Cosmic Origins Program Analysis Group (COPAG) Science Analysis Group (SAG) 4: Technology Needs for Future Far-IR Telescopes and Instruments

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The far-infrared region of the spectrum (~25 – 400 μm) is critical for probing the cool, dense interstellar medium out of which new stars and planetary systems form. In recent years, the enhanced capabilities of *Herschel* and other facilities have provided a wide range of exciting new results ranging from observations of water molecules in protostellar disks to measurements of the dust continuum and fine structure cooling lines in distant galaxies. Future far-IR space missions are needed to learn when the first generation of stars formed and discover their influence on subsequent star and galaxy formation; to learn how galaxies evolved throughout the history of the cosmos; and to understand the physics and chemistry of star and planetary system formation. These are fundamental goals of NASA's Cosmic Origins program.

Since 2002, with refinements in the years leading up to the 2010 Decadal Survey, the US astronomical community has steadfastly supported a widely-publicized plan for U.S. involvement in space-based far-IR astrophysics. The "Far-IR Community Plan," as it is known, presents the science case for astronomical background-limited sensitivity, sub-arcsecond angular resolution, and moderate- to high-resolution spectroscopy. The Community Plan describes single-aperture and interferometric space mission architectures that would be capable of providing science-driven measurement capabilities, and it calls for a focused, coherent technology investment program, highlighting certain key technologies. More recently, the European far-IR community reached very similar conclusions and summarized its recommendations in a white paper submitted to ESA in May 2013. Through the EU Seventh Framework Programme, Europe is presently investing in Kinetic Inductance Detectors (SPACEKIDS program) and enabling technology for a space far-IR interferometry mission (FISICA program). In preparation for its SPICA mission, Japan is also investing in far-IR space mission enabling technology, such as cryocoolers.

The US Far-IR Community Plan served as the basis for the technologies described in this report. The COPAG, through SAG 4, has simply fleshed out the details. The COPAG finds that development of the technologies outlined in Table 1 is key to enabling a future space far-IR mission. If NASA is to lead or participate in such a mission, these are the technologies in which NASA should make a strategic investment.

Table 1. Technology Needs for Future Far-IR Telescopes and Instruments (page 1 of 4)

