Interferometry Concept for the Far-Infrared Surveyor

D. Leisawitz,[a] L. Mundy,[b] M. Rizzo,[b] and the Space Infrared Interferometric Telescope (SPIRIT) Study Team[c]

[a] NASA Goddard Space Flight Center, Greenbelt, MD; David.T.Leisawitz@nasa.gov

[b] Department of Astronomy, University of Maryland

[c] Members of the study team are listed on the front cover of the 2010 Decadal Survey white paper, which is available at http://asd.gsfc.nasa.gov/cosmology/spirit/

The Far-IR Science Interest Group will meet from 3 – 5 June 2015 with the intention of reaching consensus on the architecture for the Far-IR Surveyor mission. This white paper describes one of the architectures to be considered by the community. One or more companion papers will describe alternative architectures.

As summarized in a white paper endorsed by 296 scientists from 21 nations, including 54 from the United States ("Sub-arcsecond far-infrared space observatory: a science imperative"; http://www.firi.eu/), a far-IR observatory providing sub-arcsecond angular resolution is needed to accomplish many of the community's science goals in the post-Herschel era. Interferometry offers the flexibility needed to satisfy this requirement while avoiding a fundamental limitation inherent in single aperture telescope solutions, where the aperture size must be large enough to satisfy *both* angular resolution *and* sensitivity requirements. At far-IR wavelengths (~25 – 400 μm), a cryogenic meter-class telescope can satisfy the community's needs for continuum and spectral line sensitivity, but fall short of meeting the resolution requirement by more than an order of magnitude. On the other hand, an interferometer's maximum baseline length can be chosen to satisfy the angular resolution requirement, and its telescopes can be sized to meet the sensitivity requirement.

This paper summarizes key science drivers for a spatio-spectral far-IR interferometer (§1), briefly describes the Space Infrared Interferometric Telescope (SPIRIT) "C" design, which emerged from a mission concept study conducted in 2004-5 (§2), outlines potential modifications that might be made to address new scientific objectives (§3), and summarizes the main technology requirements for the mission (§4).

1. Key Science Drivers for a Far-IR Interferometry Mission

Of all the possible science goals for a Far-IR Interferometry mission that is both affordable and technically feasible in the next decade, several stand out as compelling mission design drivers:

- Image protoplanetary disks and measure the distributions of H_2, HD, water vapor and ice, and dust to learn how the conditions for habitability arise during the planet formation process;
- Image structures in a large number of debris disks to find and characterize exoplanets through their interactions with the disks; and
- Understand the formation, merger history, and star formation history of galaxies, and the role of AGN in galaxy evolution.

ALMA's recent image of the disk around HL Tau (Fig. 1) illustrates the potential for high angular resolution observations to overcome model degeneracy and unambiguously advance our understanding of the planet formation process. A far-IR interferometer will make important complementary measurements of the water and total molecular gas distribution in proto-planetary disks. Such measurements can only be made with a space-based observatory; water lines and far-IR spectral features from ice are unobservable from the ground, and model-dependent uncertainties come into play when CO is used as a tracer. JWST will make valuable 28 μm (ground state) H_2 line observations, but will barely resolve proto-planetary disks in the nearest star forming regions. A far-IR interferometer will be able to image these disks at wavelengths around their spectral energy distribution peaks, *map* the 28 μm line emission, measure the ground state HD line at 112 μm to address optical depth effects, and, most excitingly, map the distributions of gas-phase (many far-IR lines) and solid state water (crystalline and amorphous spectral features at ~45 μm) to learn how the reservoir of water in a proto-planetary disk is tapped to enable life to develop on a planet like Earth. Laypersons will appreciate the science community's desire to understand why habitable planets exist, and urge policy makers to invest in this pursuit.

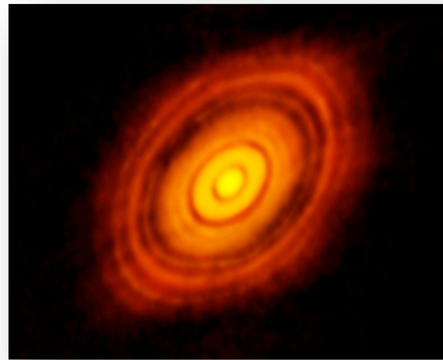

Figure 1 – A far-IR interferometer will map the distribution of water and molecular hydrogen in disks like HL Tau.

