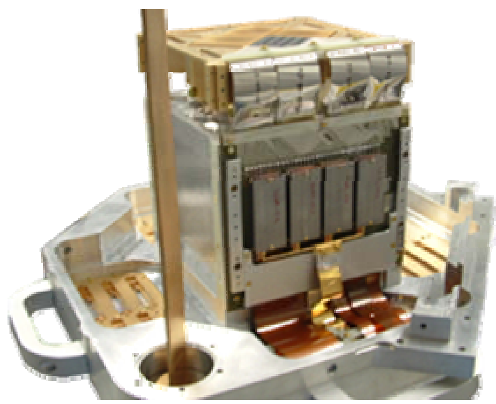
Superconducting Detector Arrays for Far-Infrared to mm-Wave Astrophysics

James J. Bock (James.Bock@jpl.nasa.gov, 818-354-0715)
Jet Propulsion Laboratory, California Institute of Technology

Philip Appleton[a], NHSC, Caltech
Lee Armus[a], IPAC
John Bally[a], U. Colorado
Dominic Benford, GSFC
Andrew Blain[a], Caltech
Matt Bradford, JPL/Caltech
Asantha Cooray[a], UC Irvine
Mark Devlin, U. Penn
Scott Dodelson[a], FNL
Darren Dowell[a], JPL/Caltech
Paul Goldsmith[b], JPL
Sunil Golwala[a], Caltech/JPL
Shaul Hanany[b,c], U. Minnesota
Martin Harwit[b], Cornell
Wayne Holland[a], UK ATC
William Holzapfel, UC Berkeley
Matt Kenyon, JPL
Kent Irwin, NIST
Eiichiro Komatsu[a], U. Texas
Andrew Lange, Caltech/JPL
David Leisawitz[a,b], GSFC
Adrian Lee, UC Berkeley
Brian Mason, NRAO
John Mather, GSFC
Harvey Moseley, GSFC
Steve Meyer[b], U. Chicago
Steven Myers[a], NRAO
Hien Nguyen, JPL
Valentyn Novosad, ANL
Bernard Sadoulet[a], UC Berkeley
Gordon Stacey[a], Cornell
Suzanne Staggs, Princeton
Paul Richards, UC Berkeley
Grant Wilson, U. Massachusetts
Min Yun[a,b], U. Massachusetts
Jonas Zmuidzinas, Caltech/JPL

[a]*Lead author of a Scientific White Paper benefiting from this development*
[b]*Lead author of a Programmatic White Paper requiring this technology*
[c]*Primordial Polarization Program Definition Team Chair*



SCUBA2 Focal Plane

Abstract: Detector technology will determine what is scientifically possible in far-infrared and millimeter-wave astrophysics in the next decade. Focal planes with large, background-limited detector arrays will be the enabling capability for studies of inflation via CMB polarization, the evolution of large-scale structure via CMB lensing and SZ surveys, the formation and evolution of galaxies, the early stages of star formation, and the development of accretion and debris disks in stellar systems.

These ambitious goals are the centerpieces of both space-borne and ground-based programs seeking to harness the ongoing revolution in long wavelength detector technology, with both pixel sensitivity and array format doubling roughly every two years. Much of this progress is due to the emergence of new superconducting detector and multiplexer concepts. Superconducting detectors also have scientific applications in X-ray astronomy, optical-UV astronomy, and dark matter detection, with numerous examples of technical cross-fertilization. Successful continued development of these technologies relies on a small community of scientists and technologists who are also actively engaged in deploying and demonstrating these technologies in astrophysics projects and instruments.

1. Scientific Opportunities

The programs planned in the far-infrared, sub-millimeter, and mm-wave bands in the upcoming decade promise rich scientific return in astrophysics and cosmology [S1-S23]. This region of the spectrum provides access to the cosmic microwave background (CMB), infrared luminous galaxies, and an unobscured view of early star formation and forming planetary systems. Detector technology is the driver behind the dramatic leaps in capability required for these investigations. Successful development of large-format, high-sensitivity focal plane arrays enable a range of observations from ground-based and orbital platforms [P1-P11]. Superconductivity offers a band-gap ideally suited to the far-IR/mm-wave band, provides for low dissipation readouts needed for arrays, and is thus the natural basis for far-IR/mm-wave detector arrays. These technologies have close analogs to the energy-resolving sensors [S24] used in X-ray, UV, and optical astronomy, and their development will bring technical synergy to these applications.

1a. Inflation and CMB Polarization: The theory of Inflation, a period of exponential expansion in the early universe, explains the high degree of isotropy in the CMB, the approximately flat geometry of the universe, and the low abundance of magnetic monopoles. The generic predictions of Inflation have been verified in precise measurements of CMB temperature and polarization anisotropy. Despite passing increasingly rigorous experimental tests, the physical basis of Inflation remains elusive. If related to grand-unification, as many theorists suspect, the energy scale of Inflation would be $\sim 10^{16}$ GeV, well beyond the reach of terrestrial particle accelerators, but possibly detectable via a polarization signature in the CMB.

