Far-IR/Submillimeter Space Interferometry: Scientific Motivation and Technology Requirements [1]

David Leisawitz, William Danchi, Michael DiPirro,
Lee D. Feinberg, Dan Gezari, Michael Hagopian,
John C. Mather, S. Harvey Moseley, Jr, and Robert F. Silverberg
NASA Goddard Space Flight Center, Greenbelt, MD
William D. Langer, Michael Shao, Mark R. Swain, and Harold W. Yorke
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
Johannes Staguhn and Xiaolei Zhang
NASA GSFC and Raytheon ITSS, Greenbelt, MD
David.Leisawitz@gsfc.nasa.gov
(301) 286-0807

Abstract—Far infrared interferometers in space would enable extraordinary measurements of the early universe, the formation of galaxies, stars, and planets, and would have great discovery potential. Half the luminosity of the universe and 98% of the photons released since the Big Bang appear at far-IR and submillimeter wavelengths (40 to 500 μm). Because the Earth's atmosphere prevents sensitive observations from the ground at wavelengths shorter than about 300 μm, and large effective apertures are required to achieve sub-arcsecond angular resolution, this is one of the last unexplored frontiers of observational astronomy. We present the engineering and technology requirements that stem from a set of compelling scientific goals and discuss possible configurations for two proposed NASA missions, the Space Infrared Interferometric Telescope (SPIRIT) and the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS).

TABLE OF CONTENTS

1. INTRODUCTION

Recognizing the potential of new detectors and cryogenic telescopes in space to provide background limited sensitivity at far infrared and submillimeter (FIR/SMM) wavelengths, we began to consider how best to explore the wealth of astrophysical information in this spectral region [9]. A major advantage of space observations in the FIR/SMM is that this regime coincides with a minimum in the natural sky background spectrum between the local zodiacal light emission and the cosmic microwave background [6]. We are particularly motivated by questions about the evolution of primordial structure in the universe and the formation of galaxies, stars, and planets. Poor angular resolution has always been a major limitation at these wavelengths. Even the next generation of space-based infrared telescopes will have inadequate angular resolution to take full advantage of this unexplored regime.

Our aim in this paper is to answer the following questions: Why is it important scientifically to attain angular resolution comparable to that of the Hubble Space Telescope (HST) in the far infrared and submillimeter? How can this be accomplished during the next two decades using technologies now within reach? The instrument type that shows the greatest promise is a Michelson imaging and spectral interferometer. Two missions - the Space Infrared Interferometric Telescope (SPIRIT) and the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) - were recently added to NASA's strategic plan. We derive engineering and performance requirements from the science requirements for these missions and describe early mission concepts. The enabling technologies for SPIRIT and SPECS are briefly described here and in greater detail by Shao et al. [12].

2. WHY INTERFEROMETRY?

A lack of angular resolution stands as the major obstacle to scientific progress in the FIR/SMM rather than a shortage of light collecting capability. The universe produces a huge number of photons at these wavelengths. Sub-arcsecond angular resolution is essential to address key science questions. Resolution in the hundredths of arcseconds would be required to resolve distant, young galaxies or protoplanetary systems in nearby star forming regions.

Table 1 - Angular resolution comparison of representative instruments

Instrument	Angular Resolution (arcsec)	Spectral Region
VLBA [a]	0.001	radio
ALMA [a]	0.01	millimeter
Keck 10m w/ AO [a]	0.02	near-IR
HST [a]	0.05	visible
NGST [a]	0.1	near-IR
Galileo's telescope	3	visible
SIRTF [a]	5	mid-IR
JCMT-SCUBA [a]	14	submillimeter
FIRST [a]	20	far-IR
SOFIA [a]	30	far-IR

[a] VLBA = Very Long Baseline Array; ALMA = Atacama Large Millimeter Array; AO = adaptive optics; HST = Hubble Space Telescope; NGST = Next-Generation Space Telescope; SIRTF = Space Infrared Telescope Facility; JCMT-SCUBA = James Clerk Maxwell Telescope, Submillimetre Common-User Bolometer Array; FIRST = Far Infrared and Submillimetric Space Telescope; SOFIA = Stratospheric Observatory for Infrared Astronomy.

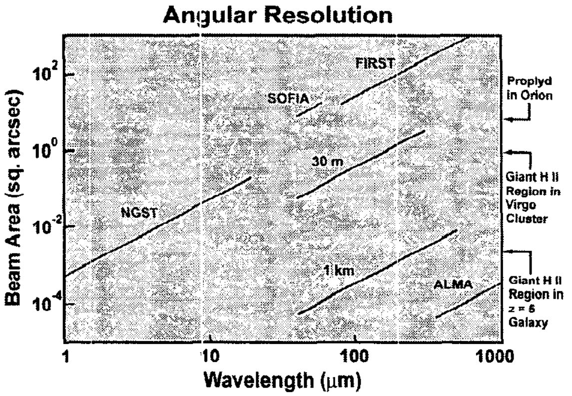


Figure 1 - The angular resolution of a 30 m interferometer would improve upon that of the next generation instruments SOFIA and FIRST by an order of magnitude. A 1 km interferometer would provide resolution comparable to that of the NGST or the ALMA.

Table 1 lists several contemporary instruments, sorted according to their spatial resolving power. Notice that all the FIR/SMM telescopes appear at the bottom of the list and provide resolution comparable to that of the human eye. Of the FIR/SMM telescopes listed, only the *James Clerk Maxwell Telescope* (JCMT) is currently operating; the others will become available over the next several years. A further thousand-fold gain in resolving power will be needed after the *Far Infrared and Submillimetric Space Telescope* (FIRST) is launched in 2007 before telescopes operating in this spectral region rival their visible and near-IR counterparts.

For a fixed wavelength, the achievable angular resolution is determined by the primary mirror diameter of a filled aperture telescope or the maximum baseline separation of an interferometer. At 300 μm, a mirror size or interferometer baseline length of 30 m yields only 2.1 arcsec resolution; it takes a 1 km mirror or baseline to reach HST-class resolution. Figure 1 compares the angular resolution provided by 30 m and 1 km apertures with that of several other planned telescopes.

