XV. Technology Status and Roadmaps

Although our baseline design for SAFIR appears remarkably achievable, based on missions being developed now, it is clear that realizing the full potential of the observatory will require high value technology advances, and these advances should dictate routes for near term investment. In this section, we identify four lines of technology that show great promise for SAFIR and, very significantly, for many high priority Universe missions. For each of these, we review the state-of-art, consider critical needs for improvement, and roadmap an investment strategy for the agency that would result in the necessary capability for SAFIR.

A. Detector Technology
Mid- and far-infrared detectors need expansion to larger formats that can take advantage of the large field of view of SAFIR. Detector sensitivities that are a factor of ten greater than currently available would allow background-limited performance at all wavelengths even in moderate resolution spectrographs. Efforts to date provide credible routes to these, but need investment. By providing a platform for test and operational characterization, SOFIA will offer missions like SAFIR important resources.

B. Mirror Technology
Lightweight, stiff, cryo-capable mirror technologies are of great importance to large space telescopes. Efforts to date are close to achieving the characteristic needed for SAFIR, but need renewed investment. The AMSD program to identify relevant substrate designs is reviewed.

C. Distributed and Active Cryocooling
SAFIR is likely to need active cryocoolers coupled not just to focal plane instruments, but to the inner layer of the sunshield. The first technology to be considered is the active cooler to provide the 4K environment for the optical components. Second, we describe the technology developments needed for passive (radiative) cooling of the sunshield. Finally, we summarize active cooling technologies for the instruments, which require <<1 K temperatures for their detectors (see also Section VII).

D. Large Deployable Structures
Packaging and autonomous deployment of large telescope systems is being dramatically advanced by JWST, but new strategies, such as mirror stacking and boom deployment would be highly enabling for the SAFIR mission. The needs for large membrane mirror technology and the DART system are discussed in Appendix C.

A top level technology roadmap timeline is provided at the end of this section.

A. SAFIR Detector Technology

Motivation for Larger Format Far Infrared Detectors

Optical arrays are now in use with tens of millions of pixels. In contrast, the largest space far-infrared array is the 32x32 Spitzer photoconductor array. The situation is the same across the entire wavelength range that we are considering for SAFIR. To answer the fundamental science questions that can be addressed by SAFIR, 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 Spitzer, much larger arrays will be needed to cover useful areas of sky. The time required to measure a given section of sky to a specified noise level scales as [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. This subject has been reviewed in a previous report -- Young, E.T, et al. 2002, "Detector Needs for Long Wavelength Astrophysics", NASA Infrared, Submillimeter, and Radio Detector Working Group.

In the far-infrared and sub-millimeter, SAFIR will provide immense advances in both sensitivity and angular resolution. In many instances, Spitzer observations are confusion-limited. The full power of SAFIR will only be realized if future imagers can preserve the inherent angular resolution provided by the observatory. Hence, proper sampling will be an important element of any camera design. For 70 μm with a 10 m telescope, this requirement translates to $\lambda/2D$ pixels of only 0.7 arcsec. At the same time, it will be highly desirable to have array fields of view of at least 1 arcmin, to allow efficient mapping. Indeed, many of the key objects of interest such as nearby galaxies, star forming regions, and evolved stars have structures on arcmin scales. These two goals imply far-infrared detector arrays of 128x128 or even larger formats—clearly beyond the current generation of fabrication techniques.

Experience with large format arrays at other wavelengths shows that such instruments quickly become the workhorse instruments at an observatory. Certainly, the ongoing experience with Spitzer amply demonstrates the need for larger, more sensitive arrays on larger telescopes. Spitzer has also demonstrated the power of large format arrays for spectroscopic investigations. Extending these capabilities to longer wavelengths will be essential for SAFIR. In this section we touch on a number of areas of astronomy that will demand larger arrays.

• Detector Performance Requirements

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.

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 XV.A-1 below shows the flux (lF_l) 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 100–400 μm, and by the Cosmic Microwave Background at wavelengths longer than 400 μm.

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 XV.A-2 at left 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 W 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 $(\tau/R)^{1/2}$.

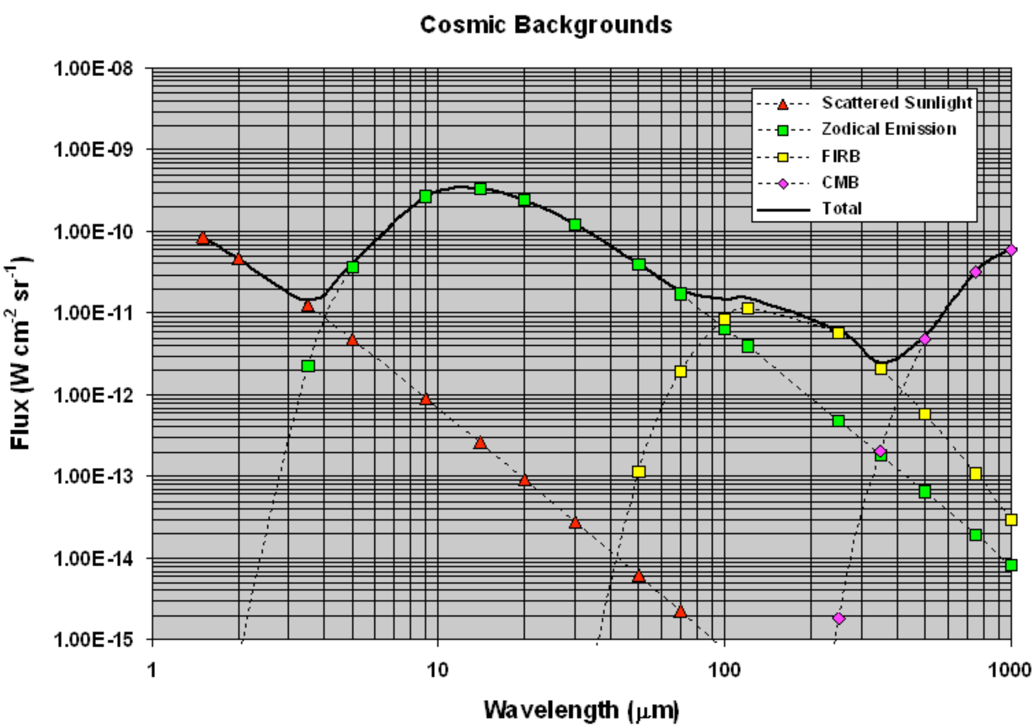


Figure XV.A-1: Astronomical background levels from infrared to millimeter wavelengths.

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, Spitzer reaches the confusion limit in as little as 40 seconds even in regions of low background.

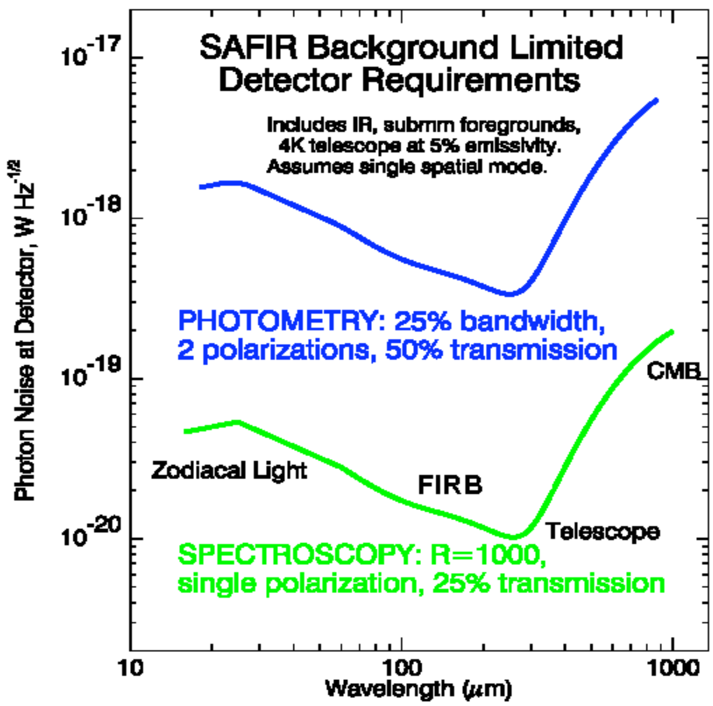


Figure XV.A-2: Photon noise defining background-limited performance for SAFIR.

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 XV.A-2 would have to be interpreted accordingly. A discussion of the various limits can be found in Rieke et al. (1995, "Detection Limits in the Far-Infrared", Space Science Reviews, 74, 17).

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 XV.A-3 shows that the quantum limit is not important for ground-based or airborne submillimeter telescopes where the background is dominated by hot thermal emission of the optics or

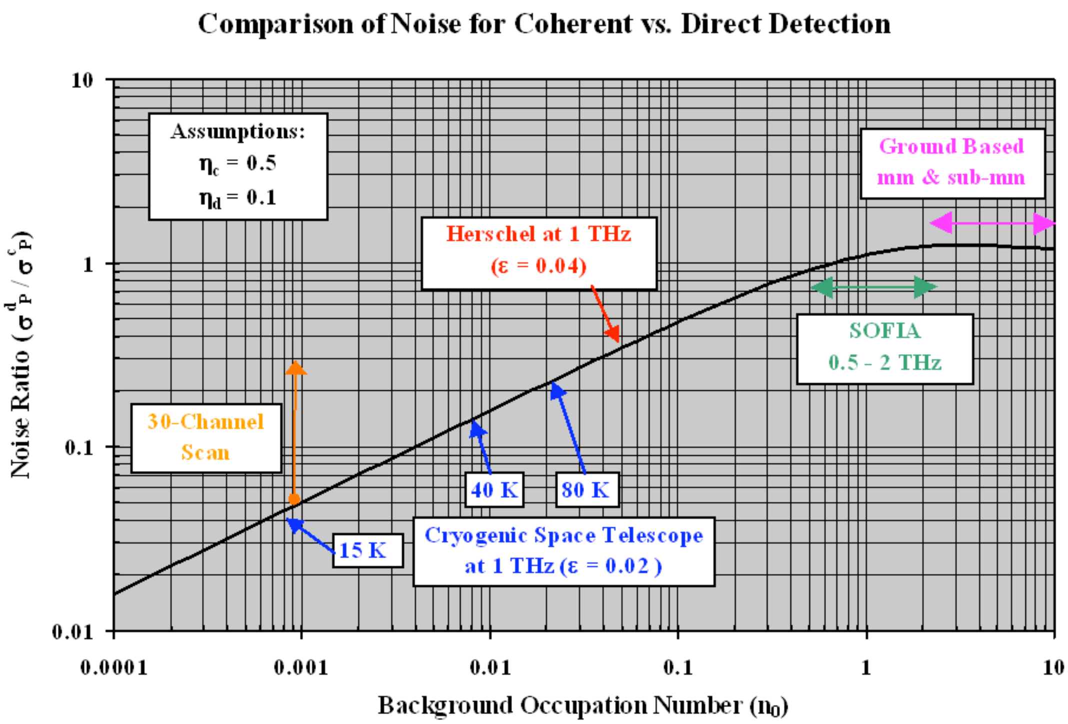


Figure XV.A-3: Noise of an ideal direct detector σ^d_P with system efficiency η^d=0.1 divided by the noise of an ideal coherent detector σ^c_P with a system efficiency of η^c=0.5. The vertical arrow shows the sensitivity penalty associated with a 30-channel sequential spectral scan. The indicated temperatures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

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 50 GHz (λ = 6 μm); 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 $\lambda = 200\ \mu$m 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. Figure XV.A-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 1.5–2 THz (λ >200 - 150 μm). In addition, coherent detection is competitive at low frequencies where quantum noise is not an issue.