CMB polarization serves as a new observable of Inflation. Gravitational waves produced by inflation impart a polarization signal to the CMB which can be distinguished from that of scalar perturbations by its B-mode vector properties. The amplitude of the inflationary polarization signal depends on the properties of Inflation, and can be used to distinguish between models [S1]. Due its profound cosmological implications, a program [P1] of sub-orbital experiments are planned to first probe the amplitude of inflationary polarization, followed by the Einstein Inflation Probe satellite experiment [P2] to extract all cosmological information available in polarization. Inflation may also produce a measurable departure from scale invariance and non-Gaussianity [S2]. Large arrays of background-limited, polarization-sensitive detectors will be needed to provide a sensitivity increase more than 10 times that of *Planck*, operating from 30 – 300 GHz [P3] for removal of polarized Galactic foregrounds [S3].

1b. Fine-Scale CMB Maps and the Sunyaev-Zel'dovich Effect: The full CMB sky has been mapped with excellent precision down to an angular resolution of 0.2º by WMAP, and smaller regions have been surveyed down to ~0.1º. At finer angular resolution, more of the primordial power spectrum from Inflation is revealed. Secondary effects on the CMB encode new cosmological information, primarily into higher-order correlations of the CMB, and into correlations of the CMB with other tracers of large scale structure and kinetics [S4]. For example, measurements of the gravitational lensing of the CMB by the intervening matter field are sensitive to the growth of structure and to the geometry of the universe, and thus probe the nature of the dark energy at early times and the effect of neutrino mass on structure growth. Moreover, fine-scale maps of the CMB can be used to find clusters of galaxies through their unique spectrum. With optical follow-up to determine redshifts, and ancillary measurements to constrain the mass selection function, the number density of clusters as a function of redshift or mass can be obtained. The number density depends on the dark energy density and history [S5].

Fine-scale maps of the CMB temperature will come from SPT and ACT using kilopixel arrays in dedicated surveys. New instruments will measure the fine-scale polarization and temperature anisotropy at better sensitivities, and make high-resolution maps of clusters to probe the details of their formation and use as astronomical standard rulers [S6].

1c. Far-Infrared Galaxies: Far-infrared observations are coming of age as a probe of the origins and evolution of galaxies. More than two decades ago, IRAS discovered a class of galaxies in the local Universe whose total power output rivals the quasars, but for which more than 90% is emitted in the far-infrared. The energy sources for these luminous infrared galaxies are so deeply embedded that virtually all of the energy is absorbed and re-radiated in the far-IR by dust. While they may be detectable, these galaxies cannot be meaningfully studied in the optical or even the near-IR. ISO and Spitzer surveys in the mid and far-IR have shown that this dusty galaxy population is rapidly evolving, meaning that dust-obscured energy produced when the universe was half its present age was 10 - 30 times more powerful than today, and larger than the energy released in the UV / optical at that time.

The first forays into ground-based sub-millimeter imaging reveal a cosmologically significant [S7] class of galaxies dominated by thermal infrared emission. These galaxies are even more luminous than local analogs, and must have large star formation rates (~1000 M_{sun} / year), massive AGN activity, or both. Based on limited redshift surveys, they appear to have a history similar to the quasars, with an abundance peaking when the universe was 2-3 billion years old. Based on their history, and their huge power output, it has been suggested that they represent the formation phase of giant elliptical galaxies [S8]. New imaging instruments are now being deployed (Herschel and instruments in Table 2) which will outstrip present surveys by several orders of magnitude.

The key to studying these galaxies is far-infrared spectroscopy, offering a rich suite of lines largely immune to dust extinction that probe the phases of the interstellar medium in its ionized, neutral atomic, and warm molecular phases. Measurement of these gas-phase and solid-state features provides redshifts, gas masses, metal content, dust properties, and physical conditions from which luminosities, stellar populations, star formation histories, and AGN content can be derived [S9, S10]. Wideband far-infrared spectra provide a perfect complement to high-resolution measurements with ALMA [S11]. The far-infrared may reveal H_2 and metal fine structure lines which are thought to regulate the formation of the first galaxies [S12]. Very sensitive detectors on a cold space-borne telescope will enable dramatic gains in sensitivity [P4, P5]. The JAXA-led SPICA mission, a planned 3.5 meter 5 K telescope currently in phase-A study in Japan, provides an opportunity for US participation [P6], paving the way for the arrays planned for SAFIR/CALISTO [P7] and SPIRIT [P8].

1.d Star Formation: The processes involved in the active formation of stars are mostly contained within dense, dusty molecular clouds, and the far-infrared is particularly important since most of the luminosity emerges in this band, especially in the early onset of star formation. Although most sites of star formation have now been identified, there is widespread agreement that new wide-field, high-resolution, multi-wavelength continuum surveys are needed to characterize protostellar clumps in an unbiased and unconfused way [S13-S16], which motivates far-IR capability beyond Herschel [P4, P5]: larger apertures (single dish or synthesized), and larger detector arrays. Unbiased chemical surveys are needed, which can be accomplished for large samples with grating spectrometer surveys.

Polarization measurements at far-infrared/submillimeter wavelengths provide unique information about the magnetic field in interstellar clouds, both in orientation and field strength. Sparse measurements suggest that magnetic fields dominate the energetics of diffuse Galactic gas [S17, S18] and likely play an important role in molecular cloud evolution as well [S19]. Given our lack of knowledge of the field strength and structure in most interstellar clouds, and the small number of techniques available for measuring magnetic fields, far-infrared/sub-mm polarimetry should be fully explored. Existing measurements of polarized thermal emission show pervasive alignment of dust grains, leading to the prospect of mapping magnetic fields in the entire Galaxy.