Beyond the ability of a particular solution to satisfy a set of science requirements, technical feasibility and cost are fundamental issues for consideration when choosing between an interferometer and a filled aperture telescope. Another issue might be the potential of a particular architecture to validate technologies that will be needed for later generations of instruments. The cost of a 30 m interferometer, based on three independent, albeit preliminary estimates, is about half the cost of the *Next Generation Space Telescope* (NGST). Such an interferometer could be built as a deployable boom. A 30 m class filled aperture telescope or a 1 km class interferometer would likely be comparable in cost to NGST.

While the filled aperture telescopes would far surpass their interferometric counterparts in light collecting ability, this would represent a true advantage only if the additional photons are necessary to make the desired measurements. For example, high-resolution ($R = \lambda/\Delta\lambda \sim 10^6$) spectroscopic observations of very faint objects would require a light collecting area perhaps measuring hundreds of square meters. Other compelling science objectives, such as those outlined in the next section, can be achieved, however, with somewhat lower spectral resolution and relatively modest mirror sizes. At the physical scales we hope to resolve in distant galaxies, galactic bulk motions will broaden emission lines to at least tens of km/s. If the goal is to detect those lines, not to use them to model the dynamics of individual star forming regions, then $R = 10^4$ spectroscopy is adequate. The science goals given below for telescopes in each size class could be accomplished with *either* a filled or a sparsely filled aperture telescope.

Finally, consider the enabling potential of each instrument configuration resulting from technology validation. Several of the technologies needed to build a 1 km interferometer (e.g., a cooling distribution system) could be tested on a smaller filled aperture telescope. If the ultimate aim were to construct an enormous cryogenic filled aperture telescope, then the smaller filled aperture telescope would be a logical choice. However, a 30 m interferometer is the more natural precursor to a km-class interferometer and would validate all the needed technologies except formation flying.

3. COMPELLING SCIENCE UNIQUELY ENABLED BY FIR/SMM INTERFEROMETRY

About half of the luminosity and 98% of the photons released since the Big Bang are now observable in the far infrared. Evidence for this can be found both in the spectral energy distributions of individual galaxies [13] and in the FIR/SMM background found by the Cosmic Background Explorer (COBE) [2], [3], [6]. Based on their JCMT/SCUBA observations and referring to this background, Cowie and Barger [1] conclude that it is created primarily by a population of ultraluminous infrared galaxies (ULIRGs), most of which lie in the redshift interval z = 1 - 3. The COBE and SCUBA results have stirred great interest in the scientific community, and there is growing recognition that galaxies of more modest luminosity also contribute to the FIR/SMM background. Now we need a better picture of the FIR/SMM sky, a picture as clear and rich with information as the famous Hubble Deep Field.[2]

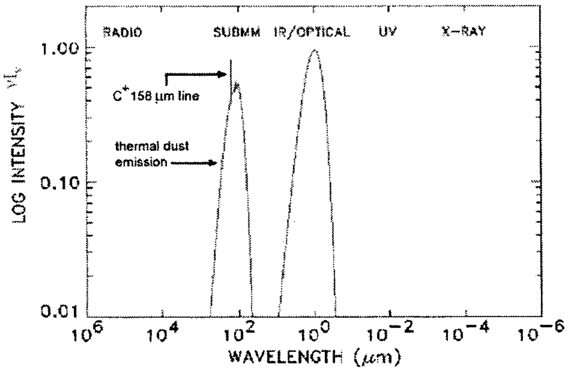


Figure 2 - Spectrum of the Milky Way galaxy, indicating the importance of the C^+ 158 μm line and showing that approximately half of the light is emitted in the far-infrared. In ULIRGs the FIR/SMM luminosity can be orders of magnitude stronger than the near-IR/optical luminosity, which comes directly from stars. This FIR/SMM spectrum was measured by the *Far Infrared Absolute Spectrophotometer* on NASA's COBE satellite.

Because the mechanisms that give rise to FIR/SMM emission are well understood, and because this emission is only minimally affected by extinction, it can be used to measure physical conditions in the early universe, in galaxies regardless of their distance, and in star and planet forming regions, which are naturally dusty environments. Interstellar dust warmed by absorbed starlight glows in the wavelength interval of 40 – 200 μm, emitting a modified Planck continuum spectrum that can be characterized by a dust temperature and spectral index. A warmer spectrum may indicate enhanced star formation or galactic nuclear activity. In resolved galaxies individual H II regions and supernova remnants appear as bright, discrete IR sources and are characterized by exceptionally warm continuum emission. Often these signposts of massive star formation are concentrated in the arms of spiral galaxies or in other sites of high gas and dust density, offering clues to the role of galactic scale events (e.g., tidal interactions) in the star formation process. Star formation is episodic in many galaxies, occurring in bursts that may have been more frequent during the galaxy-building era. The shape of the continuum spectrum can also be used to measure dust properties such as the grain size distribution or material composition.

The FIR/SMM spectral region also contains a number of important interstellar gas cooling and diagnostic lines. For example, the C^+ 158 μm line is emitted by UV-illuminated molecular clouds, especially clouds associated with massive young stars. The 158 μm line, the brightest line in the spectrum of the Milky Way (Figure 2), could provide a direct measure of the amount of star forming activity in distant galaxies. A large number of FIR/SMM H_2O and CO lines serve as coolants and bear valuable information about the conditions in collapsing star-forming molecular clouds [5], [10]. Rest frame mid-IR neon line emission can be used to probe the physical conditions in the interstellar medium and distinguish thermal from nonthermal emissions [14]. Spectral patterns of bright lines can be used to measure redshifts and the kinematics of gas within distant galaxies, revealing rotation curves in some cases and information about mergers, interactions, and galaxy formation in others.