• Current Capabilities for SAFIR: Technologies for Direct Detection

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 XV.A-1, 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 previously 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.

Photoconductors

Photoconductors provide a number of significant system-level advantages that continue to make them important detectors in the far-infrared. Most importantly, because they have well defined cutoff wavelengths, high levels of performance can be attained without the need for sub-Kelvin cooling. Second, photoconductors produce large signals that are compatible with silicon-MOSFET amplifiers, allowing a direct technology path to advances in silicon device advances. Additionally, photoconductors can have a wider dynamic range than bolometers.

Conventional Photoconductors

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 Spitzer (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 Spitzer arrays are the result of a long development process and are a major achievement. The 70µm array (Figure XV.A-4 below) 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. Figure XV.A-5 shows the PACS 400-pixel stressed array that will fly on Herschel. In this array, stress is applied to a column of 16 pixels and 25 of these stressing rigs are stacked to make the full array.

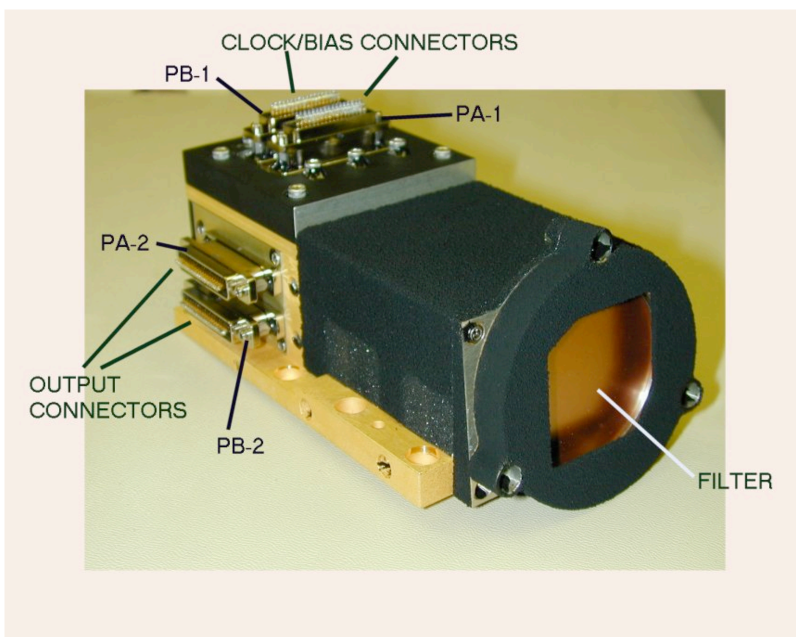


Figure XV.A-4: The Spitzer/ MIPS Ge:Ga Array. The array is 32x32 format and covers the wavelength range 50 - 110 µm.

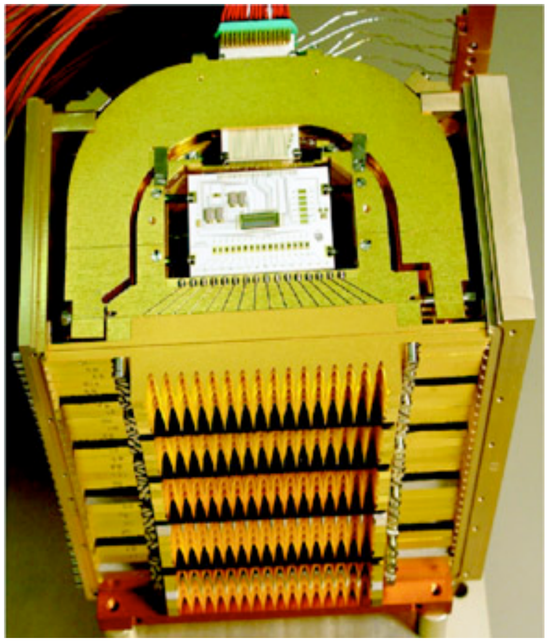


Figure XV.A-5: PACS stressed photoconductor array.

Impurity Band Conduction (IBC)* IR Detector Arrays

At shorter wavelengths shorter than 36 μm, conventional 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. Figure XV.A-6 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.

A modest NASA program to produce longer wavelength IBC detectors from Ge has made steady progress. However, methods for producing the required epitaxial 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 400 μm. 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.

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

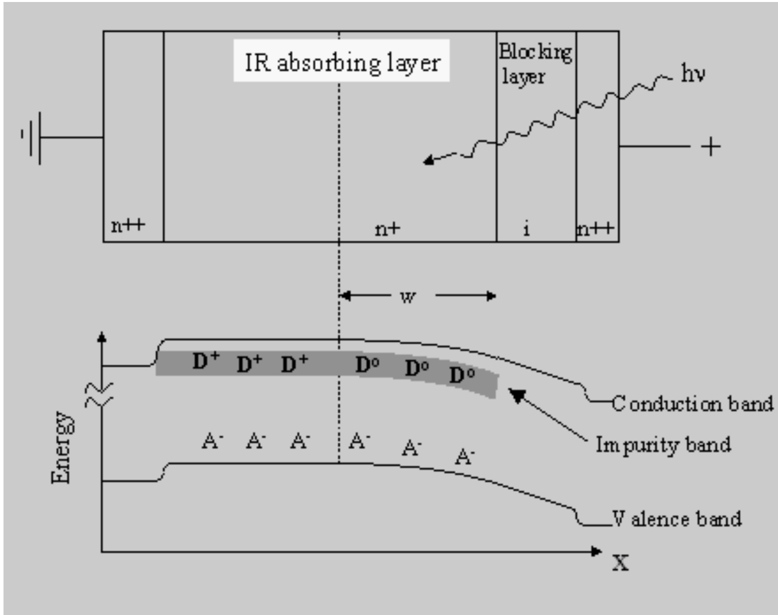


Figure XV.A-6: Representative Structure of n-Type IBC Detector; (b) Band diagram of the detector. (Haller and Beeman 2002).

Readout Technology

Since temperatures of less than 3 K will be needed to suppress dark current in long wavelength photoconductors, 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) reestablish 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.

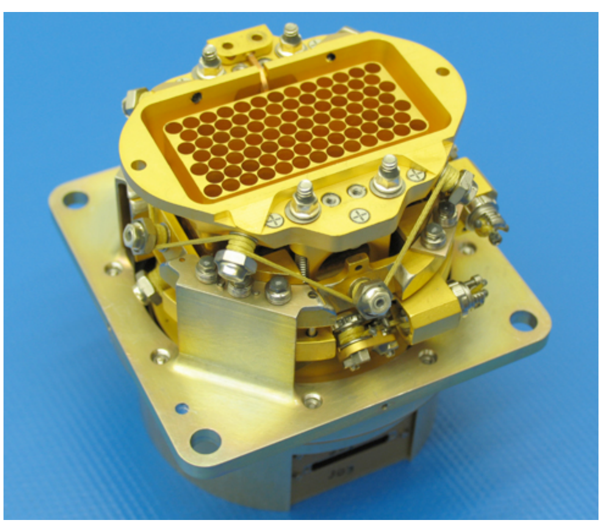


Figure XV.A-7: SPIRE Spider Web bolometer module

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 2000 μm in many experiments including NASA pathfinder ground based instruments, balloon experiments such as BOOMERANG, MAXIMA and BAM, airborne instruments such as HAWC and SAFIRE on SOFIA, and on the forthcoming HFI radiometer on Planck and SPIRE on Herschel. Figure XV.A-7 shows the SPIRE Qualification Model bolometer module, which is representative of the current state of the art in semiconductor bolometer systems.

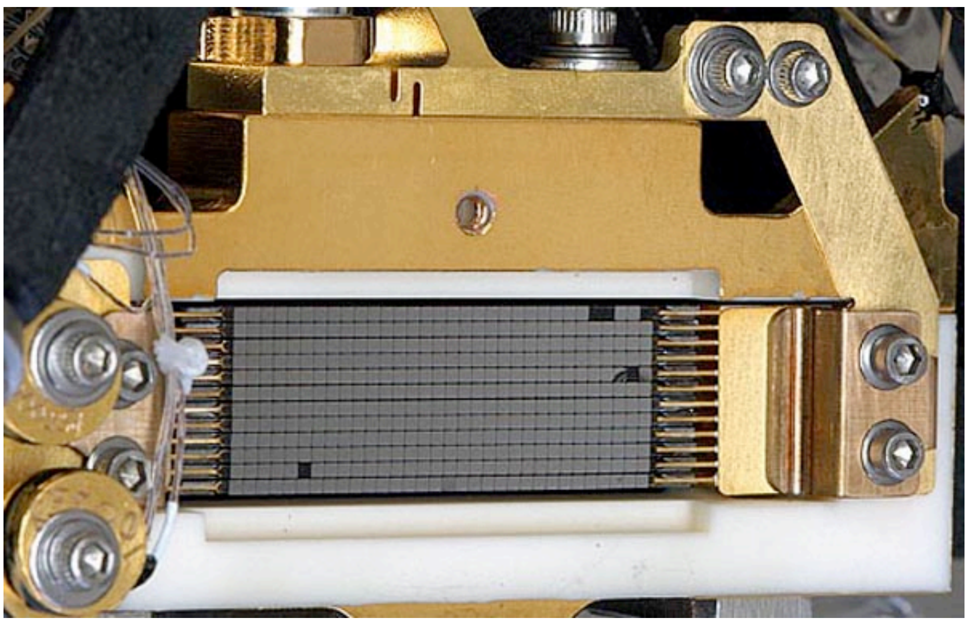


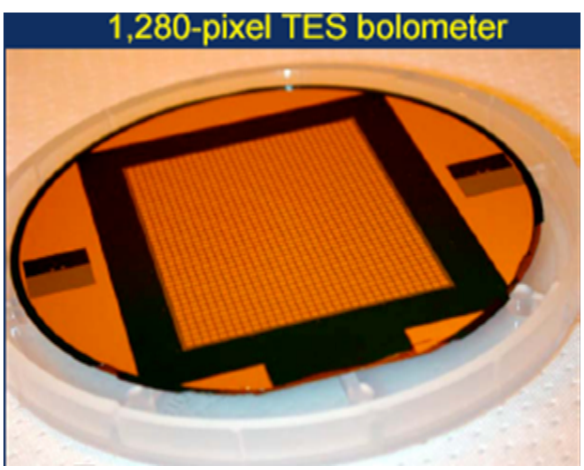
Figure XV.A-8: Close packed 12x32 HAWC bolometer for use on SOFIA.

The SOFIA airborne observatory will achieve spatial resolutions in the far-infrared that will allow the most detailed maps of far-infrared sources to date. As the facility far-infrared camera for SOFIA, HAWC will provide high resolution mapping - up to 6" - and photometric capability in its four passbands from 40 μm through 300 μm. The detector array for HAWC, shown in Figure XV.A-8 above, is the largest cryogenic bolometer array in the world with a 12x32 format of 1 mm x 1mm pixels. It operates from a 200 mK bath to provide background-limited performance in a Nyquist-sampled pixel at each wavelength. Fabricated using the NASA/GSFC pop-up detector architecture, the HAWC array provides >50% broadband quantum efficiency and >95% filling factor. This technology features implanted silicon thermistors, photolithographic production, and optional wavelength-tuned resonant cavities for even higher efficiency for fixed wavelength operations. SOFIA served as the driver and major funding source to develop this technology from the conceptual stage to a flight instrument, and will play an important role in future infrared sensor development efforts as a target operational platform.