Name of technology	Detector technology			Observatory-level technology		Cryo-cooling technology	
	Large format, low noise Far-IR direct detectors	**Ultralow-noise Far-IR direct detectors**	**Coherent Far-IR detector arrays**	**Large, cryogenic far-IR telescopes**	**Interferometry for far-IR telescopes**	**High Efficiency Cryocoolers**	**High Performance Sub-Kelvin Coolers**
Brief description	Future NASA Far-IR missions require large format detectors optimized for the very low photon backgrounds present in space. Arrays containing up to tens of thousands of pixels are needed to take full advantage of the focal plane available on a large, cryogenic telescope. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	Future NASA Far-IR missions require detectors optimized for the very low photon backgrounds present in space for spectroscopy. Arrays containing up to thousands of pixels are needed to take full advantage of the spectral information content available. Detector sensitivity is required to achieve background-limited performance, using direct (incoherent) detectors to avoid quantum-limited sensitivity.	NASA's SOFIA observatory as well as suborbital and space missions could achieve a significant observational capability increase by upgrading its single-pixel coherent (heterodyne) spectrometers to arrays.	Large telescopes provide both light gathering power, to see the faintest targets, and spatial resolution, to see the most detail and reduce source confusion. To achieve the ultimate sensitivity, their emission must be minimized, which requires that these telescopes be operated at temperatures that, depending on the application, have to be as low as 4K. Collecting areas on the order of 10m diameter are needed.	Interferometry in the far-IR provides sensitive integral field spectroscopy with sub-arcsecond angular resolution and R ~ 3000 spectral resolution to resolve protoplanetary and debris disks and measure the spectra of individual high-z galaxies, probing beyond the confusion limits of single-aperture far-IR telescopes. A structurally-connected interferometer would have these capabilities. Eventually, the formation-flying interferometer envisaged in the 2000 Decadal survey would provide Hubble-class angular resolution. Telescopes are operated at temperatures that have to be as low as 4K.	Optics and refrigerators for far-IR and certain X-ray missions require very low temperatures of operation, typically roughly 4 K. Compact, low-power, lightweight coolers suitable for space flight are needed to provide this cooling. 4K cryocoolers provide the heat sink for sub-Kelvin coolers.	Optics and detectors for far-IR and certain X-ray missions require very low temperatures of operation, typically in the tens of milli-K. Compact, low-power, lightweight coolers suitable for space flight are needed to provide this cooling.
TABS category	8.1.1	8.1.1	8.1.1	8.1.3	8.1.3	8.1.3	8.1.3
Goals and Objectives	Detector format of at least 16x16 with high filling factor and with sensitivities (noise equivalent powers) of 10^{-19} W/√Hz are needed for photometry. Fast detector time constant (~200 μsec) is needed for Fourier-transform spectroscopy.	Detector sensitivities with noise equivalent powers of $\approx 3 \cdot 10^{-21}$ W/√Hz are needed for spectroscopy, arrayable in a close-packed configuration in at least one direction.	Develop broad tunable bandwidth array receivers for operation at frequencies of 1THz – 5THz, Arrays of at least 16 pixels would be required to have significant impact. Should include optics and accompanying system components.	The goal is to develop a feasible and affordable approach to producing a 10m-class telescope with sufficiently high specific stiffness, strength, and low areal density to be launched, while maintaining compatibility with cryogenic cooling and far-IR surface quality/figure of ~1μm RMS.	The goal is to develop a feasible and affordable (Probe-class) approach to producing a 40m-class interferometer capable of launch and operation, in which a single science instrument provides both dense coverage of the u-v plane for high-quality, sub-arcsecond imaging and Fourier Transform Spectroscopy over the entire spectral range 25 – 400 microns in an instantaneous field of view >1 arcminute.	Extend JWST cryocooler technology to enable cooling from a base temperature of ~300K and cooling to ~4 K with a continuous heat lift of 180mW at 18 K and 72 mW at 4 K, with <200W of input power. Such coolers are required for several mission concepts. More stringent requirements may pertain to a large single-aperture far-IR telescope if a cryocooler is used to cool the primary mirror.	A cryocooler operating from a base temperature of ~4K and cooling to 30 mK with a continuous heat lift of 5 μW at 50 mK and 1 μW at 30 mK is required for several mission concepts. Features such as compactness, low power, low vibration, intermediate cooling and other impact-reducing design aspects are desired.

Table 1. Technology Needs for Future Far-IR Telescopes and Instruments (page 2 of 4)