Large ground-based telescopes (e.g. GBT, CCAT [P9], LMT [P10]) have the potential to make comprehensive protostellar surveys with high spatial resolution using very large ~10^6 element detector arrays. CMBPOL [P2] may also carry out high-sensitivity all-sky measurements of polarized interstellar dust in bands $\nu \geq 500$ GHz in order to characterize the role of magnetic fields in Galactic structure and star formation.

1e. Circumstellar Disks: The far-infrared/sub-mm part of the spectrum offers unique and vital insight into the formation and evolution of other solar systems [S20-S23]. At these wavelengths, the emission from the bulk of the circumstellar dust and gas is most readily detected. Far-infrared/sub-mm observations of protoplanetary disks sample the mass and chemical composition of the material from which planets form and, with sufficient angular resolution, test theories for their assembly. Debris disks trace the subsequent evolution of solar systems and constrain the positions of unseen planets due to their dynamical interaction with the dust.

ALMA, with its exquisite angular resolution and large collecting area, will be a giant leap forward in observations of circumstellar disks. However, key transitions of molecular hydrogen, water, and hydrides emitted by younger, gas-rich disks are in the far infrared, beyond the spectral coverage of ALMA. Large ground-based telescopes, using large-format ~10^6 element arrays will provide high-resolution wide-field mapping, to survey candidate star clusters and catalog a large sample of circumstellar disks for high-resolution imaging with ALMA. A new generation of chemical surveys of protoplanetary disks coming from Herschel can be extended to gas-poor systems using a high-sensitivity spectrometer on SPICA [P6] and SAFIR/CALISTO [P7]. High resolution far-infrared images with the SPIRIT interferometer [P8] will provide detailed maps of dust and line emission.

1.f. Synergy with Energy-Resolving X-ray, UV/Optical and Dark Matter Detectors: Superconducting detectors also promise revolutionary new capabilities for calorimetry. Imaging spectroscopic detectors for soft X-rays, 1-10 keV, with high resolution, $E/\Delta E \sim 1000 - 5000$ are planned for the Japanese NeXT mission and eventually for IXO. Such detectors will be used to study the velocity structure of material in accretion disks around black holes, and conduct high-resolution spectroscopy over wide fields in galaxy clusters, supernova remnants, etc. Energy-resolving NIR, optical and UV detectors can provide coarse spectroscopy with microsecond time resolution and high quantum efficiency to study spectroscopic phenomena with fast time variation like pulsars, obtain photometric redshifts for high-redshift galaxies, and study the temperature, pressure, and ionization state of the cosmic web. Finally, there is substantial technical overlap with detector development for particle dark matter searches [S24].

Development for calorimetry has driven the state of the art in understanding the physics of the TES films and cryogenic multiplexing electronics. A variety of other detectors may also be appropriate for calorimetry, including MKIDs, magnetic microcalorimeters, and SIS and NIS tunnel junctions. Cross-fertilization between FIR/submm/mm and these other efforts has been fruitful in advancing the state of the art for all such applications.

2. Technology

Far-infrared / mm-wave scientific capability is predicated on continuing the geometric growth of detector sensitivity and formats over the last 6 decades, shown in Fig. 1, into the next decade.

Individual detectors achieved photon noise limited performance for ground-based imaging in the 1990s. The photon noise from only astrophysical sources, achievable in space with a cold telescope, ~10^{-18} W/√Hz and varying somewhat with wavelength, is now within demonstrated sensitivities. Imaging and polarimetry in the next decade will thus be driven not by detector sensitivity but by array formats. Far-infrared spectroscopy from a cold telescope however requires sensitivity ~10^{-20} W/√Hz to reach the astrophysical photon noise limit. Already new devices have been demonstrated that approach this requirement. Achieving this sensitivity in working detector arrays remains a challenge for the coming decade.