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. With well established semiconducting thermistor technology 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 in number of pixels.

There has been much recent effort on thermal detectors using 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 increases the response speed, improves the linearity, provides some suppression of Johnson noise, and isolates the bolometer responsivity from changes in infrared loading or heat sink temperature. The benefit in linearity, however, 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, permitting the use of a SQUID as a multiplexer. 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. However, at the performance levels required for reaching the background limit in a SAFIR imager (NEP ~ 10^{-18} $W/Hz^{1/2}$), bolometers must be operated below 0.1 K.

Most notable is the development effort for the SCUBA-II instrument for the JCMT. The instrument will use 1280-element arrays of Transition Edge Superconductor (TES) bolometers bump bonded to SQUID multiplexers fabricated at the National Institute of Standards and Technology. The first prototype arrays have been fabricated. Figure XV.A-9a shows the SQUID multiplexer and Figure XV.A-9b shows the array of TES bolometers that is indium bump bonded to the multiplexer. Success of cryogenic multiplexing schemes will be essential for the construction the required array formats for SAFIR. One concern regarding the future use of large format SQUID mulitplexing is that NIST is currently the only provider of this technology. The maintenance of that foundry or the development of other foundries is a critical issue if multiplexed SQUID readouts are to be widely adopted.



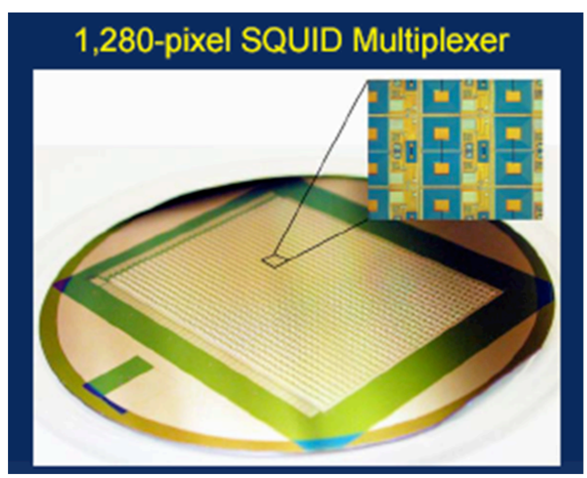


Figure XV.A-9: (a, at left) SQUID Multiplexer array. (b, at right) Array of TES bolometers. The two parts are indium bump bonded to produce the 1280-element SCUBA-II array.

• Developmental Technologies

The path to reaching the sensitivity levels required for a high resolution spectrometer, NEP ~ 10^{-20} $WHz^{-1/2}$, is unclear. New effects such as the quantization of thermal conductance in the bolometer support legs may limit the improvement achieved in bolometers by lowering the temperature and by geometrical means. Consequently a number of novel approaches are being explored.

If a superconductor is operated at temperatures well below the transition temperature, most of the electrons are bound in Cooper pairs. Photons of sufficient energy can break these Cooper pairs, and the resulting two single excited electrons or quasiparticles can be detected by various methods. The readout is designed to be sensitive to these quasiparticles, but not to the pairs. Because there is a definite energy cutoff associated with the breaking of the Cooper pairs, the generation-recombination noise of this class of detectors shows an exponential temperature dependence. A number of quasiparticle sensing schemes have been considered including tunneling junctions and kinetic inductance detectors. Results to date have been promising, but the technology is still in its early stages. Examples of pair-breaking detectors are the Superconducting Tunnel Junction detectors and the Kinetic Inductance Detectors.

In the Hot Electron Bolometer (HEB) direct detector, the bulk material that is heated is replaced by electrons in a very thin metal film. Because of weak electron-phonon coupling in the device, the incoming radiation heats the electrons to a temperature appreciably above that of the lattice. This temperature change can be sensed in the same manner as for a conventional TES bolometer. Submicron sized devices operating at 0.1 K could, in principle, reach the desired sensitivity levels. Currently, this technology is in the earliest proof of concept stage of development, and significant effort will be required to address issues such as fabrication, performance limitations, optical coupling, and readout technology.

• Current Capabilities for SAFIR: Technologies for Coherent Detection

A coherent receiver system usually consists of a local oscillator (LO), which produces a monochromatic signal at frequency n_{LO}; a "mixer", which is a nonlinear device that down-converts the signal collected by the telescope at frequency n_s to a lower microwave frequency $n_{IF} = |n_s - n_{LO}|$, 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 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 two of the quantum limit at millimeter wavelengths. However, mixer performance above 1 THz (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 high frequencies.

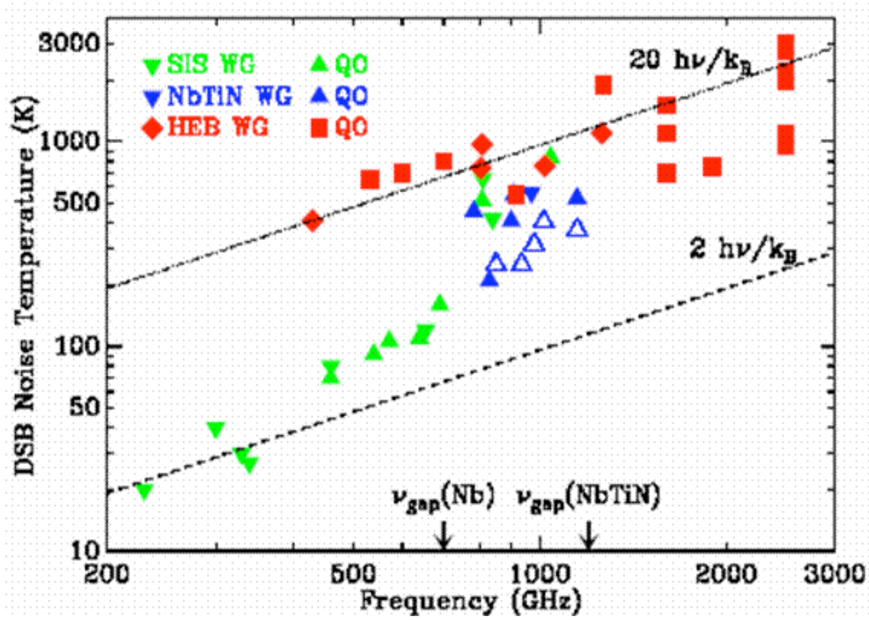


Figure XV.A-10: Achieved DSB mixer noises as a function of frequency for various technologies. The lines indicate 2X and 20X the quantum noise limit of $h\nu/K_B$. From Zmuidzinas and Richards (2004 Proc. IEEE, 92, 1597).

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 (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 (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 (200-188 μm).

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 (λ ~ 120 μm). Figure XV.A-11 illustrates an example device. Typical performance levels are a factor of 20 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.

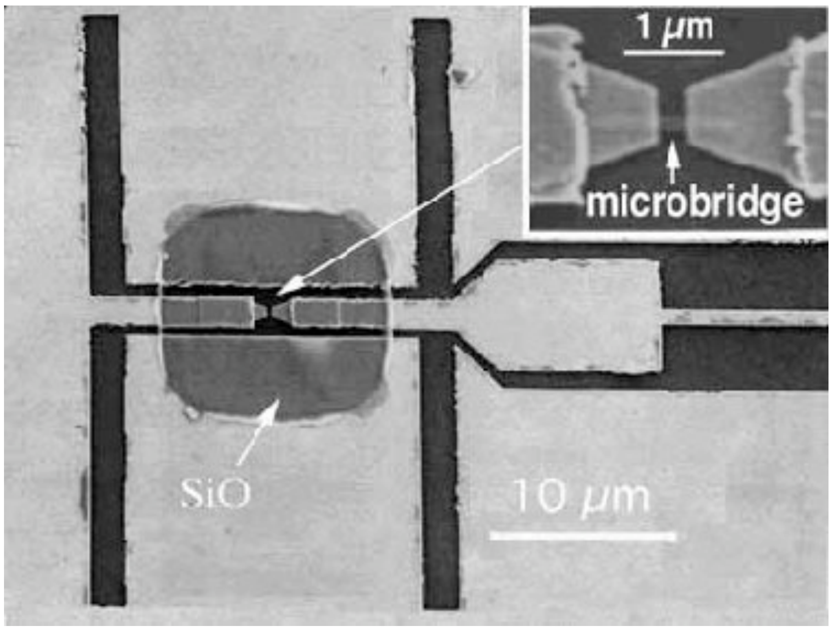


Figure XV.A-11: Microbridge HEB mixer designed for frequencies as high as 2.5 THz (from JPL).

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. At present, there are no proven technologies for ***wide-band*** LO sources above 2 THz.

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 (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 (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 (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.

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 semiconductor 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 bandwidths. An alternative technique for wide band (10-20 GHz) spectroscopy has been proposed, involving optical modulation of a visible or near-IR laser.

• Summary of Current State of the Art

Direct Detectors

- No military or commercial technology is available for long wavelength direct detectors.

- Flight Ge:Ga photoconductor arrays for Spitzer have 1024 pixels at 70µm, and 40 pixels at 160 µm, with MOS multiplexers. These arrays can reach the background or confusion limit in non-heroic integration times

- Work on has begun on IBC detectors from Ge or GaAs that have the potential to 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. It is unlikely that it will be possible to scale JFET amplifier technology to much larger arrays. Larger arrays using MOSFET readouts are under development for the Herschel mission.

- Superconducting TES bolometers with SQUID amplifiers up to several thousand pixels are under development for ground-based observatories. Performance levels of NEP ~ few x 10^{-18} W $Hz^{-1/2}$ have been demonstrated for smaller scale systems.

Coherent Detectors

- Mixers operate at nearly the quantum noise limit for frequencies below ~500 GHz (600 µm) but performance degrades to 10-20 times the quantum limit above 1 THz (300 µm).

- A number of local oscillator (LO) technologies are in use, including frequency multipliers, lasers, and vacuum tube devices, but broad-band capabilities beyond 2 THz have not been demonstrated.

- Only small mixer arrays have been built.

• SAFIR Detector Development Roadmap

The detector systems for SAFIR are unique in their combination of wavelength coverage, format, and sensitivity. These are listed in Table XV.A-1 below. A significant investment by NASA will be required to bring these sensors to the needed level of performance and maturity to realize the scientific potential of the SAFIR mission. At the long wavelengths there is virtually no military or commercial development activity, and advances in these systems have generally been associated with particular space astronomy missions such as IRAS, ISO, Spitzer, and Herschel.

Key Detector Technologies

Direct Detectors

The largest gap between existing capabilities and those needed to fully exploit SAFIR is in array sizes. Both imaging and spectroscopic applications will require arrays in excess of 10^4 elements. The increase in format is comparable to the jump from ISO to Spitzer. The risk to the mission concept will be a huge decrease in observing efficiency. Given the importance of properly sampling the point spread function in imaging investigations (or the spectral response function for spectroscopic investigations), the time to complete a map is directly proportional to the number of pixels in the array. Indeed, the larger arrays will enable qualitatively different investigations than the current technology provides.

We strongly support the development of large format bolometer arrays. The technical approaches closest to achieving the needed performance are TES systems with SQUID multiplexed readouts. Current efforts are focused on relatively high background ground-based applications, so special efforts will be needed to address the specific needs of SAFIR. 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.

Continued work toward very large photoconductor arrays remains important. The system-level advantages of photoconductors make them the devices of choice for many applications. The realization of Impurity Band Conduction detectors that operate at far-infrared and submillimeter wavelengths should be pursued and would result in a breakthrough in the construction of high performance far-infrared arrays. Readouts for far-infrared photoconductors need continued development.