Name of technology	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Coherent Far-IR detector arrays	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	High Efficiency Cryocoolers	High Performance Sub-Kelvin Coolers
TRL	Single detectors are at ~TRL5, but demonstrated array architectures are lagging at ~TRL3. Sensitive, fast detectors (TES bolometers and MKIDs in small arrays) are at TRL 3 for application in an interferometric mission.	Single detectors are approaching TRL3.	For SOFIA, only single pixel receivers have been developed for flight; arrays of 16 pixels are approaching TRL~4.	JWST Be mirror segments may meet requirements now, so TRL5 with an extremely expensive technology; TRL3 exists for other materials.	Wide field-of-view spatio-spectral interferometry has been demonstrated in the lab at visible wavelengths with a testbed that is functionally and operationally equivalent to a space-based far-IR interferometer. Current TRL is 5 for a 40 m Probe-class far-IR interferometer.	Existing Stirling and J-T coolers with worse performance are high TRL. The TRL is 4 for far-IR interferometric mission application.	Existing magnetic refrigeration demonstrations have achieved TRL3-4.
Tipping point	TRL5 with transition edge sensors could be achieved within 3 years with moderate investment; with MKIDs within 4-5 years. TRL 6 can be attained in 4 years for interferometric mission application.	TRL4-5 with transition edge sensors could be achieved within 3 years with moderate investment; with MKIDs within 4-5 years.	TRL4-5 could be achieved within a few years, and would enable flight opportunities on SOFIA	TRL4 could be achieved within 3 years with modest investments using existing materials.	By extending support for an ongoing NASA project, TRL6 can be achieved at moderate cost in 2 years.	Modest investments based on existing demonstration to reach tipping point. Substitute ^{3}He for working fluid in JWST cooler, then reach TRL 6 for a far-IR interferometer within 3 years.	Modest investments based on existing technology to reach tipping point. Continuous ADR developed for IXO can be matured to TRL 6 for far-IR focal plane cooling to tens of mK in 2 years.
NASA capability	NASA has laboratory fabrication facilities at GSFC and JPL currently working at a low level on these technologies.	NASA has laboratory fabrication facilities at GSFC and JPL currently working at a low level on these technologies.	NASA has laboratory fabrication facilities at JPL currently working at a low level on these technologies.	NASA has cryogenic mirror testing capabilities at GSFC, MSFC, and JPL; mirror production would likely rely on industry partnerships.	NASA has invested in the lab testbed and associated modeling and algorithm development through ROSES APRA, and has invested in a balloon far-IR interferometry experiment that will fly in 2015.	Industry is well-suited for this work.	NASA has cryogenic refrigerator fabrication and testing capabilities at GSFC, with some relevant experience at JPL.
Benefit	Sensitivity reduces observing times from many hours to a few minutes (≈100x improvement), while array format increases areal coverage by 10x-100x. Overall mapping speed can increase by factors of thousands. Sensitivity enables measurement of low surface brightness debris disks and protogalaxies with an interferometer.	Sensitivity reduces observing times from many hours to a few minutes (≈100x improvement). Overall observing speed can increase by factors of thousands.	Observations would be significantly (>10x) faster in imaging applications.	Low-cost, light-weight cryogenic optics are required to enable the development of large aperture far-IR telescopes in the 2020 decade. Large apertures are required to provide the spatial resolution and sensitivity needed to follow up on discoveries with the current generation of space telescopes.	40 m class interferometric baselines are required to provide the spatial resolution needed to follow up on discoveries made with the Spitzer and Herschel space telescopes, and to provide information complementary to that attainable with ALMA and JWST.	Space qualified 4 K cryocoolers will replace expendable cryogens, which are huge consumers of volume and mass, drive mission cost, and limit mission lifetime. Large-capacity cryocoolers are required to achieve astrophysical photon background-limited sensitivity in the far-IR and meet sensitivity requirements to achieve the science goals for future far-IR telescopes or interferometers.	Sub-Kelvin cryocoolers are required to achieve astrophysical photon background-limited sensitivity in the far-IR and meet sensitivity requirements to achieve the science goals for future far-IR telescopes or interferometers. Sub-K goal is also important for certain X-ray detectors.

Table 1. Technology Needs for Future Far-IR Telescopes and Instruments (page 3 of 4)