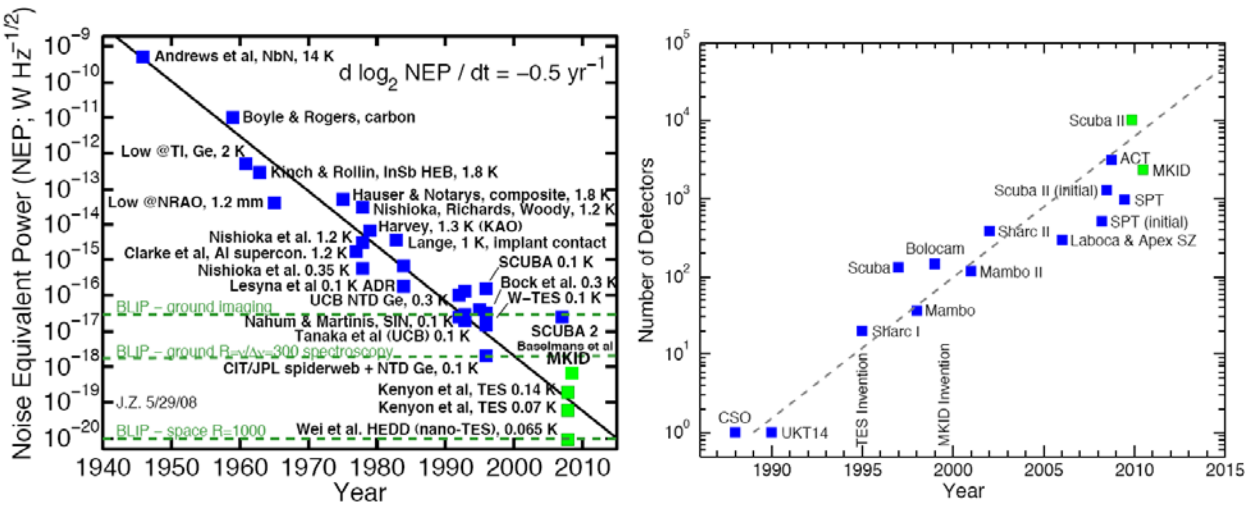


Fig. 1. Detector sensitivity **(left)** has historically doubled every 2 years over the past 70 years. Detector arrays **(right)** have doubled in format every 20 months over the past 10 years.

Two detector technologies show promise to develop the arrays needed in the next decade. Transition-edge superconducting (TES) bolometers and Microwave Kinetic Inductance Detectors (MKIDs) are based on different principles of superconductivity. TES bolometers have demonstrated NEPs sufficient for imaging, with good low-frequency noise stability. Multiple instruments are currently in development based on arrays up to 10,000 detectors using both time-domain multiplexing (TDM) and frequency-domain multiplexing (FDM) with SQUIDs (Superconducting QUantum Interference Devices). MKIDs have recently demonstrated competitive sensitivity, and plans are afoot to field the first astronomical camera based on this technology. Both sensors show potential to realize the very low ~10^{-20} W/√Hz sensitivity needed for space-borne spectroscopy. RF-based multiplexing offers a large increase in the multiplexing factor compared with SQUID TDM/FDM, a key for developing the next generation of arrays with up to 10^6 elements.

2b. Detectors: <u>*TES Bolometers*</u>: A TES bolometer is a thermal detector where photons are absorbed and thermalized and the resulting energy is sensed as a temperature rise (see Fig. 2). A TES film serves as a sensitive thermometer based on the steep change in resistance in the superconducting-to-normal transition region. The temperature of a TES can be tailored by using a bilayer film consisting of a thin layer of normal metal and a thin layer of superconductor, resulting in a tunable transition temperature. Bolometers can be made more sensitive by decreasing their thermal conductivity and temperature. For achieved thermal isolation and heat capacities, this requires operational temperatures in the range of 50 - 300 mK.

TES sensors are voltage-biased, providing strong electro-thermal feedback that linearizes detector responsivity and reduces the response time, offering advantages over semi-conducting bolometers. TES bolometers are inherently low impedance devices, so they are well matched to DC SQUID amplifiers, which have a large noise margin over the detector noise. This permits the bolometer to be read out in a multiplexed fashion by SQUIDs operating at the base temperature of the bolometer. TES bolometers can be made with filled absorbers for maximum mapping speed, or coupled to antennas. Theoretical descriptions of TES bolometers are well-developed in explaining most aspects of response, noise, and dynamical behavior. TES bolometers have demonstrated near-ideal noise performance in full systems, though work remains to eliminate all excess noise. Large-format arrays are presently being used in several instruments and the basis of many more planned in the near future (see Fig. 3 and Table 2).

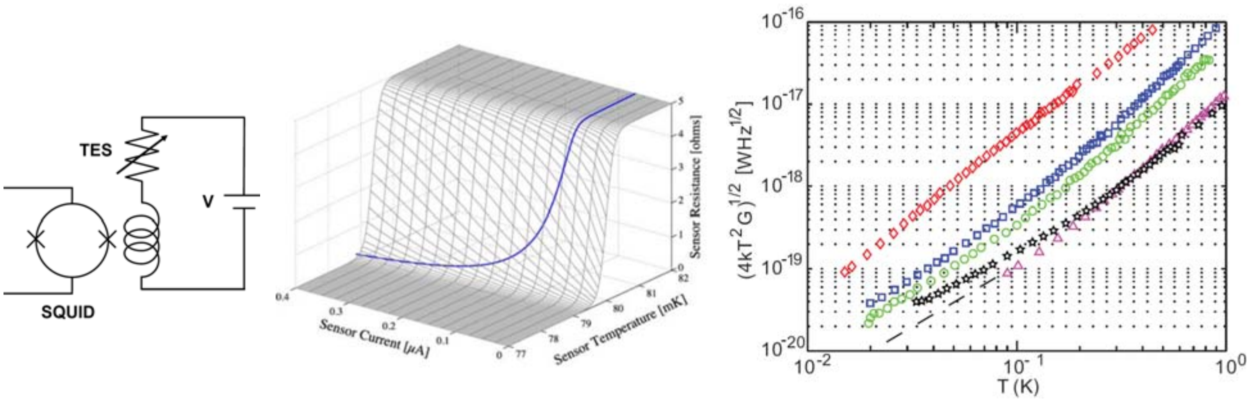


Fig. 2. Left: A TES bolometer is voltage biased on its superconducting transition, and readout with a SQUID current amplifier. The voltage bias maintains the device in the middle of the transition **(center)** through negative electrothermal feedback, with electrical power compensating for changes in optical power. **Right:** Silicon nitride beams can provide sufficient thermal isolation for phonon noise equivalent power in the 10^{-20} W/√Hz regime.