The sensitivity levels needed for a low-background spectrometer in the sub-millimeter (NEP ~10^{20} $WHz^{-1/2}$) have not been demonstrated even at the single pixel level. Research to reach this level may require new detector types as well as improvements in existing technologies.

Improvements in Coherent Systems

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 (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 (300 - 100 μm) where systems are more than an order of magnitude less sensitive than fundamental limits.

For submillimeter heterodyne receivers, a priority is continued local oscillator development, where higher frequencies, wider tuning bandwidths, and more output power are all important. For space applications, the power consumption of local oscillator sources is an important consideration, and improvements in this area will enable larger systems. The development of arrays of coherent receivers will provide significant improvements in mapping speed.

Risk Mitigation

Given the central role that high performance detector arrays will play in the scientific return of SAFIR, this Roadmap fully supports the notion of multiple technical approaches when possible. For direct detectors, work on both photoconductor systems and bolometer systems should be supported to provide a hedge against technical difficulties. Similarly, for coherent systems, we have identified more than one approach for some of the key subsystems such as mixers and local oscillator sources.

Validation and Demonstration Approach

A key point that has been demonstrated many times is that experience with complete observing systems is required to fully understand the nuances of astronomical detectors. The translation of a laboratory concept to a useful instrument requires attention to a host of details that are important in building up a complete system. At SAFIR wavelengths where many of the detector systems are unique to space astronomy, the need for system level demonstrations is particularly pressing.

Support for Infrastructure and Intermediate TRL Detector Development

Mechanisms, such as the APRA 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. It will be important for NASA to develop the resources to support this type of engineering as a complement to the existing grants program.

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.

Science Investigation	Measurement Capability	Current State of the Art	Required Detectors
Measurement of FIRB/ Galaxy LF	Deep FIR Surveys	~1000 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 > 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

Table XV.A-1 Summary of Detector Needs

Synergy with the Suborbital Program

For much of the SAFIR wavelength coverage, the Earth's atmosphere is completely opaque. Hence, the opportunities for demonstrations on ground-based telescopes are particularly limited. We recognize the importance of observing platforms such as SOFIA or balloons for the demonstration of many of these technologies. At the same time, some of the observing conditions (such as the ultra-low backgrounds of a space-borne spectrometer) cannot be duplicated in a suborbital environment. In those cases, specialized laboratory test systems will be essential in systems verification.

B. SAFIR Mirror Technology

The Advanced Mirror System Demonstrator (AMSD) program was a collaborative project between NASA, Air Force, and NRO to develop lightweight mirror technology that would enable potential space optical missions for all three agencies. This program laid the groundwork for the present state of art in cryogenic mirror substrates for SAFIR, and can be considered a model for future efforts, and we review that effort here.

AMSD had two fundamental goals. Firstly, to develop technical processes which would dramatically reduce the cost, schedule, and weight for large-aperture optical systems. Secondly, to mitigate programmatic cost, schedule, and weight risk to potential missions. The primary objective of the AMSD procurement was to advance the technology in the production of a very low mass mirror system that can be produced at a low cost and with short manufacturing times. Mirror system performance objectives were demonstrated at both ambient and cryogenic temperatures. A secondary objective was to provide mirrors in support of NASA/DOD flight demonstration programs.

AMSD was conducted as a phase down select competition. Eight study contracts led to five Phase 1 contracts. Four concepts were selected for fabrication under Phase 2, but only two Phase 2 mirrors were completed and tested at 30 K, a beryllium mirror manufactured by a consortium of companies lead by Ball Aerospace and a ULE® manufactured by Kodak (now ITT).

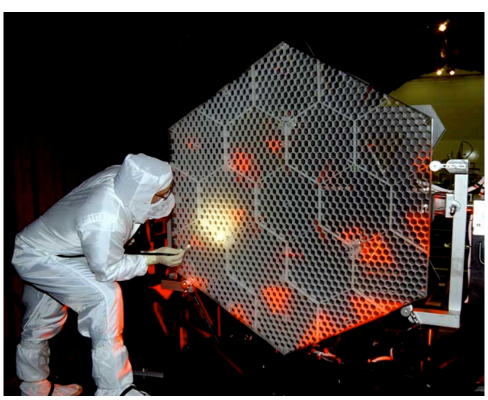


Figure XV.B-1: ULE® Glass AMSD Mirror

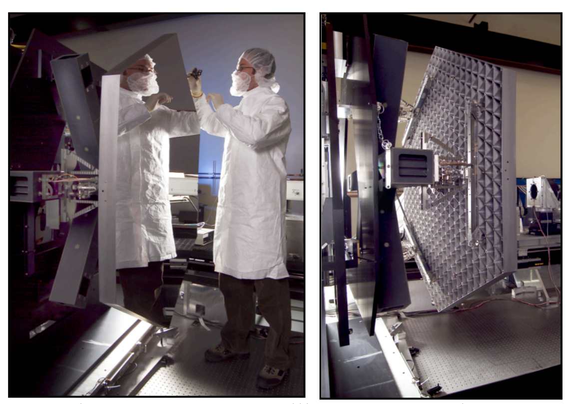


Figure XV.B-2. Beryllium AMSD Mirror

The AMSD program is a model for future NASA missions. It presented two mature technologies to the JWST program for consideration. The competition between these two technologies advanced the TRL of both, resulted in better defined proposal plans and significantly reduced total cost to the program. Potential return on investment to the government could be on the order of $5 to $10 for each dollar invested. These advantages would never have been realized without a parallel development, phased down select competition. Additionally, the results of AMSD were significant in selecting the JWST prime contractor and fundamental in selecting the JWST primary mirror material. AMSD formed a basis for estimating JWST ambient and cryogenic performance, manufacturability, schedule, cost and risk.

Using lessons learned from AMSD, a phased down-select process is recommended to mature the most promising candidates from TRL-2 to TRL-4/5. Multiple sub-scale mirrors of different technologies and at least one full scale mirror should be designed, built and characterized at temperatures of less than 10 K. The goal is to demonstrate mirrors suitable for far-IR with an areal density of less than 10 kg/m^2, aperture of 1 to 2 m and cost of less than $500K per square meter. The result will dramatically reduce cost, schedule, weight and risk for large-aperture cryogenic optical systems. The effort should be conducted in three phases. Phase 1 should perform design trades for up to 7 different concepts. Phase 2 should build 3 to 5 sub-scale (0.5 m diameter) spherical mirrors and test them at < 10 K. Phase 3 should build one or two full size (~1.0 to 2.0 m diameter) mirror segments and test them at < 10 K. The selection criteria for Phase 2 and Phase 3 should include but are not limited to: technical performance, best value (i.e. highest performance for lowest production cost & schedule), potential to advance the state of the art, and scalability to 25 m class telescopes.

There are multiple technical solutions that can achieve the SAFIR mirror requirements. Candidate mirror materials include Beryllium (Be), Silicon Carbide (SiC) and Magnesium Graphite Composite (MgGr). As shown in Figure XV.B-3, material properties that predict success include specific stiffness (ratio of stiffness to density) and thermal stability (ratio of thermal conductivity to CTE). Given its planned use on JWST, Beryllium is the incumbent for SAFIR. It has the highest specific stiffness of all potential materials. However, its thermal stability is relatively low. Fortunately, for SAFIR, this is not a serious issue. On AMSD, the worst case Be cryogenic figure change was approximately 170 nm rms. Thus, to achieve a 1 μm rms figure at <10 K, one simply needs to fabricate the ambient figure to better than 0.8 μm rms. Obviously, any candidate mirror material with a higher thermal stability than Be is a good choice for SAFIR. These materials include SiC and MgGr.

The other issue is specific stiffness. SAFIR desires mirrors with >200 Hz free-free stiffness and <10 kg/m^2 areal density. A recent design study by Xinetics reported on at Tech Days 2003 indicates that SiC mirrors can be designed to achieve both requirements (Figure XV.B-4). And, any material with comparable or higher specific stiffness should be able to achieve both. For example, IABG has demonstrated a 0.5 m C-SiC mirror with a 7.8 kg/m^2 areal density and Ball has demonstrated a 0.5 m Be mirror with 9.8 kg/m2.

To achieve the goal of developing cost-effective 4 K mirrors, duplicate the best practices and implement the lessons learned from the highly successful AMSD project: collaboration, focused parallel development paths and progressive down-select.

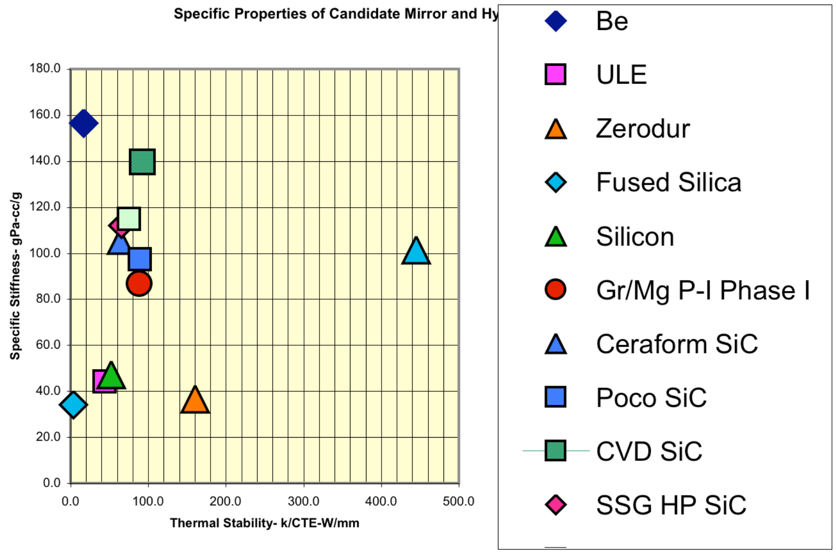


Figure XV.B-3: Specific Properties of Candidate Mirror Materials (MMCC Tech Days 2003)

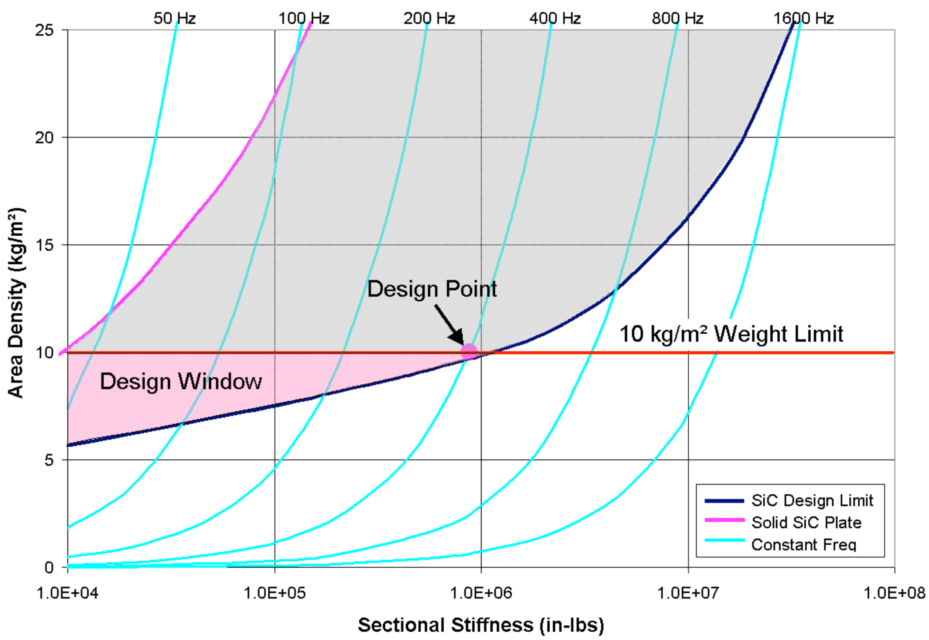


Figure XV.B-4: SiC Stiffness to Weight Trade for 1 meter Hex (Xinetics Tech Days 2003)

Mirror Concept Design and Trade Study

In Phase 1 of an AMSD downselect program, we would expect to issue 5 to 7 sub-contracts to design mirrors that meet the requirements in Table XV.B-1. Contracts will be for up to 6 months. Emphasis will be placed on determining candidate mirror concepts capable of operating in a space environment, i.e. space qualified materials, susceptibility to radiation and micrometeoroids, thermal stability, mechanical stability from vibration and slewing, launch survival, etc. Emphasis will also be placed on exploring fabrication processes capable of achieving the desired cost and schedule goals. For example, particular attention will be given to pursing replication and/or slumping, MRF and/or reactive plasma polishing, etc.

