Monolithic Microwave Integrated Circuit
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NEP	Noise Equivalent Power
NGSS	Next Generation Sky Survey
NGST	Next Generation Space Telescope
NICMOS	Near Infrared Camera Multi Object Spectrometer (on HST)
NIR	Near-Infrared (1 - 5 μm)
NRAO	National Radio Astronomy Observatory
OSS	Office of Space Science
PACS	Photoconductor Array Camera and Spectrometer (on Herschel)
PC	PhotoConductive
PV	PhotoVoltaic
QE	Quantum Efficiency
QWIP	Quantum Well Infrared Photoconductor
RF	Radio Frequency

ROSS	Research Opportunities in Space Science
SAFIR	Single Aperture Far Infrared Telescope
SAFIRE	Submillimeter and Far Infrared Experiment (on SOFIA)
SARA	Space Astronomy Research and Analysis
SCUBA	Submillimetre Common-User Bolometer Array
SED	Spectral Energy Distribution
SHARC	Submillimeter High Angular Resolution Camera
SEU	Structure and Evolution of the Universe
SIN	Superconducting-Insulator-Normal
SIRTF	Space Infrared Telescope Facility
SIS	Superconductor-Insulator-Superconductor
SMEX	Small Explorer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPIRE	Spectral and Photometric Imaging REceiver (on Herschel)
SQUID	Superconducting Quantum Interference Device
SSAC	Space Science Advisory Committee
SSE	Space Science Enterprise
STJ	Superconducting Tunnel Junction
Sub-mm	Submillimeter (200 to ~1000 μm)
TES	Transition Edge Sensor.
TPF	Terrestrial Planet Finder
TRL	Technology Readiness Level
WFC3	Wide Field Camera 3 (on Hubble Space Telescope)
WIRE	Wide Field Infrared Explorer
YSO	Young Stellar Object

Appendix B. NASA Technology Readiness Levels Summary

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and flight qualified through test and demonstration (ground or space)
TRL 9	Actual system flight proven through successful mission operations