Dusty debris disks were discovered with IRAS, and four such disks were resolved with Spitzer. Herschel's observation of the Fomalhaut disk (Fig. 2) illustrates the power of far-IR imagery to show structures that can reveal the presence of planets and enable derivations of their masses and orbits. Only a small handful of debris disks are as close as Fomalhaut (7.7 pc), but a great deal more can be learned about planetary systems if many are resolved like the disk in Fig. 2. To expand the sample to >100 disks without compromising spatial resolution requires much higher angular resolution than was available with the 3.5 m Herschel telescope. ALMA will image some debris disks, but they'll be seen far out on the Rayleigh-Jeans tail where the flux per beam is small (Wootten, Mangum and Holdaway 2004, ASP Conf. 324, p. 277). By observing debris disks at the wavelengths where they're brightest, a far-IR interferometer will detect structures in many disks. These measurements will be particularly useful for finding evidence of planets in wide orbits around their host

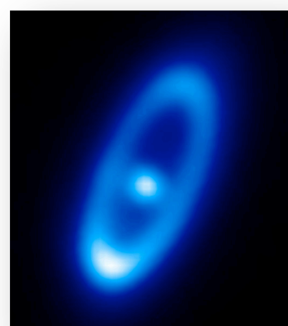

Figure 2 – Dust concentrations and gaps in debris disks point to the presence of planets in wide orbits around their host stars.

stars, complementing transit, radial velocity, and micro-lensing observations, which are observationally biased toward the detection of planets in close orbits.

JWST will measure starlight from galaxies out to high redshifts to learn how galaxies formed and evolved. Complementary observations with angular and spectral resolution comparable to JWST, but at longer wavelengths, will be essential to understand how the interstellar medium – the reservoir of material from which stars form – responds when galaxies interact and merge, and to fully understand galactic nuclear activity and its effects on galaxy evolution. Half or more of a typical galaxy's light, the dominant interstellar gas cooling lines, and lines whose ratios are diagnostic of physical conditions in the interstellar medium, are emitted at rest frame mid and far-IR wavelengths. Important information will be lacking until we fully exploit the far-IR and submillimeter spectral region. Herschel, the largest telescope flown to date, made confusion noise-limited extragalactic deep field observations (Fig. 3 inset, lower-right corner), but angular resolution comparable to that of JWST (Fig. 3 background image) is needed to study individual galaxies unambiguously. At coarse resolution, the spectral content of every spatial resolution element is statistically similar to that of every other spatial resolution element. Spectral decomposition will be limited in its ability to tease out information and complete our understanding of galaxy formation and evolution. The combined power of high angular resolution and spectroscopy available with an interferometer will accomplish this objective.

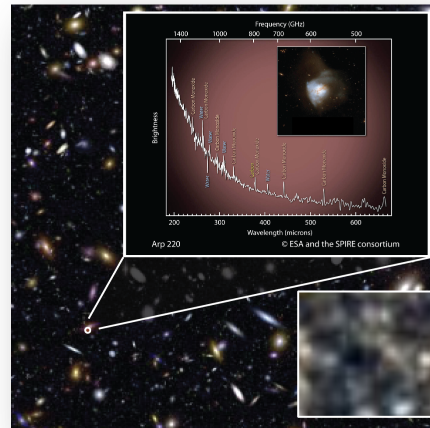

Figure 3 – After JWST and ALMA, high angular resolution and spectroscopy in the far-IR will be needed to complete our understanding of galaxy formation and evolution.

2. Technical Capabilities of the Studied Mission Concept

In 2004, NASA studied SPIRIT as a candidate "Origins Probe." The study was conducted according to methodology described by Mission Systems Engineer D. DiPietro (2014, http://www.dtic.mil/ndia/2014system/16863WedTrack3DiPietro.pdf) and yielded a design reference mission, a mature pre-Phase A design concept, and an independently validated grass roots cost estimate (Leisawitz et al. 2007, Adv. Sp. Res., 40, 689). The study team iterated through three design cycles. The SPIRIT "C" design – the most advanced of three concepts studied – will serve as an excellent starting point for future studies of a space-based far-IR interferometry mission. Its estimated lifecycle cost, including technology development, I&T, launch, and operation, is $1.3B in FY09 $s.