Participants for Phase 1 will be selected based upon the potential of their mirror technologies to achieve SAFIR's technical and programmatic needs – as demonstrated by previous NASA, Air Force, Army, NRO and/or DARPA funded research. Table XV.B-2 lists most of the recent NASA cryogenic mirror SBIR Phase I contracts by year and indicates which have received a Phase II award. Technologies to be considered for the recommended technology development effort include but are not limited to: cast beryllium and/or AlBeMet; gas infusion borosilicate, fused and/or extruded glass; various types of cast and/or machined silicon-carbide and carbon/silicon-carbide; silicon foam and silicon-carbide foam; magnesium graphite composites and/or polymer matrix composites; graphite epoxy; replicated nickel; nano-laminates and membranes.

Parameter	Phase 2	Phase 3	Units	Notes
Diameter	0.5	~ 1 to 2	meter	1
Prescription	Sphere	Sphere		2
Shape	Round	Hexagonal		
Areal Density	< 10	< 10	kg/m^2	3
Radius of Curvature	2.5	16	meter	4
Radius Matching	TBD	TBD	μm	5
Surface Figure at < 10K	~ 1	~ 1	μm rms	6
Wavelength (HeNe required)	0.6 to 800	0.6 to 800	μm	7
Operating Temperature	< 10	< 10	K	8
Cooling Mechanism	Passive or Active	Passive or Active		8
Cost per unit area	< $500K	< $500K	$/m^2	9
Max Fixed Cost	$100K	$400K		10
Production Schedule	< 9	< 18	months	11
Segment Stiffness (goal)	> 200	> 200	Hz	12
Gravity Sag	< 5	< 5	μm PV	13
Seg Dynamic Survival (goal)	> 20	> 20	G's	12

Table XV.B-1: Low-Cost Cryogenic Mirror System Demonstrator Specifications

Given its planned use on JWST, Beryllium is the leading candidate material for SAFIR. However, it is relatively expensive to manufacture. Several new concepts to reduce fabrication cost need investigation. These include near net shape casting, acid etching and substrate slumping to a replication mandrel. Near net shape casting offers the potential for lower cost substrates. Slumping offers the potential for significant cost reduction in grinding/polishing. The feasibility of Be mirror slumping was demonstrated during the AMSD program when the Be mirror underwent a shape change during a stress-relieving thermal cycle. Additionally, the cryogenic figure shape change demonstrated on AMSD is completely consistent with the SAFIR specification.

Silicon Carbide is the heir apparent to Beryllium – partly because of its non-toxicity. It has similar performance properties and a perceived fabrication cost advantage. There are many different methods for fabricating SiC mirrors. MSFC is funding several projects to quantify the suitability and scalability of these processes and has tested SiC mirrors from multiple vendors including: Coors, ECM/IABG, POCO, SSG, Trex and Xinetics. It is impossible to describe all the different processes and report the test results. But, here are some highlights. The POCO SuperSiC process performs all fabrication steps on relatively inexpensive graphite foam before its conversion into pure single-phase Beta SiC. This foam can be machined to tolerances of 25 µm. The optical surface is polished into a layer of CVD SiC that is deposited on the front surface. For 1 to 2 m class mirrors, multiple blocks of machined graphite can be bonded before conversion. SSG currently has a Phase I SBIR with MSFC to study the feasibility of replicating SiC substrates to SAFIR requirements without the need for any grinding or polishing. Trex has the ability to grow via CVD SiC mirrors directly on a mandrel. Xinetics is pursuing a SiC substrate with nanolaminate surface technology. Coors is teamed with Boostec who made the 3.5 m diameter SiC mirror for the Herschel telescope.

Yr	Company	Title	Center	P-II
04	QED	Sub-aperture Stitching Interferometry for Large Convex Aspheric Surfaces	GSFC	TBD
04	MMCC	Ultra-Lightweight Hybrid Structured Mirror	GSFC	TBD
04	RAPT	Rapid Damage-Free Shaping of Lightweight SiC Using Reactive Atom Plasma Processing	GSFC	TBD
04	SSG	Low-Cost, Silicon Carbide Replication Technique for LWIR Mirror Fabrication	MFSC	TBD
04	CRG	SynLam(TM) Primary Mirror Evaluation	MSFC	TBD
03	Bauer	Integration of Full-Spectrum Metrology and Polishing for Rapid Production of Large Aspheres	GSFC	Yes
03	QED	Improved Large Segmented Optics Fabrication Using Magnetorheological Finishing	MSFC	Yes
03	Xinetics	Ultra-Lightweight Cryogenic Active Mirror Technology	JPL	No
03	Schafer	Actively Cooled Silicon Lightweight Mirrors for Far-IR and Sub-MMOptical Systems	MSFC	Yes
03	Trex	High Volume, Low-Cost Production Process for High-grade Silicon Carbide Optics	GSFC	TBD
02	CCI	Multiform SiC Structures for Lightweight Space-Based Mirrors	GSFC	No
02	Tinsley	Computer Controlled Optical Surfacing of Bare Beryllium Aspheric Optics	MSFC	Yes
02	PwdrMet	Light Weight Concepts for Mirrors	GSFC	Yes
01	Bauer	Extended range profiling	GSFC	Yes
01	SSG	SiCf/SiC Composites w/ Variable Fiber Form for Fracture-tough Reaction Bonded SiC Composites for Monolithic SiC Optical Instruments	GSFC	Yes
01	MER	A Graded Density SiC Foam for Lightweight Optics	GSFC	No

Table XV.B-2: NASA SBIR/STTR Optics Related Phase I Awards

A related material is Silicon foam. Schafer Corp currently has a Phase II SBIR contract with MSFC to build a 0.5 m diameter actively cooled cryogenic mirror. Several smaller Schafer foam mirrors have been cryogenically tested at MSFC with good results.

Another material with significant potential is Magnesium Graphite. Its specific stiffness is similar to SiC and some forms of MgGr have very good thermal stabilities – implying a complete figure stability for ambient to cryo. Also, it offers attractive mass production opportunities. MgGr blanks are easy to machine and can be coated with CVD Si for the optical surface. Alternatively, CVD SiC can be deposited. MgGr is a relatively new material and is currently the subject of an SBIR Phase I study.

Cornerstone Research Group has an SBIR Phase I with MSFC to study the suitability of its polymer matrix composite material for SAFIR. This material is essentially glass foam. With its 0.6 g/cm^3 density (20% lower than SiC), it has the potential to produce extremely low areal density mirrors. Additionally, Cornerstone has developed the ability to 'tune' the materials CTE. Mirrors are fabricated by replication. The material is applied to a mandrel and cured.

Hextek's Gas-Fusion™ technology is promising because it offers the ability to meet the SAFIR structural, optical, thermal and programmatic requirements. Its closed back offers high stiffness and dynamic stability; the 100% fusion bonds and radius corners at the core and face sheet intersections are robust and proven to survive high G-force rocket launches. It has been proven to 1.5 m apertures, and is scaleable to >2 m. Historical data and testing at MSFC demonstrates borosilicate glass to be highly stable at cryogenic temperatures. And finally, the Gas-Fusion™ technology offers tremendous cost and schedule savings due to its use of low cost material, and its efficient use of capital, material and labor in manufacturing. (Production blank fabrication timing is expected to be 1-2 months for each 1.0-2.0 m segment at a cost of ~\$100K/m^2.) Figure XV.B-5 shows a mirror purchased by MSFC and cryo-testing to 30 K.

Figure XV.B-5: 25 cm, 14.5 kg/m^2 Gas-Fusion™ substrate (potential for < 8kg/m^2)

ATK/COI has a Carbon Fiber Reinforced Composite (CRFC) material with a copper cladding. ATK/COI has cryogenic experience from two different mirrors: its 30 K NMSD Glass/Composite Hybrid mirror and its 70 K FIRST Prototype. FIRST demonstrated 10 kg/m^2 at 2 m but only achieved a surface figure of 5 μm rms at 70 K. NMSD was 11 kg/m^2 at 1.6 m and achieved approximately 1 μm rms at 25 K after cryo-null figuring (CNF). CNF was required to correct cryo-quilting and low-order deformation. To overcome this quilting problem, ATK/COI has developed a new co-curing process to seal the laminates from moisture effects, plus the addition of a copper layer that is thick enough to be optically finished using low-cost diamond turning. This approach also completely eliminates the fiber-print limitation.

Note 1: Mirror diameter is defined as the physical extent of the substrate. Mirror diameter for Phase 3 is measured flat-to-flat across the hexagonal shape. Each vendor is encouraged to manufacture the largest mirror that their process can fabricate, meets the requirements and costs no more than \$400K total. Vendors must show scalability of their mirror concept to a 2 m flat-to-flat segment.

Note 2: A spherical mirror is specified only to simplify optical testing. Vendors must use fabrication processes that are traceable to manufacturing off-axis SAFIR segments (assume a 16 m radius of curvature parabolic primary mirror).

Note 3: Areal Density is defined the same as for JWST, it includes mirror substrate and all hardware necessary to kinematically attach substrate to a provided test mount. Vendors are responsible for providing all mounting hardware to connect their mirror to the provided test mount. Vendors must show scalability of their mirror concept areal density to a 2 m segment.

Note 4: Phase 3 radius of curvature depends upon whether the Vendor proposes to test in MSFC's small chamber or in the XRCF. The small chamber can accommodate mirrors up to 0.8 m in diameter with a radius of 2.5 to 3.5 m. The XRCF can accommodate mirrors up to 4 m in diameter with a radius of 10 to 25 m.

Note 5: Given that the mirrors will be cooled to a fixed operating temperature, radius variability on-orbit should not be an issue. To avoid using an on-orbit radius actuator, the mirror fabrication process must be able to produce segments with a repeatable radius of curvature. This tolerance is defined by the need for mirror phasing. For a 20 μm system, phasing places a segment-to-segment radius-matching requirement of better than 0.5 μm peak-to-valley sag. For a 16 m radius 2 m diameter segment this translates into a radius matching specification of approximately 0.5 mm.

Note 6: Surface figure is defined to be after removal of tilt, focus and ambient gravity sag. Surface figure is reported over the full optical aperture to within 10 mm of the physical aperture. For Phase 2, the required surface figure must be achieved at ambient. For Phase 3, the required surface figure must be achieved at <10 K. Vendors may uses cryogenic actuators to achieve the figure specification provided that they are included in the total cost and areal density budget. A premium is place on vendors who can achieve a smooth figure at <10 K without significant mid-spatial frequency errors, i.e. quilting or print-through. A surface PSD will be calculated for each mirror based on test data.