The FIR/SMM region is unique in the electromagnetic spectrum in its potential to aid our understanding of the evolution of structure in the universe. To learn how galaxies form and evolve we need the ability to measure their total luminosities, redshifts, metal abundances, gas kinematics, and morphologies at least back to a redshift z ~ 3, which corresponds to a time when the universe was a small fraction of its present age. Emission at wavelength λ_0 in the rest frame of a distant galaxy is redshifted to wavelength $\lambda = \lambda_0(1+z)$. For example, 0.5 μm starlight from a galaxy at z = 3 would be observed at 2 μm, where it could be seen with the NGST. Likewise, 100 μm dust emission from the same galaxy would be observed at 400 μm. It is essential but not sufficient to measure starlight redshifted toward the near-IR, as this accounts for only half of a galaxy's luminosity. Indeed, most of the sources that comprise the FIR/SMM background are extremely faint in the optical and near infrared [1]. Dust obscures our view of the universe at

---

[2] See http://oposite.stsci.edu/pubinfo/pr/96/01/HDF.html

Table 2 - Science goals for FIR/SMM interferometers

30 m interferometer	1 km interferometer
Fully resolve the cosmic IR background and make spectroscopic measurements needed to characterize the sources	Measure the luminosity history and element and dust formation history of the universe
Measure the spectra of protostars and exozodiacal dust disks to constrain star and planet formation models	Probe physical conditions in galaxies back to the epoch of their formation
	Image exozodiacal dust clouds to study dust temperature, density, and grain size distributions and learn how planetary systems form

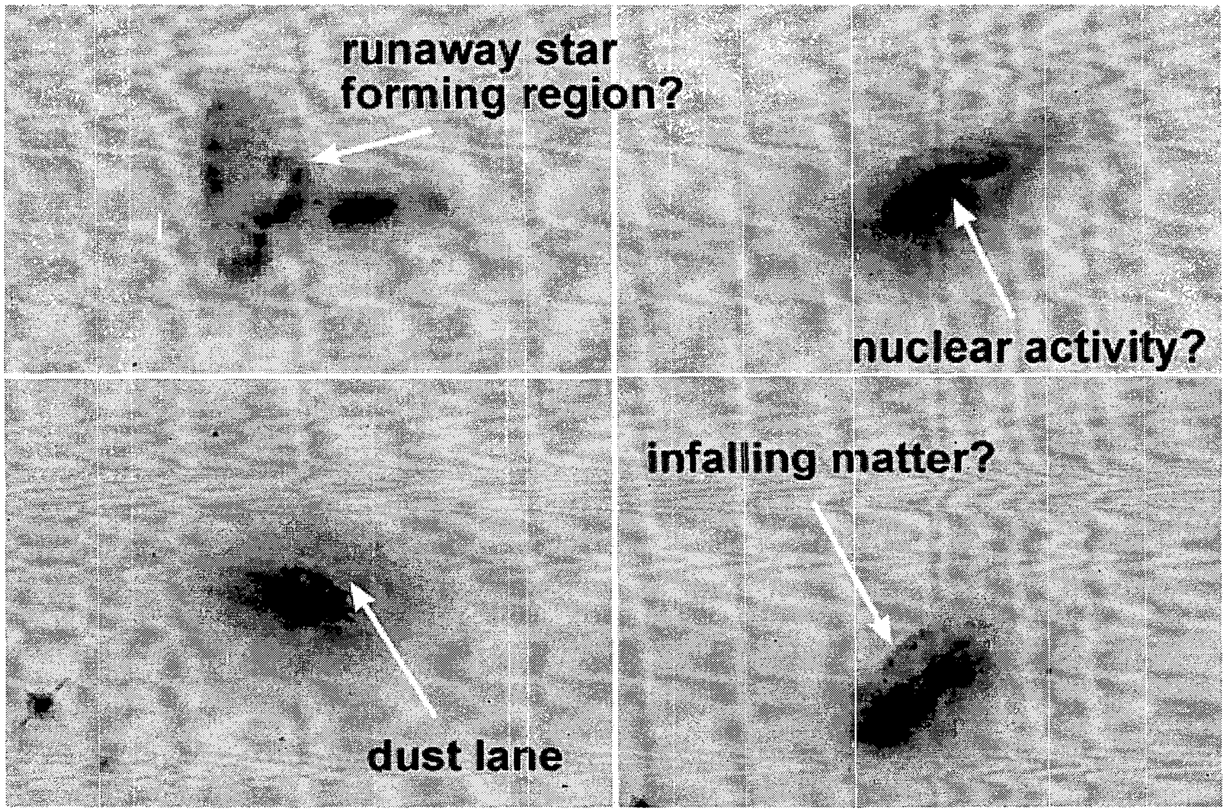


Figure 3 - Visble wavelength observations of four ultraluminous infrared galaxies obtained with the Hubble Space Telescope show features likely to be sites of concentrated FIR/SMM emission, demonstrating the need for high angular resolution at these wavelengths. Each of these galaxies measures only a few arcseconds in diameter. Additional IR bright spots are likely hidden from view by dust and not seen here. Images courtesy of K. Borne and NASA.

short wavelengths, often frustrating attempts to measure star formation rates accurately or peer into the centers of galaxies or star forming regions. For example, studies of Active Galactic Nuclei have thus far been hampered by our inability to see into the dust-obscured galactic nuclear region.