As illustrated in Figure 4, SPIRIT "C" has two 1-m diameter light-collecting telescopes cryo-cooled to 4 K and a central, equally cold Michelson beam combiner attached to a deployable boom. The afocal, off-axis telescopes direct clean 10 cm diameter collimated beams toward the beam combiner. The optical delay line has four output ports, one for each wavelength channel. The shortest wavelength band (25 - 50 µm) makes one pass through the delay line and exits through a metal mesh beamsplitter. Successively longer bands (50 - 100, 100 - 200, and 200 - 400 µm) go through additional reflections before exiting the delay line. The physical stroke of the delay line is sufficient to provide spectral resolution, R ≥ 3000 at the geometric mean wavelength in each band.

The SPIRIT telescopes are mounted on trolleys that move symmetrically along rails to provide access to interferometric baselines ranging in length from 6 m to 36 m. The interferometer rotates approximately once per hour during an observation with the rotation axis pointing toward the target field. After each half-rotation the baseline length is adjusted. Every observation measures the "zero spacing flux" (i.e., the brightness on spatial scales resolved by the individual 1 m telescopes). The *u-v* plane sampling can be tailored to the expected spatial brightness structure in the scene and can be dense, so SPIRIT will produce excellent images. A typical SPIRIT observation sequence will sample 5,040 *u-v* points, take 29 hours to execute (24 hours for science data collection, and 5 hours for observatory slewing and telescope movements), and yield a hyperspectral "data cube" with two high-resolution spatial dimensions and a third spectral dimension, the parameters of which (field of view, angular resolution, and spectral resolution) are given in Table 1.

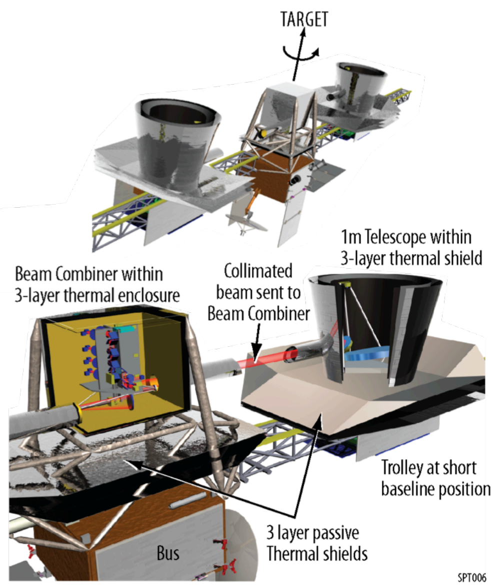

Figure 4 – The spatio-spectral interferometer SPIRIT was designed to make integral field spectroscopic observations in the 25 – 400 µm wavelength range. Key features of the SPIRIT design concept are two movable afocal off-axis telescopes and a single beam-combining instrument.

The SPIRIT "C" design provides natural background photon noise-limited sensitivity. It employs low-noise (NEP ~ 10^{-19} W $Hz^{-1/2}$) detectors, baffles to shield against stray thermal radiation, and cryogenic optics to achieve this. The detector pixel count is set to Nyquist sample a 1 arcmin square field of view in each wavelength band. The largest detector array, 14 x 14 pixels, is needed in the shortest wavelength channel. The detectors are fast enough to measure 4 samples per fringe during an optical delay scan (34 seconds), which implies a time constant τ ~ 185 µs. The dynamic range (ratio of sky brightness to noise) is at least 2500. SPIRIT has two identical detector arrays in each wavelength band, one for each of the two output ports of the Michelson beam combiner. This maximizes the signal-to-noise ratio and reduces risk.