Note 7: Mirrors must be reflective at HeNe wavelength for optical testing. Compliance with wavelength operating range can be demonstrated by showing compatibility of the mirror material with a 20 to 800 μm coating.

Note 8: Each Vendor has the option to conductively strap their mirror to a cold plate or to connect their mirror to a He source. MSFC will be responsible for the temperature of this cold plate or He source.

Note 9: Calculate cost per area based on the mirror's usable optical aperture. Report for both total fabrication cost and recurring cost only.

Note 10: NASA reserves the right to exclude any Vendor from making a Phase 3 mirror who cannot produce their Phase 2 mirror in less than 9 months. NASA plans to test all Phase 2 mirrors regardless of how long they take to fabricate.

Note 11: NASA reserves the right to exclude any Vendor from making a Phase 3 mirror who cannot produce their Phase 2 mirror for less than $100K.

Note 12: Vendors are encouraged to make mirrors that can survive a launch dynamic environment of 20 G's and are as stiff as possible. Verification can be by measurement or model.

Note 13: To facilitate optical testing, the gravity sag shall not be greater than 5 μm peak-to-valley.

Cryogenic Characterization

Marshall Space Flight Center (MSFC) has extensive experience testing cryogenic mirrors. Since 1999, MSFC has performed more than 40 cryogenic tests characterizing optical performance at temperatures below 30 K on over 15 different mirrors, including: Ball 0.5 m SBMD, COI 1.6 m NMSD, Ball 1.4 m AMSD, Kodak 1.4 m AMSD, Goodrich 0.5-meter Pathfinder, IABG 0.5 m C-SiC, Xinetics 0.5 m SiC, Brush Wellman 0.5 m Joined Beryllium, Kodak 35 cm LTF ULE, Kodak 25 cm LTF Fused Silica, Schafer 15 cm Silicon Foam, POCO 25 cm SiC, Hextek 25 cm Gas-Fusion and Schott Bonded Zerodur mirrors. Additionally, MSFC has experience cryogenic testing components such as large graphite epoxy structures and cryogenic actuators.

The large cryogenic test chamber (XRCF) has a 6 m diameter by 18 m liquid nitrogen shroud and a 4.5 m by 14 m gaseous helium shroud. The XRCF can test mirrors with radius of curvature ranging from 10 to 25 m. It was used to test SBMD, NMSD, AMSD and some of the 0.5 m technology mirrors. The small chamber has a 1 m diameter by 2 m gaseous helium shroud. It can test mirrors up to 0.8 m with radius of curvatures ranging from 2.5 to 3.5 m. Diameters larger than 0.8 meter start to encounter thermal boundary issues. Both chambers have optical windows that allow all metrology instrumentation to remain in ambient conditions. Available test equipment includes two instantaneous phase-measuring interferometers (4D PhaseCAM and ADE IPI), an AOA Shack-Hartmann Wavescope and a Leica Absolute Distance Meter. The instantaneous interferometers allow data acquisition in the presence of mechanical vibration. The large chamber can achieve temperatures of <20 K in 36 hours, the small chamber can do it in < 6 hours. To achieve sub-10 K temperatures, mirrors will be either conductively cooled via a thermal strap to a cold plate or actively cooled.

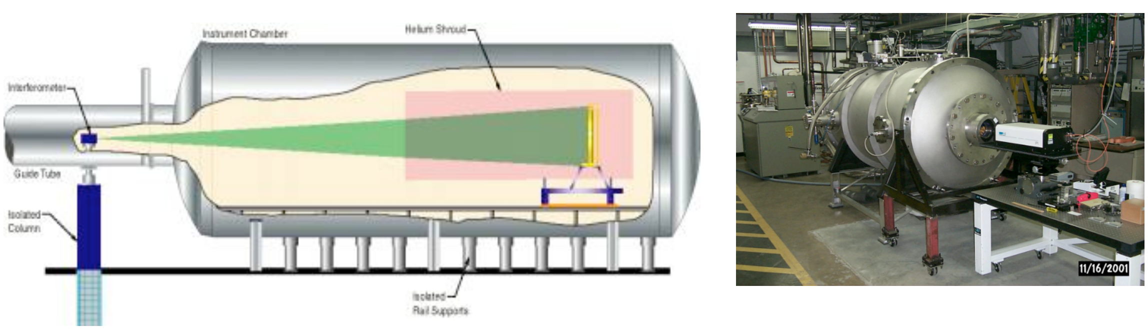


Figure XV.B-6. MSFC large cryogenic test chamber (XRCF) & Small Cryogenic Test Chamber.

C. Cryocooling Technology

Active Cooling Technology for Telescope and Structure

Telescopes for the far infrared require cooling to temperatures near 4 K, to reduce the thermal emission from the telescope and achieve background-limited performance. Figure XV.C-1 shows the tradeoff in telescope size versus surface temperature, for a fixed signal-to-noise ratio for three wavelengths of interest for SAFIR. A warmer telescope requires a collecting area which increases rapidly with temperature; note that the vertical axis is telescope diameter. Clearly the only practical approach is to operate the telescope near the knee of the sensitivity curve. For SAFIR, a telescope at 4 K yields true background-limited performance.

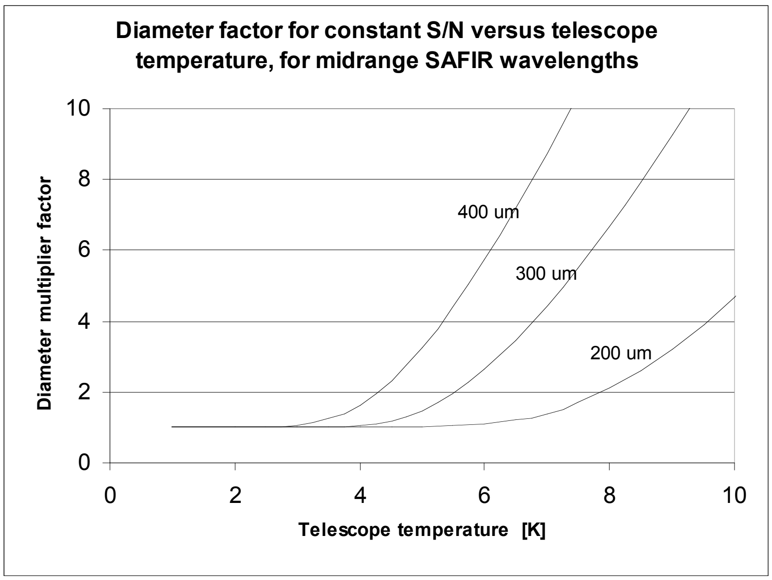


Figure XV.C-1: Diameter factor for constant point-source S/N versus SAFIR telescope temperature, for wavelengths of interest to SAFIR. Calculation assumes telescope emissivity of 0.05, and background-limited operation based on a simple model of the Lockman Hole [following E. L. Wright, IAU Symposium on Extragalactic IR Background, 2000]. It can be seen from this plot that small reductions in telescope temperature are worth large increases in telescope aperture in the background-limited submillimeter.

Based on detailed studies of JWST, and assuming much more optimized structure and coatings, the lowest temperature attainable by passive radiative cooling is in the range 7—10 K, depending upon location and other conditions (see below). Thus, in order for SAFIR to achieve these lowest temperatures, the telescope will have to employ active cooling to further reduce the temperature. Cooling a 10 m, deployed telescope to 4 K is a realistic goal, but one that requires development of active coolers capable of adequate heat lift at 4 K with a lifetime of 5-10 years, acceptable coefficient of performance, and cold heads which can be physically remote from the high-power components of the cooler and deployable along with the telescope mirror and optical components. Cooling to 4 K will be required at many distinct locations; all telescope primary elements, plus secondary, tertiary etc components of the telescope, and an optical baffle around the instruments all must be held at 4 K. Additionally, the coolers will be required to provide heat lift at higher temperatures, typically around 15 K and 40 K, to intercept conducted thermal loads and improve the radiative thermal environment.

Capability	Requirement	SOA	Development Path
Advanced High Capacity Cryocoolers	150 mW @ 4K 1 W @15K, 5—10 years life	6 K components, 4 K lab demos	ACTDP in development
High thermal stability on large primary and all optical components	0.1 K uniformity, stability under load changes	new requirement	little ongoing
Distributed cooling of segmented primary and all telescope optics	heat lift at 4 K from primary segments	new requirement	little ongoing
Deployable multiple cold points	10—20+ cold points for cooling all components	JWST will have single deployed ACTDP cold head	little ongoing

Table XV.C-1: Requirements for Cryocoolers and Cooling Performance

No space-qualified coolers exist to meet the requirements of SAFIR, in any of the particulars. Single-stage Stirling and Pulse Tube coolers are currently operating in space at ~60 K, and multiple-stage machines at 10-35 K are expected to reach TRL 5 by 2007, but none provide cooling remote from the warm components. The Planck sorption cooler will launch in 2008 and provide 18 K remote cooling, but without deployment. Figure XV.C-2 shows the status of coolers existing and under development. Several laboratory coolers have demonstrated 4 K in isolated components under no-load conditions, but with operational efficiencies inferior to the 500 W/W requirement for SAFIR.

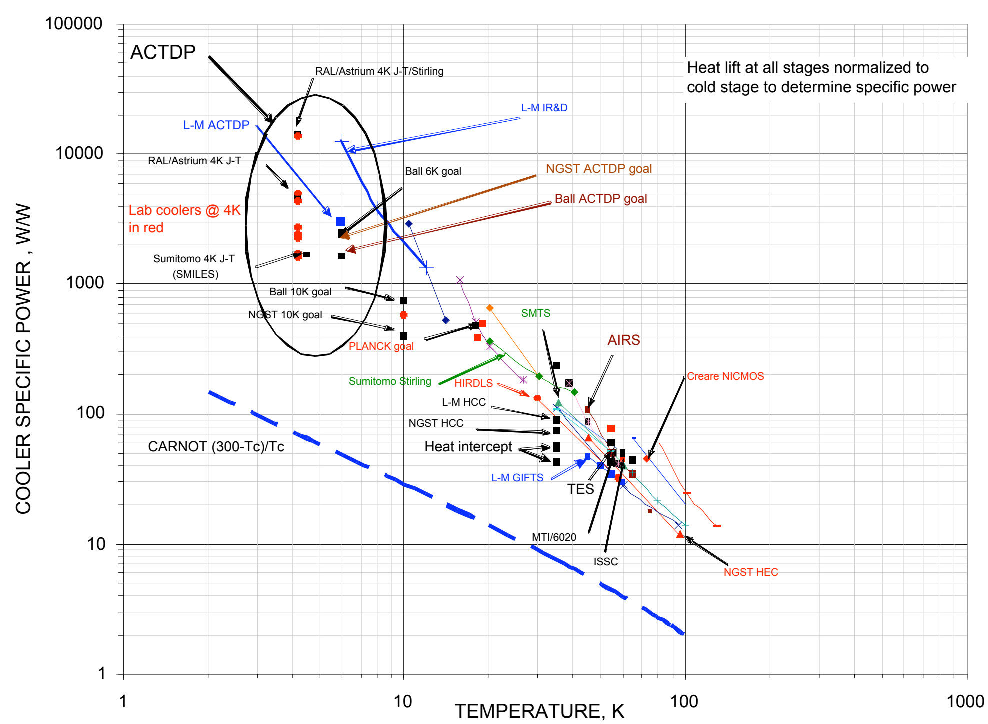


Figure XV.C-2. Status of cryocoolers existing or under development. Several laboratory coolers have demonstrated 4 K in components, under no-load conditions. (Plot from Dean Johnson, JPL.)