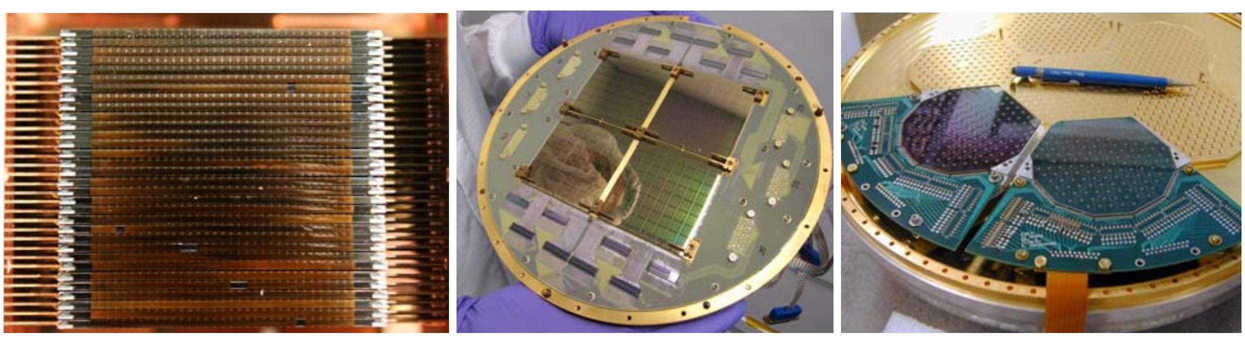


Fig. 3. Focal planes based on TES bolometers. **Left:** The 220 GHz ACT array, comprising 32 x 32 1 mm^2 TES detectors built as rows. The 1x32 detector chips were fabricated at NASA/GSFC, integrated onto silicon cards, and read out with TDM electronics from NIST and UBC. **Center:** The 150 GHz BICEP2 focal plane with 512 polarization-sensitive antenna-coupled bolometers made at JPL coupled to TDM SQUID readouts. **Right:** The EBEX focal plane in assembly using feed-coupled spiderweb TES bolometers and FDM readouts fabricated at UC Berkeley.

MKID Sensors: The basic operating concept of an MKIDs sensor is explained in Fig. 4. The major attractions are simplicity, flexibility, and the large arrays are enabled by RF multiplexing. MKIDs are in principle limited only by quasiparticle generation-recombination noise to NEP ~ 10^{-20} W $Hz^{-1/2}$. Their sensitivity degrades gracefully with increased optical loading. MKIDs are now approaching the state of the art for sub-mm arrays. The first large-scale MKID system is a camera being constructed for the CSO, to be delivered in 2010 with a 24 x 24 array of antenna-coupled spatial pixels each simultaneously sensing four spectral bands with a total of 2034 detectors. This instrument will demonstrate MKIDs in a ground-based application comparable in scale and sensitivity to current TES-based focal planes.

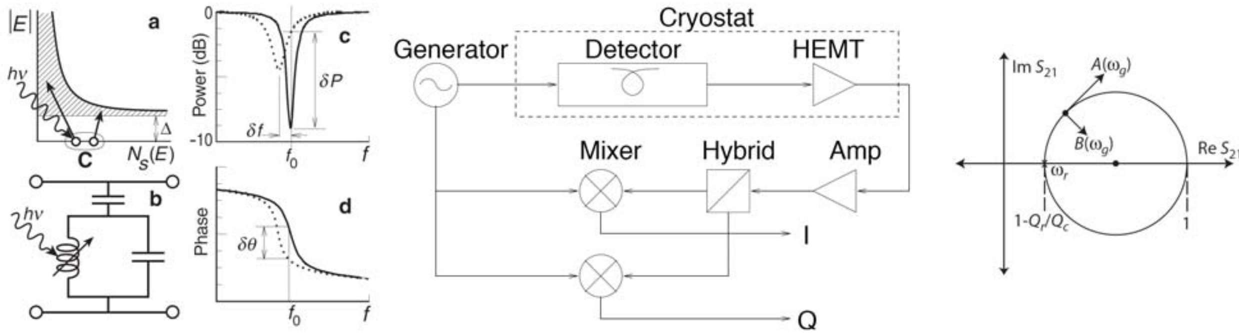


Fig. 4. Left: **a)** Photons break apart superconducting (Cooper) electron pairs with ~0.2 meV binding energy, creating single electrons or **b)** The parallel LC equivalent circuit for a superconducting resonator, whose transmission response is shown in **c)**. Breaking Cooper pairs increases the surface inductance L_s and (microwave) surface resistance R_s of the film, which reduces the center frequency f_0 and quality factor Q_r of the resonator. **Center**: Setup for measuring the complex forward transmission, $S_{21} \propto I + jQ$. Sweeping the generator frequency yields the resonance circle shown on the **right**. At generator frequency ω_g, the complex vectors $A(\omega_g) = \partial S_{21} / \partial \ln\omega_r$ and $B(\omega_g) = \partial S_{21} / \partial Q_i^{-1}$ illustrate the adiabatic response to changes in its resonance frequency ω_r and internal dissipation Q_i^{-1}. These directions are orthogonal, so the two effects may be measured simultaneously.