Table 1: SPIRIT Origins Probe Design Parameters

Parameter	Value
Phase B start to launch	72 months (incl. 10 month margin)
Instrument	Michelson beam combiner, double Fourier
Telescopes	2 off-axis, afocal
Telescope diameter	1.0 m
Angular resolution[1]	0.3 (λ/100 μm) arcsec
Field of view	1 arcmin
Baseline range	"zero spacing" plus 6 m to 36 m
Optics temperature	4 K, cryocooled
ODL mechanism scan range	6.15 cm (physical)
Spectral resolution[1]	3175, 5058, 4265, and 3000 at 35, 70, 140, and 280 μm, respectively
Focal plane temperature	30 mK via CADR
Structure	Rigid truss
Sunshield location	Above boom
Uncalibrated point source visibility, V[1]	0.98, $V = (I_{max} - I_{min})/(I_{max} + I_{min})$
Typical time per field	29 hours (24 hours for science)
Point Source Sensitivity[1] (5σ, 24 hours)	Spectral line (10^{-19} W m^{-2}): 2.9, 1.7, 1.4 and 1.3 Continuum (μJy): 14, 20, 31, and 48, at 35, 70, 140, and 280 μm, respectively
Science data rate[1]	5.4 Mb/s
Propulsion system	Hydrazine (monoprop.)
ACS type, accuracy	6 rx wheels, 100 Nm/s, 5.0 arcsec
Star trackers	Two on boom
Slew rate (peak)	1 deg per min
High gain antenna type	Ka band, two-axis gimbal
Ground contacts	2.0 hr/2 days DSN, Ka band
Observatory mass (wet)	4497 kg (incl. 25% contingency)
Instrument power (EOL)	1081 W for beam combiner + 1036 W per telescope (incl. 25% contingency)
Launch vehicle and fairing	EELV with 5m diam., medium length fairing
Orbit	Sun-Earth L2 Lissajous
Mission life at L2	3 years (propellant for 5)
[1]Derived quantity	

SPIRIT could use superconducting Transition-Edge Sensor (TES) bolometers cooled to 30 mK, with SQUID amplifiers for readout or "Microwave" Kinetic Inductance Detectors (MKIDs). Both detector types are likely to be able to meet SPIRIT mission requirements. A Continuously-operating Adiabatic Demagnetization Refrigerator (CADR) was proposed to cool the SPIRIT detectors.

SPIRIT's telescopes will be cooled to 4 K, at which temperature their thermal emission will make a negligible contribution to the photon fluctuation noise at the focal plane, except in the longest wavelength channel. The SPIRIT thermal design provides each light collector and the beam combiner with separate cryo-thermal systems. This allows the boom structure and the telescope transport system to operate at room temperature, thus reducing mission cost and simplifying ground testing. The cryo-thermal systems consist of passive radiators and mechanical coolers, an approach that enables more effective utilization of space in the launch vehicle fairing, reduces mass, and permits longer life than a system with consumable cryogens. The two coldest sun shields are cooled partly by radiation and attached to the 45 K and 18 K stages of a cryocooler. Cold heads at 4 K are mated to the telescopes and the instrument chamber.

For further details, the interested reader is referred to the 2010 Decadal Survey white paper and related SPIRIT mission papers at http://asd.gsfc.nasa.gov/cosmology/spirit/.

Based on experience gained during the Probe study, Leisawitz et al. (2008, Proc. SPIE, 7010, 701028; available as a "SPIRIT Mission Paper" at the web address given above) took a pragmatic look at the mission design solution space for a far-IR interferometer, presented Probe-class and facility-class mission scenarios, and described optional design changes. They roughly assessed the costs and benefits of various mission design alternatives, aiming to provide a basis for further study. We draw on this information in the following section.

3. Interferometric Far-Infrared Surveyor

As a result of compromises made in an effort to find a Probe-class solution, the SPIRIT C design is sub-optimal from a purely science perspective. The science goals outlined in §1 can be achieved more efficiently with modest changes that increase the flexibility and power of the instrument. Table 2 summarizes the capabilities of a notional Interferometric Far-Infrared Surveyor (IFIS) relevant to accomplishing the stated science goals. Many of the parameters listed in Table 1 also apply to IFIS and are not repeated in Table 2. IFIS is improved relative to SPIRIT C in line sensitivity, imaging capability, and survey capability.

Table 2: Interferometric Far-IR Surveyor Description

Parameter	Value
Spectral Bands	25-50 μm, 50-100 μm, 100-200 μm, 200-400 μm
Telescopes	2 off-axis, afocal
Telescope Diameter	1.5 m
Baseline Range	2.5 to 36 meter
Angular Resolution	0.3 (λ/100 μm) arcsec
Field of View	1 arcmin
Detector Array	21 x 21 pixel (max)
Short slew/settle time	5 minutes for < 10 arcminutes
Broadband Clustered Survey Mode (5σ, 1 hour per pointing, 1 arcmin FoV)	R = 10 Point Source Sensitivity = 4, 3, 4, 4 mJy in Bands 1, 2, 3, 4
Line Clustered Survey Mode (5σ, 1 hour per pointing, 1 arcmin FoV)	R = 3000 Point Source Sensitivity = 5, 3, 2, 2 x 10^{-19} W m^{-2} in bands 1, 2, 3, 4
Line Full Imaging Mode, line sensitivity (R = 3000, 5σ, 24 hrs, 1 arcmin FoV)	Band — Sensitivity (10^{-20} W m^{-2}) 1 — 9.4 2 — 5.6 3 — 4.7 4 — 3.7
Broadband Full Imaging Mode Sensitivity (5σ, 24 hrs, 6" FoV)	Band — R — Sensitivity (μJy) 1 — 15 — 280 2 — 7.5 — 190 3 — 3.8 — 130 4 — 1.9 — 94