Name of technology	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Coherent Far-IR detector arrays	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	High Efficiency Cryocoolers	High Performance Sub-Kelvin Coolers
NASA Needs	Far-IR detector technology is an enabling aspect of all future far-IR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. However, the development serves Astrophysics almost exclusively (with some impact to Planetary and Earth studies).	Far-IR detector technology is an enabling aspect of all future far-IR mission concepts, and is essential for future progress. This technology can improve science capability at a fixed cost much more rapidly than larger telescope sizes. However, the development serves Astrophysics almost exclusively (with some impact to Planetary and Earth studies).	This technology is a key technology of benefit for NASA's next SOFIA instruments (3rd Gen).	This technology is a key enabling technology for a future NASA-built far-IR mission consistently given high priority by the far-IR astrophysics community.	Wide-field spatio-spectral interferometry is a key enabling technology for a NASA far-IR Astrophysics mission consistently given high priority by the far-IR astrophysics community. Potential applications also exist in NASA's Planetary and Earth Science programs.	This technology is a key enabling technology for any future NASA-built far-IR mission. It is applicable to missions of all classes (balloons, Explorers, Probes, and flagship observatories).	This technology is a key enabling technology for any future NASA-built far-IR mission. It is applicable to missions of all classes (balloons, Explorers, Probes, and flagship observatories).
Non-NASA but aerospace needs	This technology is primarily needed and supported by NASA.	This technology is primarily needed and supported by NASA.	Such receivers have numerous aerospace applications, remote-sensing, situational awareness, etc.	Lightweight telescopes are critically important for remote sensing applications.	Unknown but could be important.	This technology is primarily needed and supported by NASA.	This technology is primarily needed and supported by NASA.
Non-aerospace needs	Large format arrays are needed by suborbital astrophysics missions, and similar technologies find application in airport screening devices for DHS.	Unknown but could be important.	Similar technologies find application in airport screening devices for DHS.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology	Unknown but could be important.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology; other laboratory needs could be fulfilled with commercialization.	Ground based, airborne, balloon and sounding rocket telescopes could all benefit from this technology; other laboratory needs could be fulfilled with commercialization.
Technical risk	Technical risk for individual detectors is low, as the approach is relatively mature. TES bolometers and MKIDs are promising alternative technologies. Large format array technologies include integrated readout devices, which have moderate development risk.	Technical risk for individual detectors is low, as the approach is relatively mature. Large format array technologies include integrated readout devices, which have moderate development risk.	Technical risk is moderate, as basic technology has significant prior investment.	Technical risk is low, as development of many other mirror materials leverages large existing investments in industry; NASA needs in the near term can be demonstrated by testing existing technologies.	Technical risk is low, as the technique is well beyond the proof-of-concept stage and currently at TRL 5. Future work will yield insight into the practical limitations of the technique when it is applied to a space-based far-IR interferometer.	Technical risk is low, as development leverages previous investments at NASA.	Technical risk is low, as development leverages previous investments at NASA.

Table 1. Technology Needs for Future Far-IR Telescopes and Instruments (page 4 of 4)

Name of technology	Large format, low noise Far-IR direct detectors	Ultralow-noise Far-IR direct detectors	Coherent Far-IR detector arrays	Large, cryogenic far-IR telescopes	Interferometry for far-IR telescopes	High Efficiency Cryocoolers	High Performance Sub-Kelvin Coolers
Sequencing/ timing	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come as early as possible since mission definition and capabilities are built around detector performance. There is a clear plan to achieve this technology. Users identified.	Should come early since SOFIA 3rd Gen proposals are anticipated within 2-3 years.	Should come as early as possible since technology is applicable to small, medium and large missions. By 2020 for the next large far-IR astrophysics mission.	Continuation of prototype efforts will yield mature technique in time for 2015 balloon flight and enable credible discussion of the far-IR interferometer recognized as a critical “formative era” (15 – 30 year time frame) investment in the future envisaged by the NASA Astrophysics Roadmap Committee. Must reach TRL 6 well in advance of 2020 Decadal Survey.	Would be beneficial to undertake soon to take advantage of existing development momentum, to allow time for system integration and cryo-thermal system performance verification, and because the technology is applicable to small, medium and large missions. Well before the 2020 Decadal Survey to enable consideration of the next large far-IR astrophysics mission.	Would be beneficial to undertake soon to take advantage of existing development momentum, to allow time for system integration and cryo-thermal system performance verification, and to enable balloon and Explorer applications at the earliest possible time. Well in advance of the 2020 Decadal Survey.
Time and effort	3-year collaboration between NASA, university groups, and other government agencies.	3-year collaboration between NASA, university groups, and other government agencies.	5-year collaboration between NASA, industry, and other government agencies.	3-year collaboration between NASA and industry.	NASA internal development with academic and international participation in the balloon experiment. 2 years to mature to TRL 6 for far-IR applications on balloon and in space.	3-year effort in industry, plus one additional year for system integration and thermal performance verification.	3-year effort at NASA.