Coplanar waveguide resonators (see Fig. 5) now demonstrate sufficiently high quality factor to be limited by optical loading, not film quality. Such structures are easily fabricated, requiring a single superconducting film. In addition to quasiparticle generation-recombination noise, MKIDs suffer an excess frequency noise with a $f^{-1/2}$ spectrum and a level that decreases as the microwave power and operating temperature are increased due to the interaction of the resonators with a surface distribution of two-level system (TLS) fluctuators. Recent resonator designs have shown significantly reduced low frequency noise with no sacrifice in responsivity.

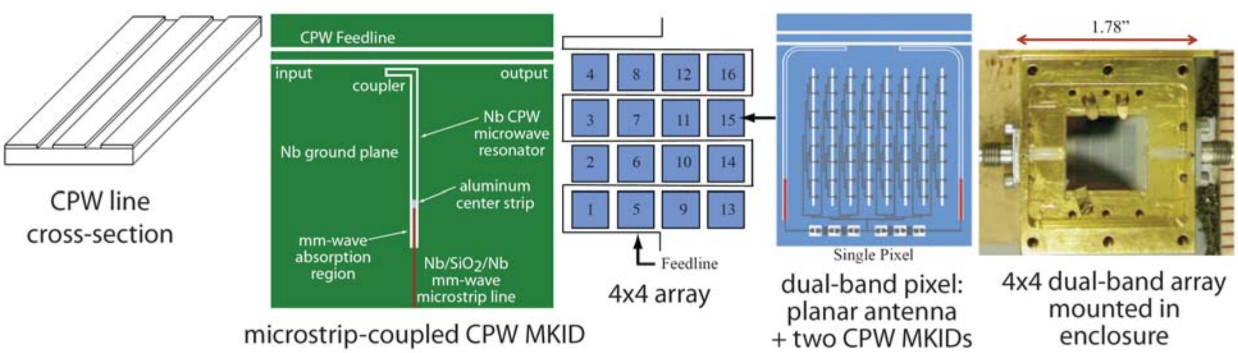


Fig. 5. Far left: the geometry of a coplanar waveguide (CPW) transmission line. **Left**: An MKID constructed using a λ/4 CPW resonator. The open-circuited end is coupled to a CPW feedline, while the mm/sub-mm radiation is absorbed at the short-circuited end. The absorption region is created by using Al for the center-strip material in this region ($2\Delta_{Al}/h$ = 90 GHz). A thin-film Nb ($2\Delta_{Nb}/h$ = 720 GHz) microstrip line couples radiation into the Al. **Right**: A dual-band pixel uses a wideband multi-slot planar antenna to collect radiation, planar lithographed filters to define the bands, and two CPW MKIDs for the two bands. A 4 x 4 array of such pixels can be frequency-multiplexed to a common feedline which is meandered between the pixels. **Far right**: A photograph of a 4 x 4 dual-band array.

A group at SRON Utrecht have made use of the fact that the TLS noise shows no apparent dissipation component above the noise floor of the cryogenic HEMT amplifier while the optical response shows both frequency and dissipation responses, resulting in dissipation-readout NEPs as low as 7×10^{-19} W Hz$^{-1/2}$ for an Al MKID. The SRON group hopes to demonstrate an MKID instrument with a few hundred pixels at either the IRAM 30 m or the APEX 12 m telescope in 2009. Thanks to the physical understanding of the TLS noise, prospects for pushing the NEP values another order of magnitude lower, into the ~10^{-20} W $Hz^{-1/2}$ territory needed for dispersive far-infrared spectroscopy needed for SPICA, are quite good using advanced resonator designs and materials.

2c. Multiplexed Readouts: One of the challenges in fielding kilopixel receivers is the development of appropriate readout technology. For large arrays, the signals must be multiplexed at cryogenic temperatures, so that a small number of wires to room temperature can read out a large number of bolometers. In the past few years, multiplexed readout technology for TES bolometers has matured, and numerous instruments are now in the field that read out a thousand or more pixels using multiplexers based on SQUIDs. New techniques based on RF multiplexing promise to extend the achievable array sizes even further.

SQUID multiplexing: SQUIDs are the amplifiers of choice for providing sensitive pre-amplification for the current signals from TES bolometers, and can be used to multiplex TES bolometer signals at the cold stage. Arrays based on two different SQUID multiplexing techniques, time-domain (TDM) and frequency-domain (FDM), have been successfully deployed in the field.