An important path to SAFIR's needs is the Advanced Cryocooler Technology Development Program (ACTDP), funded by NASA's Navigator program and administered through JPL, which is developing space-qualified coolers to provide simultaneous cooling at 6 K and 18 K, with remote cold heads, and minimal vibration and EMI. Deliveries at TRL 6 are anticipated for 2009-2010. The three technologies being pursued are shown in Figure XV.C-3.

Further development of the ACTDP compressor systems is needed in order to lower the temperature from 6 K to 4 K while achieving adequate cooling power and efficiency. This could be done by incremental improvement over the ACTDP coolers or by adding an additional cooling stage. A continuous magnetic cooler (discussed below) could do this, while using the same technology development contemplated for the cooling of the SAFIR instruments. The ST-9 effort is a potential source for further development of mechanical coolers approaching the temperature and power requirements of SAFIR., but awards have not been announced as of this writing. As is seen in Figure XV.C-2, significant improvement in efficiency and cooling power will be necessary for practical application to SAFIR.

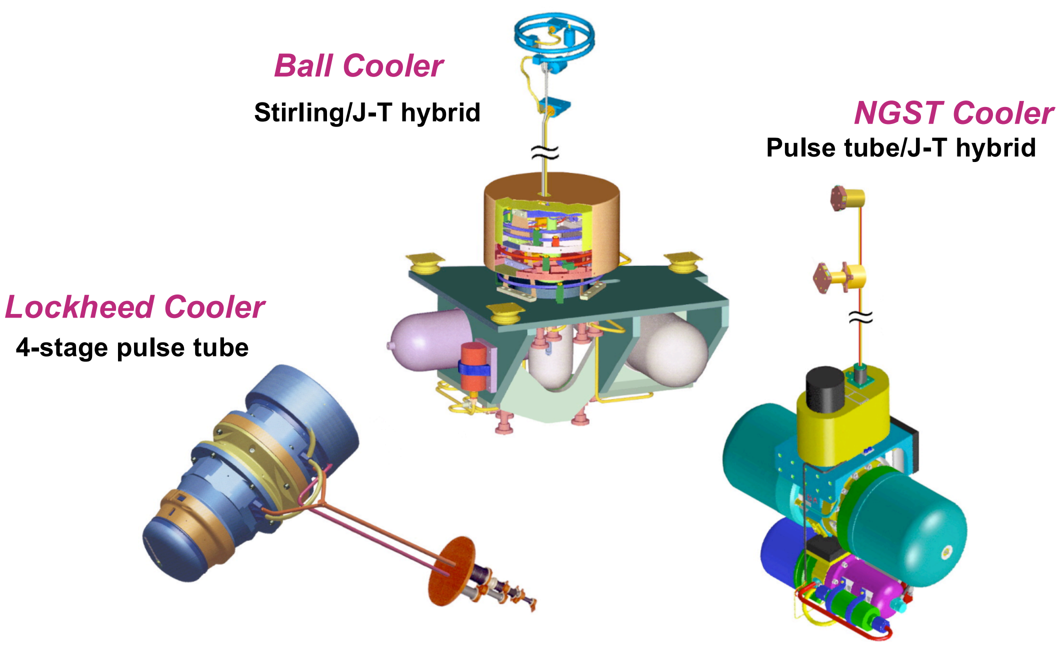


Figure XV.C-3. Three approaches are being pursued in parallel toward development of a 6 K cooler under the ACTDP effort. (Image from Dean Johnson, JPL.)

JWST has recently decided to utilize a remote cold-head mechanical cooler to cool its mid-infrared instrument (MIRI) to 7 Kelvin., with the cooler is expected to be one of the ACTDP-type designs. This effort is expected to provide significant experience to SAFIR in the integration of a remote-cold-head cryocooler, since the single cold head will be deployed along with the telescope mast.

However, the operation and deployment of a system to provide cooling to 4 K at multiple points of a segmented primary mirror, the additional optical components of the telescope, and the instrument package remains largely unaddressed. Requirements on such a system will include the need for thermal stability to 0.1 K or better under changing load conditions and across the entire 10 m diameter primary aperture. The requirement for multiple points of cooling, all at constant temperature and capable of significant load shifting while maintaining high efficiency, is a new and challenging aspect to flight coolers. Examination of forced-flow cooling systems, light-weight deployable conductive or heat-pipe structures, and possibly more exotic multi-point cooling systems is needed to ensure that these enabling technologies are available for SAFIR.

Radiative Cooling Technology for Sunshield

The SAFIR telescope will require that the flux from the Sun (and Earth and Moon assuming SAFIR is at the L2 point) be reduced by more than six orders of magnitude, thus enabling cooling of the telescope to 4 K with reasonable power, and reducing the straylight seen by the instruments to close to background-limited levels. The flux reduction is expressed differently for various configurations, but a simply stated requirement is for a sunshield with coldest, telescope-facing, layer with small emissivity at a temperature of 15 K or less. In an open-planar geometry similar to JWST, this will result in a cooling power requirement of several tens of microwatts for the telescope, consistent with development plans for active cooling.

Sunshield performance to this level is unprecedented, and will require development in the areas of thermal design, materials both sun-facing and cold-facing, performance prediction modeling, and ground validation of performance, with flight validation of model predictions likely an essential component. The JWST sunshield is expected to provide an average temperature of roughly 80 K over a smaller area, while shielding a primary mirror at ~40 K. The requirements for SAFIR will be 5 times lower for the sunshield, to permit a telescope 10 times colder. JWST will thus provide valuable validation of the design predictions, but only to temperatures significantly higher than required for SAFIR. The shields of prior space telescopes, for example Spitzer and ISO, surrounded the primary mirror and were cooled by cryogens to <5 K; this geometry is not feasible for the 10 m diameter of SAFIR, and the limited life of cryogens is incompatible with the mission.

Two areas of materials development will be particularly important in reaching the SAFIR requirement for performance during a 5-10 year mission. The sun-facing surface of the warmest layer should have the highest ratio of solar reflectance to thermal emissivity as is consistent with other mission requirements (such as electrical conductance). Currently the highest performance silver-teflon undergoes a nearly three-fold degradation in 5 years, with resultant temperature increase in 2-3 K at the coldest shield. Lower degradation and overall performance is usually obtained if electrical conductance is required. Overall, improvement is needed in the sun-facing layers to achieve longer life without degradation. The other layers of the sunshield view only cold space or other cold shields, but are sensitive to degradation from high energy plasma and micrometeors. While SAFIR will benefit greatly from the development of the JWST sunshield, the results must be tracked carefully to ensure that the full set of SAFIR requirements can be met by those developments. Since the JWST requirements are far less stringent, continued investment in long-life high-performance sunshield materials is highly prudent at this time.

Validation of thermal performance will be very difficult for SAFIR, due both to the size (larger than JWST) and the temperature. Ground validation of JWST will be difficult; for SAFIR it will be many times more so due to the 10 times lower temperature of the primary, and high sensitivity of the instruments to miniscule thermal backgrounds. Because there is no facility large enough to test a SAFIR in its fully deployed configuration at operating temperatures, thermal verification will rely in an unprecedented way more than ever on thermal modeling; in this SAFIR will follow JWST closely. JWST employs two completely independent thermal modeling teams and software analytical packages. In addition to the advanced analytical techniques developed by JWST for large cryogenic systems, a thermal model validation plan, which relies on thermal vacuum testing of assemblies, sub-assemblies, and high fidelity scale model mock-ups, is also serving as a pathfinder in developing a new paradigm for thermal verification of large cryogenic telescopes.

Thermal design for sunshield performance must be a component of the entire observatory, not just of the sunshield itself. Developments beyond those directly related to the sunshield are required, to enable the entire system to achieve performance; in particular developments in instrument design which allow the separation of warm, high-power electronics to the warm side of the spacecraft are of vital importance. The ISIM Electronics Compartment of JWST, which dissipates 200 W in close proximity to the telescope and instruments, is an example of a design that is incompatible with a 4 K far-IR observatory. While it is difficult to specify development activities outside of the scope of the sunshield itself, it is vitally important that the overall thermal performance be an integral part of the requirements for every subsystem.

Active Cooling Technology for ≪1K for the Instruments

The SAFIR instrument complement requires thermal detectors operating at the background limit at wavelengths of up to 1mm. Such detectors will necessarily be cooled to very low temperatures: 0.05 K or perhaps lower. Several candidates exist for the coolers to provide <1 K temperatures: ^{3}He sorption coolers, dilution refrigerators (open- or closed-cycle), and adiabatic demagnetization refrigerators (ADRs; either single-shot or continuous). While each of these approaches has had flight development (IRTS flew a ^{3}He cooler, XRS-1 was to have flown an ADR and XRS-2 will relaunch it, and Planck has a dilution refrigerator), the ADR features near-Carnot efficiency and complete nonreliance on gravity and so is a more advantageous choice for SAFIR at the present time.

It should be pointed out that cooling the mirror to 4K requires an extension of the existing ACTDP cooler technology. GSFC is currently developing a high cooling power continuous ADR (CADR) for operation at 10 K. This magnetic cooler has very high efficiency (at least 50% of Carnot) in the 4-10 K temperature range, and might provide a means of bridging the gap between the ACTDP and SAFIR requirements.

In order to optimize observing time, the ADR for cooling the detectors must be continuous. Two approaches have been developed for this, using either a reciprocating pair of single-shot coolers or by using a gently cycling cascade of refrigeration stages. The details of this latter approach, including a functional prototype, are shown in Figure XV.C-4 below. Such a CADR is under development for the Constellation-X mission, which has similar thermal detectors to SAFIR. These coolers have significantly improved power handling (of order 10 μW), lower temperatures, and similar efficiency as compared to single-stage magnetic coolers.

Because of the developments of ADRs for XRS, all the components have flight heritage. However, SAFIR will require an ADR with greater cooling power, lower operating temperature, and spanning a larger temperature difference. Component technologies will need advancements, but only incremental ones. These components include superconducting magnets with high field-to-current ratios, heat switches with excellent performance at very low temperatures, and paramagnetic salts. Certain systems aspects must also be considered; for instance, the impact of magnetic fields on the readout electronics of the detectors. As an example, a design exists for a toroidal ADR with better field containment in a compact configuration. A deliberate, focused program of technology development for SAFIR can produce the desired advances. Partnering with Constellation-X and far future missions such as SPIRIT and SPECS – all of which have similar detector cooling requirements – it may be suitable to establish a program like the ACTDP specifically for producing compact, efficient flight-qualifiable coolers for temperatures of 0.05 K or below.