Clustered Survey Modes. Since the far-IR sky has never been viewed at sub-arcsecond resolution before, IFIS will achieve its science goals most efficiently if it can be used to take snapshot observations of many potentially interesting fields, such as those containing water-bearing young stellar objects in nearby molecular clouds. Quick reconnaissance across closely-space (i.e., "clustered") fields can be followed by line or broadband full imaging observations of the richest target fields. IFIS can be very flexible for such surveys. For example, single baseline measurements yield spectra for many detector pixels in a 1 arcmin field of view; the observer can select the spectral resolution and sensitivity needed to find targets of interest. In crowded fields, a snapshot survey can be carried out with one or more baseline settings to create rough images, which can separate the spectra for multiple sources within a telescope primary beam on the sky. Surveys can be conducted with baseline lengths chosen to distinguish, for example, compact circumstellar disk emission from the extended emission associated with gas in a cluster environment.

Spectral line mapping. The ability to detect and map spectral lines is critical to the extraction of scientific information. Of particular importance in the science cases outlined above are specific lines of H_2O, H_2, HD, and the dominant fine structure lines that serve as coolants of the interstellar medium (e.g., C^+) and diagnostics of radiation field hardness in galaxies (e.g., redshifted mid-IR lines of ionized Ne). Since IFIS sensitivity is limited by astrophysical background photon noise, predominantly thermal radiation from interplanetary (zodiacal) and Galactic (cirrus) dust, the noise in line observations can be decreased significantly by utilizing filters centered on the key lines. For example, an R = 25 filter decreases the background NEP, translating to a five-fold increase in sensitivity over the broadband mode. A further sensitivity improvement would result if IFIS were equipped with, say, 1.5 m telescopes instead of the 1.0 m telescopes adopted in SPIRIT C. As noted in §4, telescope size is one of the trade-offs to be evaluated for cost and science return in a future mission study. Table 2 summarizes the line sensitivity achievable with IFIS when it is operated either to gather Line Full Imaging data (i.e., dense *u*-*v* plane coverage with spectroscopy at resolution R ≥ 3000) or to take spectral line snapshots with a fixed baseline (Line Clustered Survey Mode).

IFIS is an imaging interferometer. Imaging is accomplished through the traditional interferometric techniques of measuring spatial and spectral information in the Fourier domain and transforming to the image plane to make the spatial-spectral hypercube. The best image is acquired by measuring as much of the source information as possible. We envision a design change that would give IFIS access to shorter baselines than those accessible with SPIRIT C. If possible, IFIS should be able to sample baselines as short as 2.5 m, which is the telescope diameter plus 1 meter. In addition, IFIS will have an FTS mode to measure the spectrum for each pixel with the light from a single 1.5 m telescope. In Line Full Imaging Mode, IFIS will gather information from all baselines ≤36 m, combine those data with the single telescope data, and produce complete images with 0.3(λ/100μm) arcsec resolution over a 1 arcminute field of view.

Broadband Imaging. Broadband interferometric imaging requires measurements of interferometric fringes close to the zero path difference point. Some observations, such as those designed to image debris disks at distances of the order of 100 pc, require high sensitivity, but over a relatively narrow field of view. In Broadband Full Imaging Mode, IFIS will scan the optical delay line close to the peak of the white light fringe, maximizing operational efficiency for a restricted set of pixels containing the object of interest, and the *u*-*v* plane will be densely sampled, as in Line Full Imaging Mode, to obtain high-quality images with 0.3(λ/100μm) arcsec resolution.

4. Potential Enhancements and Science/Cost Trade-offs to be Studied

In §3 we described a notional concept for IFIS and identified a few desired enhancements relative to the SPIRIT C design. These and potentially other enhancements are worthy of further study. As with all space missions, the optimal design reflects the tension between science capability on one hand, and technical feasibility and cost on the other hand. Below we recommend several study topics.