Table 2 lists several particularly important objectives for FIR/SMM space interferometers in the 30 m and 1 km classes. The specific measurement capabilities needed to accomplish these goals are spectral resolution R = 1,000 or greater; a field of view measuring at least a few arcminutes; access to the entire sky; and point source sensitivity of the order of 10^7 Jy-Hz (10^{-19} W m^{-2}). Images of ULIRGs

Table 3 - Instrument dimensions and performance

Parameter	SPIRIT	SPECS
Wavelength Range	40 - 500 μm	40 - 500 μm
Spectral Resolution	up to 10^4	up to 10^4
Maximum Baseline, b_{max}	30 m	1 km
Number of Collecting Mirrors	2	3
Mirror Diameter	3 m	4 m
Angular Resolution, λ / b_{max}	2.1 arcsec at 300 μm	0.06 arcsec at 300 μm
Field of View	3.4 arcmin	3.4 arcmin
Typical Image Size	100 x 100 resolution elements at 300 μm	3,400 x 3,400 resolution elements at 300 μm
Typical Exposure Time	3×10^4 s	3×10^5 s
Typical Sensitivity, νS_ν (1σ)		
At $\lambda/\Delta\lambda$ = 1,000	$2\text{-}5 \times 10^{-18}$ W/m^2 ($2\text{-}5 \times 10^8$ Hz Jy)	$0.5\text{-}2 \times 10^{-18}$ W/m^2 ($0.5\text{-}2 \times 10^8$ Hz Jy)
At $\lambda/\Delta\lambda$ = 3 (SED mode)	$0.3\text{-}2 \times 10^{-19}$ W/m^2 ($0.3\text{-}2 \times 10^7$ Hz Jy)	$0.3\text{-}1 \times 10^{-19}$ W/m^2 ($0.3\text{-}1 \times 10^7$ Hz Jy)

obtained with the Hubble Space Telescope, such as those shown in Figure 3, illustrate the value of angular resolution in the tens of milliarcseconds, the level reached by a 1 km interferometer. Galaxy count models fitted to Infrared Astronomical Satellite (IRAS), Infrared Space Observatory (ISO), and JCMT/SCUBA observations [4] indicate that a 30 m interferometer would break through the confusion barrier quickly reached by smaller telescopes, and enable measurements of the spectra of individual high-z galaxies. Confusion now prevents us from making the desired observations.

A particularly compelling, though more speculative aim for FIR/SMM interferometry is to image the pristine molecular hydrogen that gave birth to the first generation of stars, before any heavier elements existed. Even if the highly redshifted mid-IR H_2 cooling lines prove too faint to detect, FIR/SMM space interferometers will be able to measure the cosmic history of element synthesis and dust formation through spectral line and continuum observations.

4. SPIRIT AND SPECS

Following the approach of Mather et al. [9] we describe here concepts for two FIR/SMM space interferometers designed to achieve the scientific objectives outlined in Table 3. Both are spatial and spectral Michelson interferometers that employ low-noise direct detectors and cryogenic mirrors to reach background-limited sensitivity. The Space Infrared Interferometric Telescope (SPIRIT) has a 30 m maximum baseline. The Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) has a 1 km maximum baseline. The wavelength interval of 40 to 500 μm is accessible to SPIRIT and SPECS; however, the spectral range could be adjusted at either end to provide coverage complementary to that of the NGST at shorter wavelengths and the ALMA at longer wavelengths. The instrument dimensions and estimated performance are summarized in Table 3. Sketches of preliminary designs are given in Figures 4 and 5.

Both SPIRIT and SPECS sample the synthetic aperture ("u-v" plane) densely, if not completely, to produce high-fidelity images. During an observation, which might take hours in the case of SPIRIT or several days in the case of SPECS, the flat mirrors used as siderostats sweep out a spiral pattern. To keep the geometric delay to a minimum these mirrors stay equidistant from the beam combining optics, and the plane of the spiral is perpendicular to the line of sight. On SPECS the siderostats could be tethered to the beam combiner to mitigate the need for a prohibitive amount of thruster fuel. Centrifugal forces would provide rigidity and help to stabilize the system.

A proven technique will be used to obtain spectroscopic data. By scanning the optical delay line, the Michelson design naturally yields spectral information. In this respect SPIRIT and SPECS would resemble the Far Infrared Absolute Spectrophotometer (FIRAS) that flew successfully on the COBE satellite [8].

The desired wide field of view can be obtained by using an array of detectors to make parallel observations of multiple primary beams. A laboratory instrument called the Wide-field Imaging Interferometry Testbed is being developed at NASA/Goddard Space Flight Center (GSFC) to characterize the performance of an interferometer that operates in this manner [7]. The delay line must be long enough both to equalize the path lengths for all pixels in the field of view

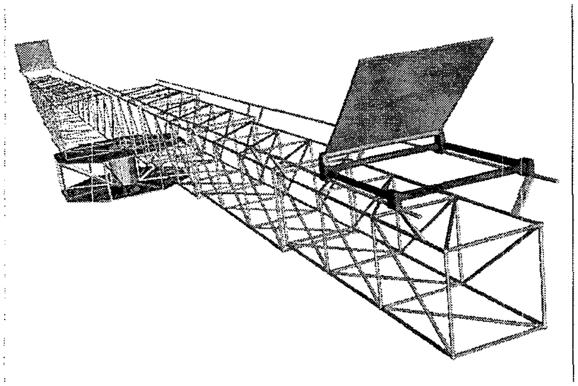


Figure 4 - Perspective view of concept for SPIRIT. Boom and flat mirrors, initially packaged in a rocket shroud, would deploy from the central platform holding the beam combining optics and delay lines (not shown). Flat mirrors move along tracks to a side-by-side position, which provides low spatial frequency information. The entire assembly spins, giving complete coverage of the synthetic aperture plane. An alternative concept uses several mirrors distributed along the boom and illuminated pairwise by movable secondary mirrors. Beam combination would be done on an optical bench located at the central hub. Drawing courtesy of A. Jones (NASA/GSFC).

and provide the desired spectral resolution at the longest wavelengths of interest. The total delay would be about one to several meters. The delay line optics and scanning mechanism would have to operate at cryogenic temperatures to keep instrument noise to a minimum.

Figure 6 shows that the sensitivity of SPIRIT and SPECS to a point source compares favorably to that of NGST and ALMA and represents a substantial improvement over the next-generation FIR/SMM instruments. Somewhat longer exposure times are assumed for SPIRIT and SPECS (see Table 3) than for the other instruments (1 x 10^4 s), but these times are reasonable considering the spacecraft movements required for image synthesis. High signal-to-noise ratio spectral energy distrubutions (SEDs) could be produced by smoothing interferometer spectra to R = 3. SPIRIT and SPECS will be able to measure the SEDs of normal, as well as ultraluminous galaxies back to the epoch of galaxy formation. They could detect the C^+ 158 μm line in a galaxy like the Milky Way at a redshift z = 1 and provide complete (R = 1000) infrared spectra of the galaxies considered likely to contribute the bulk of the cosmic far-IR background.