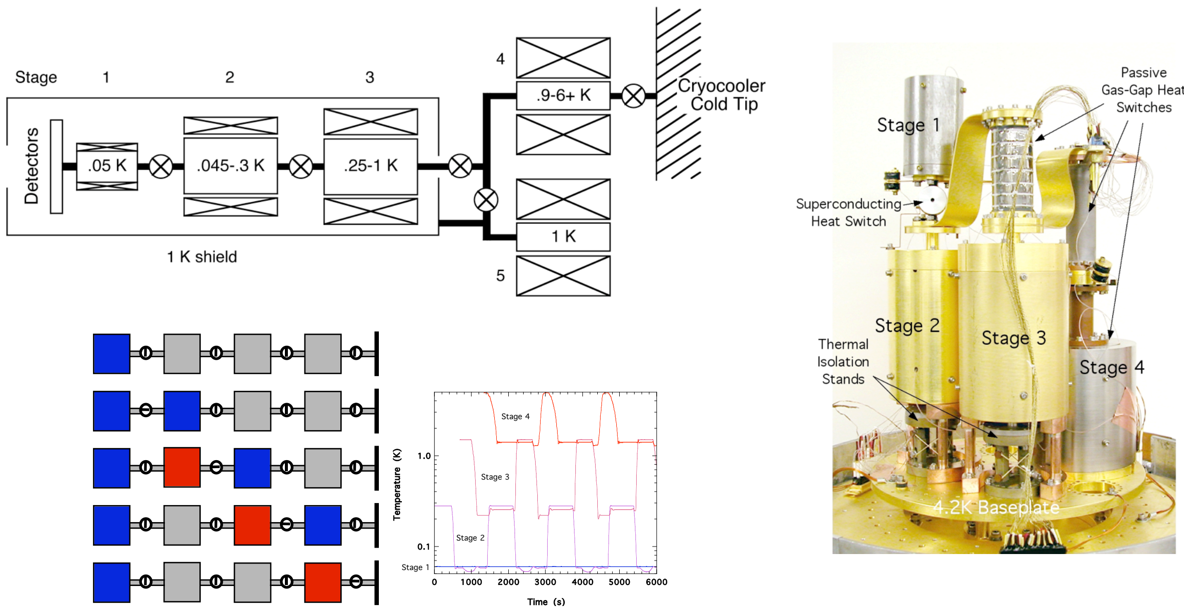


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Figure XV.C-4: (Left, top) schematic of a CADR suitable for cooling detectors to 0.05 K from a cryocooler, using 5 stages including one to cool a radiation baffle. (Left, bottom) schematic of the cooling cycle of the three coldest stages of such an ADR with temperatures of a measured prototype during cycling. (Right) Prototype CADR under development at GSFC. This unit cools detectors to <50 mK and rejects heat at temperatures up to 5 K. Currently the development is at TRL 4.

D. Structures Technology

Overall capability

Table XV.D-1 summarizes the areas where improvements to the current State-of-the-Art are needed for structural elemtns of the SAFIR mission, along with projected need dates. They includes highly conductive sunshade materials; high capacity cryocoolers; large, lightweight, cryogenic optics; thermal and dynamic disturbance reduction systems; precision deployable structures: and cryogenic mechanisms. SAFIR will also need a thermal vacuum test facility able to accommodate a 10-meter aperture telescope and verify its thermal performance at temperatures below 10K. Considerations for membrane mirrors, and the DART option, are provided in Appendix C.

Although not required to meet the SAFIR mission objectives, a capability for on-orbit servicing and instrument change-out could significantly increase lifetime and scientific productivity of the SAFIR mission. The development of a servicing vehicle and standardized electrical and mechanical interfaces for replaceable equipment modules would facilitate on-orbit servicing.

The following section describes the development of a positioning boom and associated mechanisms for our SAFIR design concept, and is included to provide additional information about its characteristics and design details.

Capability	Requirement	Date Required	Investment Start	Comments
Highly Conductive Sunshade Materials	TBD Thermal Conductivity	2015	2008	15K sunshade layer with low emissivity coating
Advanced High Capacity Cryocoolers	150 mW @ 4K 1 W @15K	2015	2008	Active Cooling for Optics and Sunshade
Large, Lightweight Cryogenic Optics	3.3-m F-F, $<25\ kg/m^2$	2015	2008	Low manufacturing costs Includes backing structure
Thermal and Dynamic Disturbance Reduction	20-mK stability <10-mas jitter	2015	2008	Stable Point-Spread-Function for high resolution imaging
Large Precision Deployable Structures	1-mm precision 50 μ repeatability	2015	2008	Sunshade, primary and secondary mirror deployment
Cryogenic Mechanisms (latches, hinges, gimbals)	25 μ repeatability 50-μrad precision	2015	2009	Capable of Operation at 10K or less
Large Thermal Vacuum Test Facilities	>20-m diameter > 30-m in height	2017	2010	Needed for end-to-end performance verification

Table XV.D-1. SAFIR Capability Development Needs

Positioning boom development

Positioning boom deployment has been discussed above as a highly enabling concept for SAFIR operations. The following section describes the development of a positioning boom and associated mechanisms for our SAFIR design concept, and is included to provide additional information about its characteristics and design details. The positioning boom isolator development would consist of proof of concept test article design, fabrication and testing over operating temperatures ranging from cryogenic (near zero K) to 300 deg K, in vacuum. Development would need to be focused in these areas:

Structural development of long and lightweight cantilever beam segments, capable of generating desired levels of structural damping.
Composite boom design would incorporate hardware features required to facilitate the damping design concept, whether passive or active. Boom design would include interface end fittings required for conveniently assembling individual boom segments with additional components required to complete the boom assembly. While use with an active set of pointing actuators eliminates the need for ultra high thermal distortion stability within the boom structure, consideration needs to be given to the design and testing of the boom in order to demonstrate high resistance to structural hysteresis and slip (no significant micro-dynamics permitted). Strength testing with load/deflection data would need to be done using test equipment sensitive enough to detect hysteresis at the levels arrived at for the pointing requirement. Dynamic settling time and transmissibility measurements would be made using simulated zero G supports and appropriate mass and vibration levels.

Positioning gimbal development of 90 to 180 degree rotary actuators, capable of very fine pointing resolution (and stability).
Actuators must include rotary cable wraps with appropriate interfaces at input and output ends of actuator assembly. Actuators must demonstrate high torque margins over the operating environment ranges. Life cycle capability must be demonstrated in vacuum over operating temperature range. The actuators must demonstrate high torque margins (100% minimum) over worst case voltage supply (~30% below nominal) and gimbal assembly drag torque conditions (coldest cable wrap and gear

reduction set) at the end of the life cycle demonstration. A minimum angular pointing resolution, negotiated from a system design analysis, must be demonstrated using measurement test capability much lower than resolution requirement. Basic demonstration of articulation range capability would be done using simulated zero G supports. Part of the articulation range would be the initial deployment sequence.

Positioning boom "harness" development, where "harness" is being used to describe anything non-structural required to be routed in parallel with the positioning boom.
A representative harness bundle would be assembled along the boom. Interfaces at harness ends of each boom segment would be demonstrated. The harness would need to be designed and fabricated having minimal impact on structural damping requirements of the boom assembly.

Positioning boom to spacecraft interface axial flexures and harness interface loop development.
Axial flexures anchoring the positioning boom to the spacecraft simulator would be required to demonstrate an adequate level of compliance required to maintain positioning boom isolation requirements. The harness loop across these flexures would need to be assembled to demonstrate that it does not significantly affect the function of the axial flexures. Strength testing of the flexures would be required, and load deflection data would need to be taken to verify the no slip, no micro-dynamics requirement.

Consideration for thermal control and associated hardware required for the various operating temperatures chosen.
A variety of applications would need to be considered. The boom could be required to operate in cold or warm, and not be a heat disturbance to payload attachments. The boom would need to have appropriate thermal optical properties to meet requirements generated by a system analysis. These properties would need to be identified and demonstrated as part of the boom assembly if they turn out to have a significant mechanical impact on boom articulation

Consideration for a launch restraint system should be provided.
Stowed load carrying capability of the completed boom assembly would need to be demonstrated. This could be done using simulated tie down restraints or commendable release mechanisms. Loads could be applied using static loads simulating quasistatic load levels of vibration testing.

E. Technology Timeline

Based on the sections above, we provide in Figure XV.D-1 a technology timeline for SAFIR in the context of other relevant agency missions. This timeline is consistent with, and correlated with results of the recent Advanced Telescope and Observatory Capability Roadmap (CRM4).

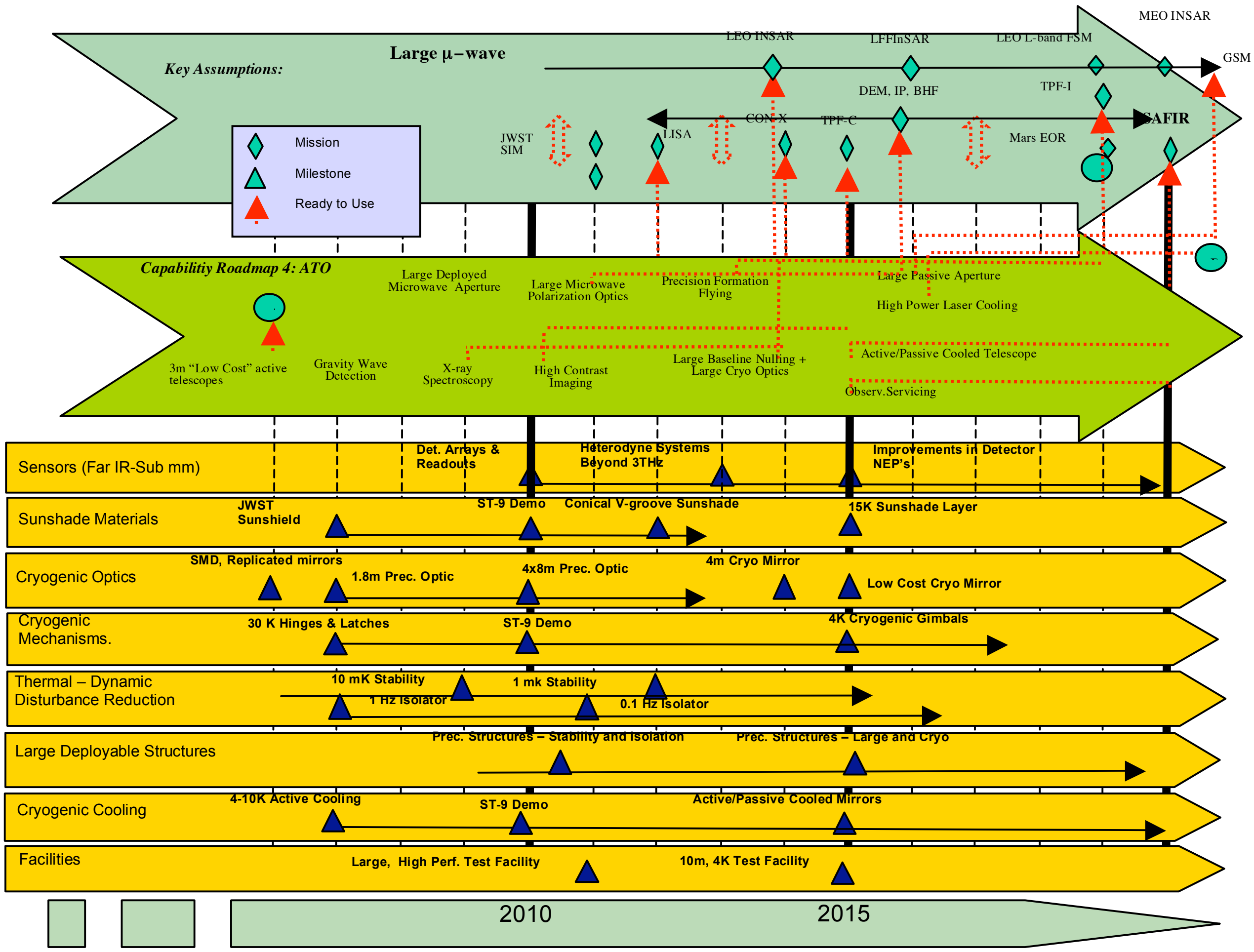

Figure XV.D-1: Technology development timeline for SAFIR. This shows the needed schedule for technology development in order to reach the nominal launch date for the mission. The green section corresponds to results from the Advanced Telescopes and Observatories Capability Roadmap team (CRM4).