Science operations. We suggest consideration of a baseline 5-year mission extendable to 10 years (same as JWST). The only expendable is hydrazine for orbit maintenance at Sun-Earth L2. A larger fuel supply can be accommodated within mass and volume constraints of the assumed Atlas V 531 launch vehicle with a medium length fairing, volume being the more precious of the two commodities in all three studied SPIRIT design concepts. Mechanism lifetime testing and other risk management strategies would have to satisfy somewhat more demanding conditions, but the effect on cost relative to the Probe concept would likely be modest. We would also introduce a funded Guest Observer program and provide enhanced data products. The entire science community will have an opportunity to propose observations and obtain funding for data analysis and publication of results. This would help to fulfill an objective recognized as important in the NASA Astrophysics Roadmap: "FIR interferometry [is] a logical starting point that provides a useful training ground while delivering crucial science."

Launch vehicle. Each of the three capability-enhancing design modifications discussed below would likely expand the launch volume requirement for the interferometer beyond that of the vehicle adopted for SPIRIT C, the Atlas V with a medium-length fairing. When last considered in 2008, the usable payload volume could be expanded by about 40% for an additional launch cost of ~$40M by using a long fairing.

Structure length and angular resolution. To a first approximation, the boom supporting the interferometer's telescopes could be expanded by ~40% if a "long" Atlas V fairing were substituted for the 5 m diameter "medium" length fairing adopted in the SPIRIT C design concept. Fairings envisioned for NASA's SLS launch vehicle are much larger still. Even the Atlas V long fairing, which exists now, could be used to improve the angular resolution to 0.2 (λ/100 μm) arcsec. More efficient packaging and alternative deployment approaches might also enable launch of a longer interferometer structure. The overall cost increase would likely be dominated by the additional launch cost mentioned above, with incremental payload costs being relatively modest. These additional costs may be worth paying for the scientific benefits they would yield.

Thermal shields and field of regard. Individual multi-layer thermal shields reduce the thermal load on SPIRIT's telescopes and beam combining instrument (Fig. 4). In the SPIRIT C design, the shields were sized to permit access to viewing angles up to 20° from the anti-Sun direction, and thus to a 40°-wide swath around the ecliptic plane, or about one-third of the sky during each year of the mission. Many high-quality astronomical targets are accessible within that field of regard (FoR), but a larger FoR is desirable.

Without changing the architecture, the FoR can be expanded a little bit with only minor adverse consequences. (With larger thermal shields, the movable telescopes could not approach the beam combiner as closely, leaving a larger hole in the short baseline sampling, and degrading the image quality. Computer simulations can be used to assess the impact on science.) Conceivably, the interferometer could visit targets in up to half of the sky without a major payload design change. The thermal shields could be moderately larger and still not require deployment if a larger rocket fairing is used.

A major architectural change would be required to give the interferometer access to the entire sky, and this would have a number of repercussions. To enable access to high ecliptic latitudes, the entire boom would have to be protected by a wrap-around multi-layer sun shade, something along the lines of the large JWST shade. The shade would have to be folded during launch and deployed, and it's not obvious that it could be packaged for launch in a long fairing without a complicated deployment scheme, so new risks would come into play. Alternatively, the shade could be launched separately and docked to the rest of SPIRIT, but this would greatly increase the mission cost and complexity. Further complications are likely to stem from the fact that the boom would be cold, so the telescope transport mechanisms would have to operate at much colder temperatures.

Telescope size, spectrometer design, and sensitivity. Cost and volume constraints led to the choice of 1 m diameter telescopes in the SPIRIT C design, but relaxation of those constraints would allow the tradeoffs associated with telescope size to be revisited. Herschel observations made more recently than the SPIRIT mission concept study suggest that some measurements will demand better sensitivity than that available with SPIRIT C, or available only in a deep exposure. The interferometer's sensitivity can be improved by increasing the size of the telescopes, or by modifying the Michelson beam combiner.

Fabrication of primary mirrors in the 1 to 3 m range meeting far-IR performance specifications is not particularly challenging. However, changing the telescope size would affect a number of design parameters. For example, to preserve the 1 arcmin field of view, the detector array dimensions would have to increase in proportion to the telescope diameter (as reflected in Table 2), and additional cryocoolers may be needed.