The engineering implications and new technology requirements that stem from the set of science goals and desired measurement capabilities envisioned for SPECS are shown in Figure 7. The mirror temperature and detector noise values are chosen to satisfy the requirement to achieve sensitivity limited by the diffuse sky brightness [6], the assumption made to estimate the sensitivity shown in Figure 6. An analogous requirements flow down chart for SPIRIT would look much like the SPECS chart, except that SPIRIT uses a 30 m deployable truss instead of formation flying. Making reasonable assumptions about the time required to develop each of the key technologies to an appropriate level of maturity, we estimate that it will be possible to launch SPIRIT in 2009 and SPECS in 2015. The preferred location for FIR/SMM interferometry is the Sun-Earth L2 point, as it is distant enough to help with cooling and pointing, yet near enough to handle a large data rate.

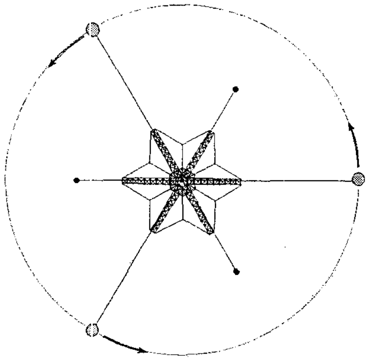


Figure 5 - Early concept for SPECS as it would appear from the target of observation. The plane of rotation is perpendicular to the line of sight, minimizing geometric delay. A central hexagonal structure contains the beam combining optics, delay lines, and a capability to obtain short spacing information with additional siderostats that move along the arms to positions close to the center. Tethers join the long baseline light collectors (flat 4 m mirrors) to counterweights (or additional mirrors) to reduce spinup as the mirrors are pulled closer to the center. Sun shields would protect all surfaces in the optical path. Note that the central structure resembles SPIRIT, except that it contains three booms instead of one. Concept and drawing courtesy of D. Quinn (NASA/GSFC).

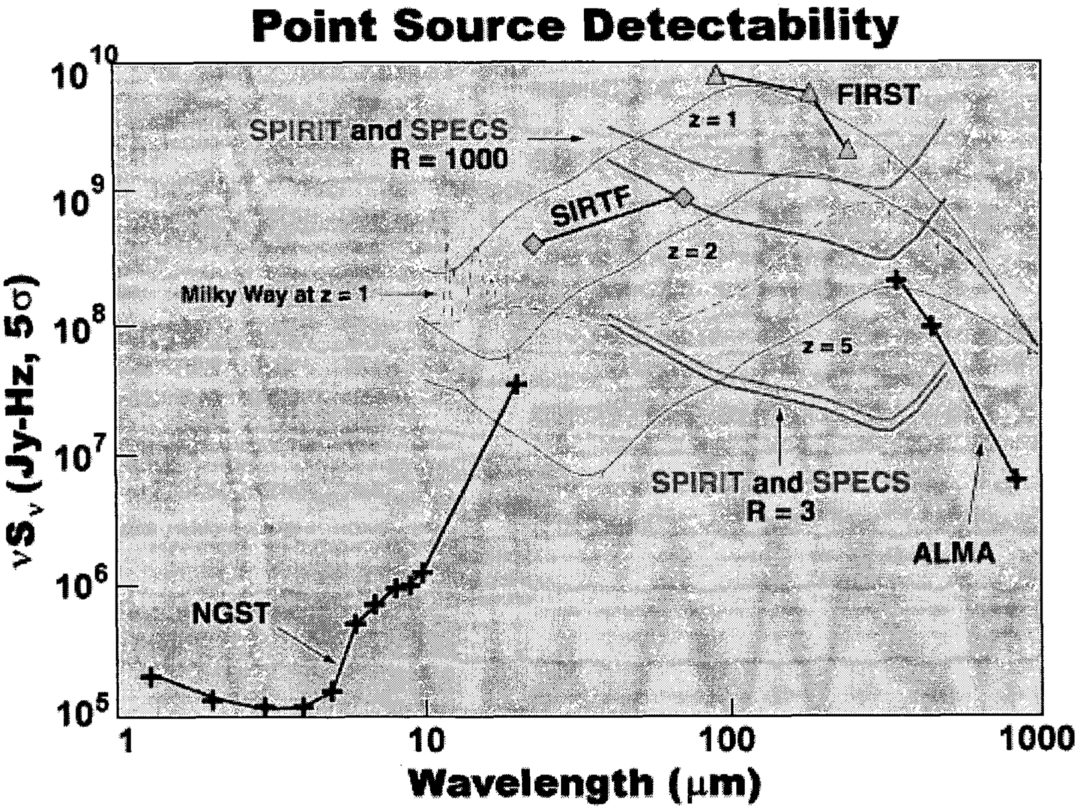


Figure 6 - Sensitivity of SPIRIT and SPECS compared with the broadband (R~3) sensitivity of other instruments (NGST, SIRTF, FIRST, and ALMA), and with representative galaxy spectra. Thin solid curves are ULIRGs at redshifts z = 1, 2, and 5; dashed curve is the Milky Way spectrum redshifted to z = 1. Small vertical arrows under the galaxy spectra mark the location of the C^+ 158 μm line. Instrument exposure times are given in the text. Galaxy spectra courtesy of E. Dwek (NASA/GSFC).