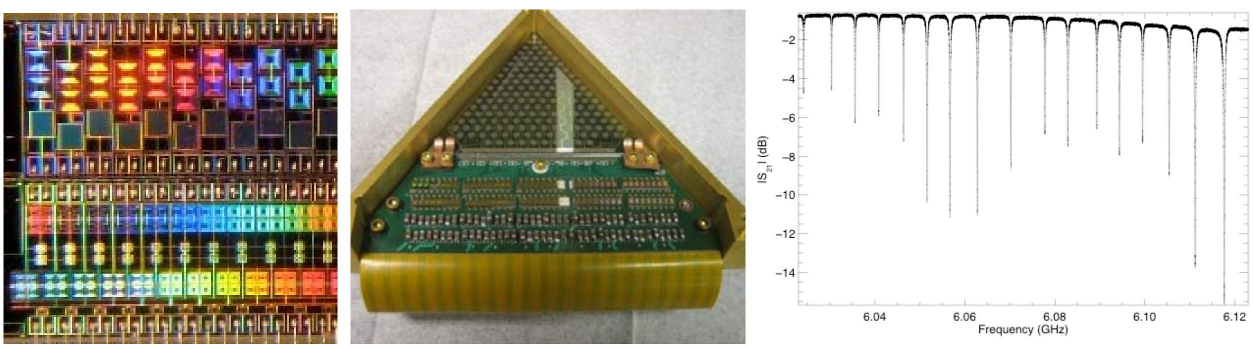


Fig. 6. Left: A 32-channel SQUID TDM chip. The 32 SQUIDs are turned on sequentially and read out through one output channel. **Center:** SPT sub-array read out by FDM SQUIDs. **Right:** closely spaced microwave resonances from an MKID array used in RF multiplexing.

In TDM, which was developed at NIST, many SQUID-coupled TES bolometers are read out through a single set of wires by turning the SQUIDs on one at a time (see Fig. 6). With proper design, the multiplexed SQUID amplifiers do not appreciably contribute to the system noise. SQUID TDM is a mature technology that is deployed in many astronomical instruments with multiplexing factors of up to 40:1.

At Berkeley, SQUID multiplexers based on FDM have also been developed. In this approach, many TES bolometers are read out biased with different sinusoidal voltages in the frequency range from 300 kHz to 1 MHz. Each bolometer is biased at a different frequency. Intensity variations from the sky-signal change the bolometer resistance and amplitude modulate the bolometer current such that the sky-signal from each bolometer is transferred to a sideband adjacent to its carrier. Thus, the signals from different bolometers are uniquely positioned in frequency space, so they can be summed and connected through a single wire to a SQUID preamplifier. SQUID FDM is a mature technology that is being deployed in multiple astronomical instruments with multiplexing factors of 8:1 and higher.

RF multiplexing: While either TDM or TFM, SQUIDs operated at MHz frequencies have sufficient performance to read out ~10^4 TES bolometers, a much higher multiplexing factor can be achieved by using superconducting microresonators to achieve dense frequency domain multiplexing at microwave frequencies (see Fig. 6). This technique uses wide bandwidth high electron mobility transistors (HEMTs) to provide several GHz of bandwidth, potentially allowing thousands of detectors to be read out through a single transmission line. This technique, developed originally at Caltech and JPL for MKIDs, is also applicable to TES bolometers coupled to resonators through dissipationless RF SQUIDs.

2d. Antenna Coupling: Superconducting low-loss RF transmission networks provide a new capability being exploited for CMB polarimetry. These devices provide a high degree of on-device functionality useful for building large arrays, including beam formation, polarization analysis, and spectral band definition. Antenna coupling offers advantages over corrugated feedhorns in efficiency, simplicity of construction, and cryogenic mass, minimizes the thermal mass of the sensor, and scales to the many frequency bands needed for the Inflation Probe. Two types of planar-antenna coupling are currently being explored, phased-array planar antennas and lens-coupled antennas. A phased-array antenna, common in radar and communications applications, combines a large number of small antenna elements in phase to provide beam directivity. A lens-coupled device uses a small antenna attached to a small lens to provide beam definition. The area under the lens is available for filters, switches, and readout components. Lens-coupled antennas are being developed to sense multiple frequency bands and two polarizations simultaneously. Superconducting transmission line can also enable truly novel concepts such as compact transmission-line spectrometers, integral with the focal plane.