In the SPIRIT mission concept study, the telescope size of 1 m was chosen after trading sensitivity for angular resolution (boom length) to meet a launch volume constraint. This trade will once again come into play if larger telescopes are considered. Superficially, it seems unlikely that telescopes as large as 3 m would be favored, as they would likely drive down the boom length intolerably, and cost too much. The payload cost can be expected to increase significantly, perhaps by two or three times the incremental cost associated with a larger rocket fairing, if the telescope is doubled in size. Nevertheless, the costs and benefits associated with increasing telescope size are such that this topic merits further study.

In summary, a number of potential enhancements should be studied for their costs and science returns. Particularly interesting are increased field of regard, sensitivity, and angular resolution, all of which are technically feasible. Based on our mission study experience, significant improvements in some, but not all, areas (e.g., FoR covering half of the sky; factor of 4 increase in sensitivity; 40% increase in angular resolution) will be achievable for a modest fractional increase in the overall mission cost, but enhancing all capabilities simultaneously may be significantly more expensive. To find the optimal design at a new price point will require careful reanalysis. That task awaits a future Science and Technology Definition Team (STDT).

5. Summary of the Technology Requirements

The technology requirements for a structurally connected far-IR interferometer overlap those for any future far-IR mission: low-noise detectors and integration of advanced cryocoolers into a cryo-thermal system with performance verification are key. Relative to the needs anticipated for single-aperture telescope, the detector arrays for an interferometer may have much lower pixel count but must be capable of fast readout, as noted above. More detailed requirements (e.g., detector NEP, pixel count, and time constant; cryocooler heat lift at various temperature stages) are given in the 2010 Decadal white paper at at http://asd.gsfc.nasa.gov/cosmology/spirit/. Unique to an interferometer is the need to develop the wide-field double Fourier (spatial and spectral) technique and associated phase referencing and image construction algorithms. Steady but slow progress has been made in all of these areas since the Decadal white paper was submitted in 2009. With a coherent plan and dedicated funding through NASA's ROSES/Strategic Astrophysics Technology program, the entire suite of mission-enabling technologies can be matured to Technology Readiness Level (TRL) 6 in time for the 2020 Decadal Survey, as indicated in Figure 5.

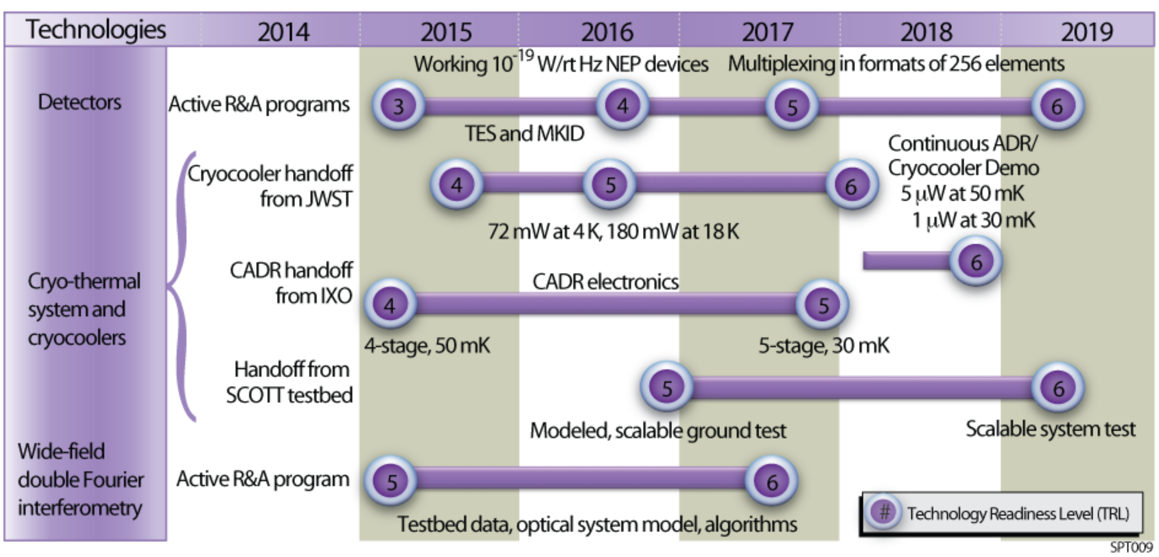

Figure 5 - The technology development plan for a space-based far-IR interferometer builds on existing heritage and past investments to mature all the mission enabling technologies from their present state to TRL 6 in four years.