5. TECHNOLOGY REQUIREMENTS

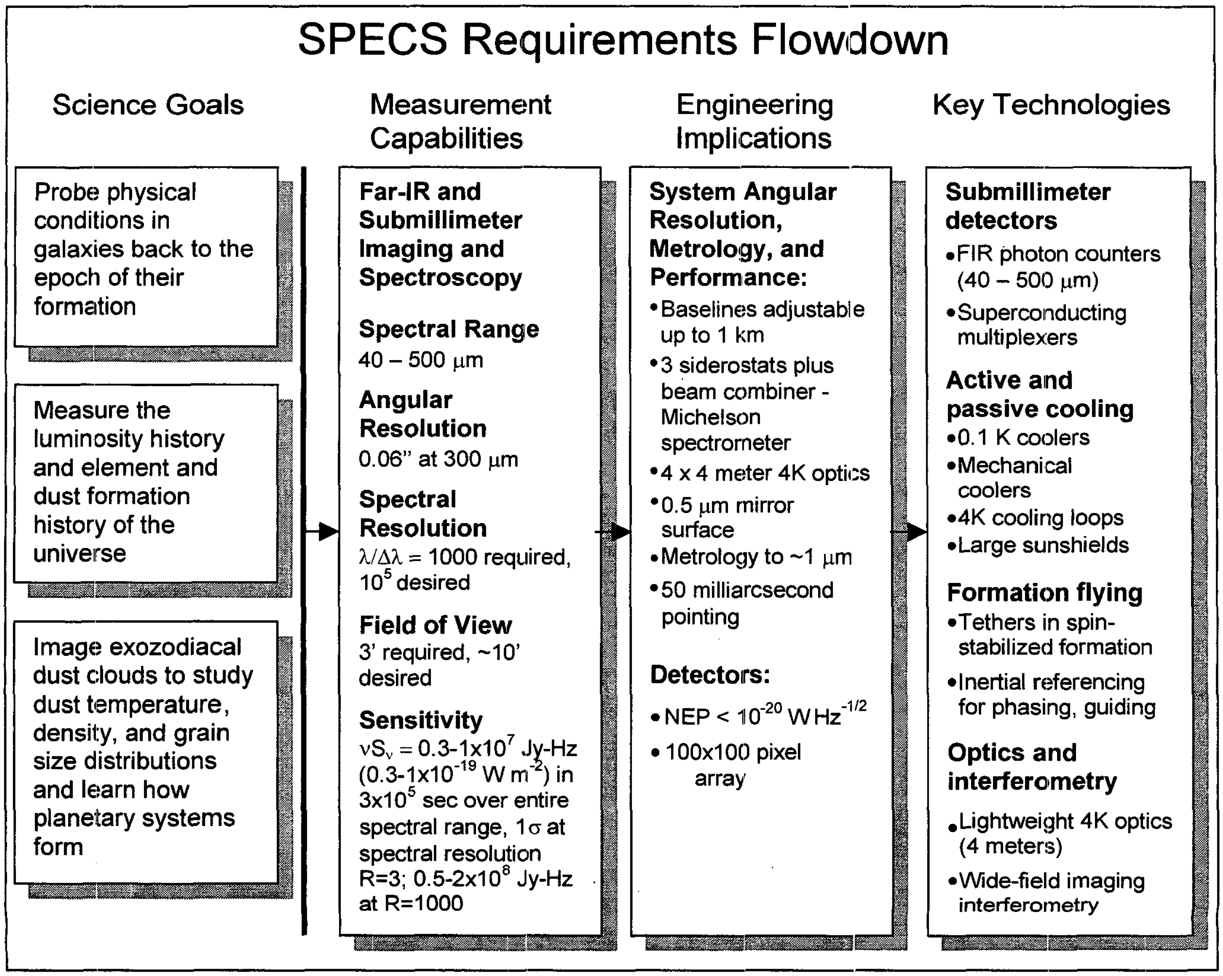
The technology requirements for FIR/SMM space interferometry can be categorized into four areas: 1) detectors, 2) cooling, 3) optics/interferometry, and 4) large structures/formation flying. The relevant technology developments currently underway in these areas are described in further detail by Shao et al. [12].

5.1 Detectors

The detector goal is to provide noise equivalent power less than 10^{-20} W $Hz^{-1/2}$ over the 40 to 500 μm wavelength range in a 100x100 pixel detector array, with low-power dissipation array readout electronics. The ideal detector would count individual photons and provide some energy discrimination, which would enable more sensitive measurements. For example, improved measurements of extragalactic C^+ 158 μm line emission could be made if the intrinsic narrow-band response of the detector were used to improve the line-to-continuum flux ratio by reducing the total detected flux, much of which comes from mid-IR zodiacal emission.

5.2. Cooling

To take full advantage of the space environment, FIR/SMM space interferometers require cold mirrors (~4 K) and detectors (~0.1 K or colder). Active coolers must operate continuously and not cause significant vibrations of the optical components. The coolers should be light in weight. Cooling power will have to be distributed over long distances (meters) and large mirror surfaces. Thermal transport devices will likely have to be flexible and deployable. Large, deployable sunshades will be needed, and they will have to provide protection without seriously compromising sky visibility. Since several stages of cooling



SPECS Requirements Flowdown

Science Goals

Probe physical conditions in galaxies back to the epoch of their formation

Measure the luminosity history and element and dust formation history of the universe

Image exozodiacal dust clouds to study dust temperature, density, and grain size distributions and learn how planetary systems form

Measurement Capabilities

Far-IR and Submillimeter Imaging and Spectroscopy

Spectral Range
40 – 500 μm

Angular Resolution
0.06" at 300 μm

Spectral Resolution
$\lambda/\Delta\lambda$ = 1000 required, 10^5 desired

Field of View
3' required, ~10' desired

Sensitivity
$\nu S_\nu = 0.3\text{-}1\times10^7$ Jy-Hz ($0.3\text{-}1\times10^{-19}$ W m^{-2}) in 3×10^5 sec over entire spectral range, 1σ at spectral resolution R=3; $0.5\text{-}2\times10^8$ Jy-Hz at R=1000

Engineering Implications

System Angular Resolution, Metrology, and Performance:

- Baselines adjustable up to 1 km
- 3 siderostats plus beam combiner - Michelson spectrometer
- 4 x 4 meter 4K optics
- 0.5 μm mirror surface
- Metrology to ~1 μm
- 50 milliarcsecond pointing

Detectors:

- NEP < 10^{-20} W $Hz^{-1/2}$
- 100x100 pixel array

Key Technologies

Submillimeter detectors

- FIR photon counters (40 – 500 μm)
- Superconducting multiplexers

Active and passive cooling

- 0.1 K coolers
- Mechanical coolers
- 4K cooling loops
- Large sunshields

Formation flying

- Tethers in spin-stabilized formation
- Inertial referencing for phasing, guiding

Optics and interferometry

- Lightweight 4K optics (4 meters)
- Wide-field imaging interferometry

Figure 7 - Requirements flowdown chart for SPECS showing the engineering implications and technology requirements that stem from the science requirements and desired measurement capabilities.

must be used to reach the required temperatures, the devices that operate in each temperature range must be able to interface with one another both mechanically and thermally.