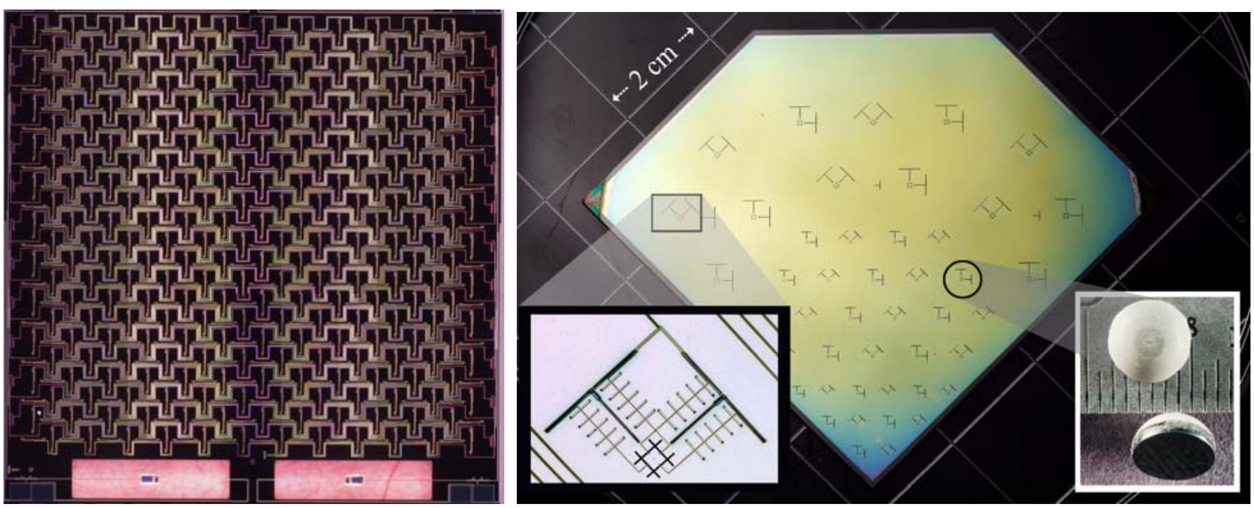


Fig. 7. Left: Planar phased-array antenna, which includes the functions of beam definition, polarization analysis, band filtering, and detection with two TES bolometers fabricated at JPL. This layout illustrates the JPL planar antenna concept. **Right:** Array of TES bolometers fabricated at UC Berkeley coupled by a dual-slot antenna and hemispherical lens. The left inset shows a close-up of a single pixel where the antenna is at bottom and the RF filters connect the antenna to the "T" shaped TES bolometer. Right inset shows and hemispherical lens with antireflection coating. This array has 90 bolometers distributed between 90, 150 and 220 GHz.

3. Development Program

NASA has historically been the leading US agency for promoting the development of long-wavelength detector technologies. In the past decade, the Herschel-Planck flight program was the basis of the NTD bolometer arrays made widely available to the US astrophysics community, and early development for Herschel began the TES bolometer arrays and SQUID multiplexers now seeing widespread application. Such programmatic NASA funding, along with dedicated technology (NASA code-R) funding, has since been eliminated. Currently, funding to reach the ambitious requirements of future space missions, summarized in Table 1, is supplied by the NASA ROSES program, along with internal funding at NASA centers, and to a lesser degree NSF, DOC and DOE funding supplemented by private sources.

Table 1. Requirements for Future Space Applications

Science	**Future Opportunities**	**Requirements**		
		NEP [W/√Hz]	**τ [ms]**	**Format**
CMB Polarization	Inflation Probe	$1\text{-}5 \times 10^{-18}$	1-30	10^4
Galaxy evolution, Star formation, Circumstellar disks	SPICA/BLISS	$3\text{-}30 \times 10^{-20}$	100	5000
	SAFIR/CALISTO imaging	3×10^{-19}	10	10^5
	SAFIR/CALISTO spectroscopy	3×10^{-20}	100	10^5
	SPIRIT	1×10^{-19}	0.2	256

The current funding structure is useful for promoting new detector concepts, but insufficient to advance increasingly complex focal planes to readiness for space. We propose a new base-technology program necessary to develop and maintain the capability to produce these arrays. In order to minimize program risk for major missions, we want the detector *systems* to be at TRL-6 by mission start, so that the missions are designed with proper systems architectures from inception. The base program will support the necessary production, integration, and test processes, including integration with electronics. In Table 2, we show a possible development sequence, which will evolve with TES and MKID technical progress.

These developments support a number of communities, and we assume the funding to field the devices will come from the projects benefiting from them. We assume that funding to test emerging concepts will come from NASA ROSES. The base technology program we describe is designed to take existing detectors into mature, large scale systems. As new ideas mature from the ROSES program, they will be included in the base technology program.

Table 2. Technological Development Path and Funding

Capability	**Current Instruments**	**Technology Milestones**	**Cost [$M/yr]**
CMB Polarimetry	ABS, ACTpol, BICEP2, EBEX, Keck, MBI, PIPER, Poincare, PolarBeaR, SPIDER, SPTpol	2010 Planar polarimeters 2011 Balloon demonstrations 2014 Large integrated arrays	5
FIR / mm Imaging	ACT, APEX, GISMO, HAWC, MUSTANG, MKID-Cam, SABOCA, SCUBA2, SPT	2009 SCUBA2 operation 2011 MKID camera operation 2013 Very large TES/MKID arrays	2
FIR / sub-mm Spectroscopy	SAFIRE, ZEUS, Z-SPEC	2010 Low-NEP TES pixels 2012 Low-NEP MKID pixels 2014 Demos of large arrays	2.5

The production of large format integrated detectors requires versatile micro-fabrication facilities and experienced staff. Successful development thus must make best use of existing facilities, and provide funding continuity so capabilities once developed are not lost. With the long intervals between major missions, this is a critical issue. Vigorous sub-orbital and ground-based instrumentation projects are essential for detector development, resulting in a rapid maturation of systems solutions that maximize instrument performance, ease integration, and reduce environmental susceptibility, all important elements in controlling the cost of major missions from the outset. Taking as input the mission requirements in Table 1 [P1, P6-P8], we estimate ~5 FTEs per facility involved in design, fabrication, and testing for the CMB program along with supporting equipment. The far-infrared imaging and spectroscopy development builds on the

CMB development and shares resources and core technologies, and can be carried out at a reduced cost with parallel development.

4. Recommendations

We propose that the compelling science goals of the next decade require an invigorated base technology development program consisting of stable NASA funding supporting the major labs carrying out this work. Such NASA programmatic funding will support the large, and increasingly complex, facilities and personnel required for the production of these large arrays. The NASA ROSES program complements this base technology funding, by promoting the emergence of new detector concepts throughout the US. Furthermore we encourage DOE to expand its development in coordination with NASA. Superconducting detectors will find immediate and compelling scientific applications on ground-based facilities, funded through NSF, and balloon-borne experiments, funded by the NASA ROSES program.

References

Science White Papers

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