5.3 Optics/Interferometry

The mirrors needed to enable FIR/SMM space interferometry must: (a) be light in weight (1 – 3 kg/m^2), (b) have a surface roughness not exceeding ~0.5 μm rms, (c) be able to be cooled to 4 K, and (d) maintain their shape to a small fraction of a wavelength when subjected to cooling or mechanical stress resulting from spacecraft rotation. Beamsplitters that can operate at 4 K and over the wavelength range 40 – 500 μm are needed. Long cryogenic delay lines (meters) are required. They must be able to stroke (full amplitude) at ~1 Hz and survive about 0.5 billion cycles, and they must impart minimal disturbance on the metering structure. Finally, as noted in section 4, techniques and algorithms for wide-field interferometry will have to be developed. The performance of a real interferometer designed to produce wide-field images must be modeled and understood.

5.4 Large Structures/Formation Flying

A variety of architectures is possible for SPIRIT, but all of them depend on the availability of a lightweight, deployable truss structure measuring at least 30 m in length when fully expanded. Any parts of the truss that will be seen by or in direct contact with the mirrors must be cryogenic. One possible design requires the deployed structure to be controllable in length. Another requires tracks and a mirror moving mechanism. Any repeating mirror movements will have to be smooth and rely on a mechanism that is robust enough to survive at least 10,000 cycles.

Imaging interferometry with maximum baseline lengths in the 1 km range implies free-flying spacecraft. The requirement is to sample the u-v plane completely, yet avoid the need for an unaffordable amount of propellant for formation flying. It may be necessary to combine tethers with formation flying to form a long-baseline observatory that maintains symmetry while rotating [11]. The system will have to be deployable, stable, and capable of being steered toward a succession of targets. A modeling effort is being undertaken at NASA/GSFC.

6. CONCLUSIONS

Far-infrared/submillimeter space interferometry has the potential to provide at least two orders of magnitude improvement in both sensitivity and angular resolution over SIRTF and FIRST, the next generation of space observatories that will operate in this spectral region. With interferometry it will be possible to achieve in the FIR/SMM a field of view, image quality, and mapping speed comparable to those of NGST in the visible/near-IR. This can be accomplished with: (1) a Michelson configuration with two or more remote reflectors at least 3 m in diameter, around a central spacecraft, (2) in deep space (e.g., the L2 point), (3) full coverage of the (u-v) plane with rapid motion and tethers to reduce fuel consumption if the span is large, (4) long stroke retroreflectors, (5) background limited far IR detector arrays with sensitivities $\sim 10^{-20}$ W $Hz^{-1/2}$ and 100x100 pixels, (6) telescope temperature ~4 K, and (7) guide star tracking for absolute phase information. If early technology development investments are directed toward meeting the specific requirements outlined in this paper, SPIRIT could be launched by 2009 and SPECS by 2015.

7. ACKNOWLEDGMENTS

The authors wish to thank their fellow members of the Far IR Interferometry Mission Study Working Group – R. Burg, M. Dragovan, E. Dwek, W. Goss, M. Harwit, D.E. Jennings, C. Lawrence, P. Lawson, L. Mundy, R. Mushotzky, D. Neufeld, J. Pedelty, D. Spergel, and E. L. Wright - for their insightful ideas and enthusiastic support. The National Aeronautics and Space Administration sponsored the studies described here.

8. REFERENCES

[1] Cowie, L. L., and Barger, A. J., 1999, In Proc. Conf., *The Hy-Redshift Universe: Galaxy Formation and Evolution at High Redshift*, ed. A.J. Bunker and W.J.M. van Breughel. (astro-ph/9907043)

[2] Dwek, E., et al. 1998, *Astrophys. J.*, **508**, 106.

[3] Fixsen, D., et al. 1998, *Astrophys. J.*, **508**, 123.

[4] Guiderdoni, B. 1999, In Proc. Conf., *The Projected Power Spectrum of the Dark Matter Inferred from Weak Lensing Surveys*, ed. S. Colombi and Y. Mellier, Editions Frontieres.

[5] Harwit, M., Neufeld, D.A., Melnick, G. J., and Kaufman, M. 1998, *Astrophys. J.*, **497**, L105.

[6] Hauser, M.G., et al. 1998, *Astrophys. J.*, **508**, 25.

[7] Leisawitz, D., Feinberg, L., Hagopian, M., Martino, A., Mather, J.C., Moseley, S. H., Jr., and Mundy, L.G. 1999, "Wide-field Imaging Interferometry," proposal submitted in response to NASA Research Announcement 99-OSS-01.

[8] Mather, J.C., Fixsen, D.J., and Shafer, R.A. 1993, *Proc. SPIE*, **2019**, 168.

[9] Mather, J.C., et al. 2000, *Rev. Sci. Inst.*, submitted. (astro-ph/9812454)

[10] Neufeld, D. A., 1998, in *AIP Conf. Proc.* **470**, *After the Dark Ages: When Galaxies Were Young*, ed. S. S. Holt and E. P. Smith (Woodbury, NY: AIP), 414.

[11] Quinn, D.A., & Folta, D.C. 2000, *Amer. Astronaut. Soc.*, 00-015.

[12] Shao, M., et al. 2000, In "Interferometry in Optical Astronomy," *Proc. SPIE*, **4006**, in press.

[13] Trentham, N., Kormendy, J. and Sanders, D. B. 1999, *Astron. J.*, **117**, 2152.

[14] Voit, M. 1992, *Astrophys. J.*, **339**, 495.

***William Danchi** has many years of experience in imaging interferometry. He is co-investigator with Dr. Charles Townes on the Infrared Spatial Interferometer. Dr. Danchi recently joined the Infrared Astrophysics Branch at NASA's Goddard Space Flight Center.*

***Michael DiPirro** is a cryogenics engineer in the Cryogenics and Fluids Branch at NASA's Goddard Space Flight Center. He is an expert on cryogenic systems and cryo-coolers for space applications. Dr. DiPirro is currently working on an Advanced Adiabatic Demagnetization Refrigerator.*

***Lee Feinberg** was, until recently, the Assistant Chief for Technology, Instrument Technology Center at NASA's Goddard Space Flight Center. In that position, he managed and was actively engaged in the early SPECS engineering studies. His expertise is in optical engineering. He played a key role in verifying the corrective optics for the Hubble Space Telescope and in developing new instruments for HST. Recently he accepted a position as lead engineer in the optical communications industry.*

***Dan Gezari** is an infrared astrophysicist at NASA's Goddard Space Flight Center. He won the NASA Medal for Exceptional Scientific Achievement for his work on infrared array cameras and research on the Galactic center. He pioneered the technique of speckle interferometry and the use of array detectors for infrared astronomical imaging. Currently Dr. Gezari is studying architectures and design concepts for the Terrestrial Planet Finder while he is on sabbatical at the Harvard-Smithsonian Center for Astrophysics.*

Michael Hagopian *is the Assistant Chief for Technology, Mechanical Systems Center at NASA's Goddard Space Flight Center, an organization comprised of over 300 engineers, with responsibility to design, analyze, build, integrate and test mechanical and electromechanical systems for spaceflight and ground-based instruments and spacecraft. His current areas of interest include large aperture systems, precision mechanisms, and end-to-end control systems. He is the lead engineering coordinator and technologist for the SPECS study team, having assumed most of Mr. Feinberg's SPECS responsibilities.*

William D. Langer *is an astrophysicist at the Jet Propulsion Laboratory. He is the US Project Scientist for the Far Infrared and Submillimeter Telescope. Dr. Langer is a radioastronomer and an expert in the areas of star formation and interstellar medium research.*

David Leisawitz *is the COBE Deputy Project Scientist. He is experienced in the fields of millimeter-wave molecular spectroscopy, radio astronomy, infrared photometry and IR data analysis, and conducts research on the interactions of massive stars with the interstellar medium. He is a co-leader with Dr. Yorke of the Far-IR Interferometry Mission Study Working Group and one of the original members of the SPECS Study Team. Dr. Leisawitz is PI of the Wide-field Imaging Interferometry Testbed.*

John C. Mather *is the COBE Project Scientist and the NGST Study Scientist. He is a Senior Fellow at NASA's Goddard Space Flight Center and a member of the National Academy of Sciences. Dr. Mather was PI of the Far Infrared Absolute Spectrophotometer, the COBE instrument that measured the spectrum of the cosmic microwave background to 50 ppm precision. Along with Dr. Moseley he is one of the originators of the SPECS idea. Dr. Mather has received many prestigious awards for his research.*

S. Harvey Moseley, Jr. *is a Senior Fellow at NASA's Goddard Space Flight Center and an expert in detector technology and infrared instruments. He recently served on the COBE, WIRE, and SIRTF-IRAC teams. Along with Dr. Mather he is one of the originators of the SPECS idea. Dr. Moseley has won many prestigious awards for his research, including the NASA Exceptional Engineering Achievement Medal and the NASA Exceptional Scientific Achievement Medal.*

Michael Shao *is the Space Interferometry Mission Project Scientist and Manager of the Interferometry Center of Excellence at the Jet Propulsion Laboratory. Dr. Shao's expertise is in the field of optical systems engineering.*

Robert F. Silverberg *is an astrophysicist at NASA's Goddard Space Flight Center with research interests in observational submillimeter and infrared astronomy. He has conducted several balloon-borne experiments, including an infrared survey of the Galactic plane. He is currently working on the Medium Scale Anisotropy Measurement/ TopHat experiments, balloon-borne instruments to study anisotropy in the cosmic microwave background radiation. Dr. Silverberg was a member of the COBE Science Working Group and the COBE Diffuse Infrared Background Experiment team.*

Johannes Staguhn *is an expert in millimeter and radio wavelength interferometry. He is a seasoned instrument builder, having developed the acousto-optical spectrometers for the AS/TRO sub-millimeter observatory and a water vapor correlation radiometer for phase correction of the Berkeley-Illinois-Maryland Array. Dr. Staguhn conducts research on the interstellar medium in the Galactic center and in the Galactic disk.*

Mark R. Swain *is an astrophysicist at the Jet Propulsion Laboratory and an expert on astronomical instrumentation. He is currently working on the Palomar Testbed Interferometer and the Keck Interferometer. Dr. Swain is PI of a research project to develop cryogenic delay lines and beam combiners for far-IR interferometry.*

Harold W. Yorke *is a Lead Scientist for Astrophysics at the Jet Propulsion Laboratory. He is a co-leader with Dr. Leisawitz of the Far-IR Interferometry Mission Study Working Group. Dr. Yorke's expertise is in the area of hydrodynamics and radiative transfer modeling of the evolution of protostars and protoplanetary disks.*

Xiaolei Zhang *is a Chief Scientist in the Raytheon ITSS Department for Astronomy and Solar Physics. Her research interests include radio and far-infrared astronomical instrumentation, as well as theoretical and observational studies of the formation and evolution of galaxies. She currently works at NASA's Goddard Space Flight Center on far-infrared interferometry mission design studies and is the Laboratory Coordinator for the Wide Field Imaging Interferometry Testbed.*