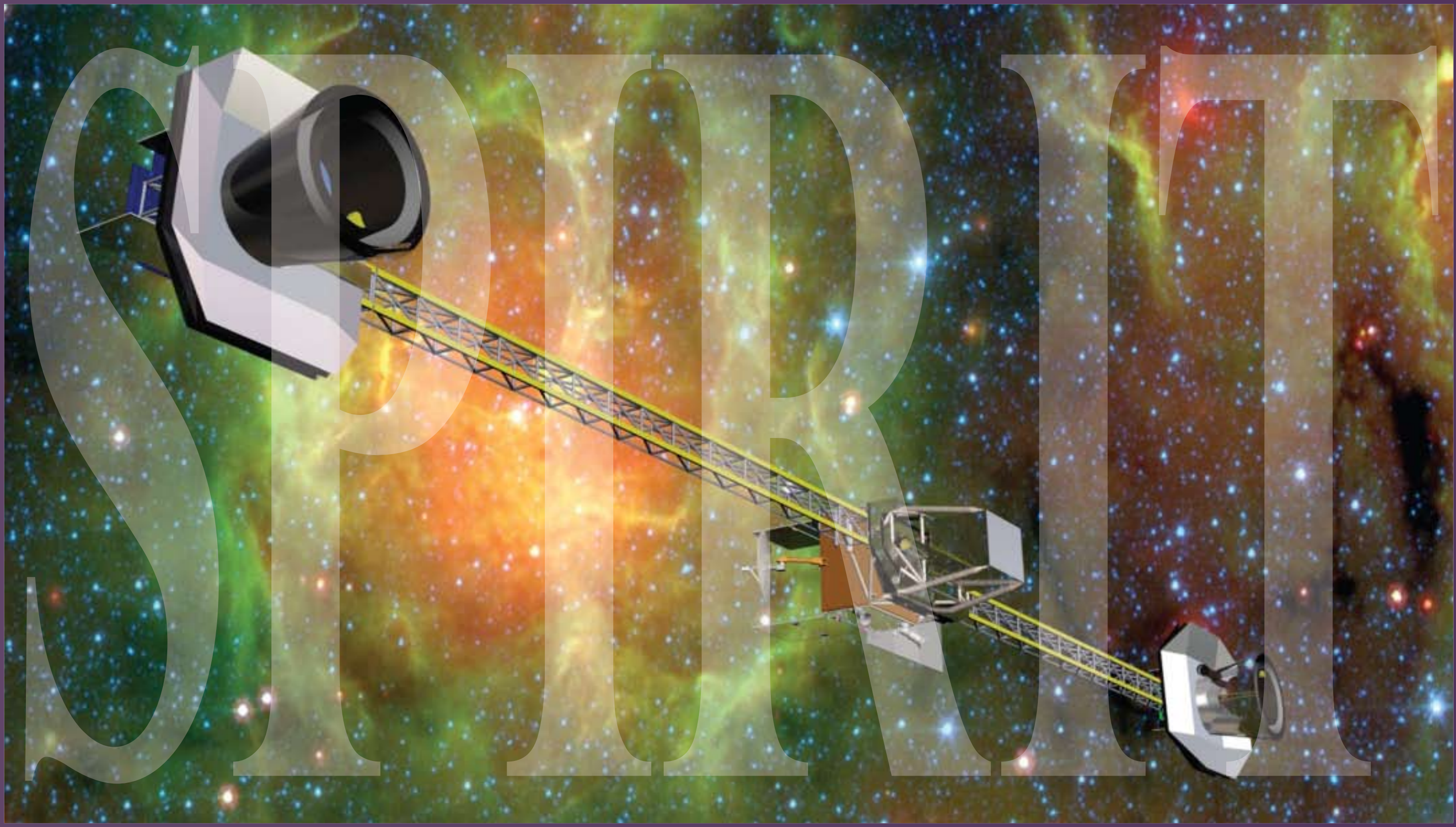
The Space Infrared Interferometric Telescope (SPIRIT): A Far-IR Observatory for High-resolution Imaging and Spectroscopy



A white paper for the Astro 2010 Decadal Survey - Submitted to the Subcommittee on Programs in response to its Request for Information

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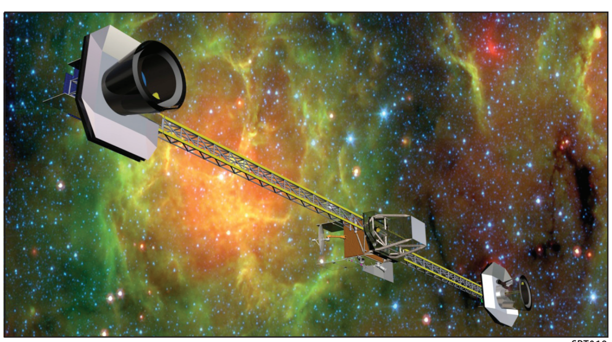
EXECUTIVE SUMMARY

SPIRIT, a space-based far-IR observatory for high-resolution imaging and spectroscopy, will address an array of compelling scientific questions: *How do planetary systems form from protostellar disks, dousing some planets in water while leaving others dry? Where do planets form, and why are some ice giants while others are rocky? How did high-redshift galaxies form and merge to form the present-day population of galaxies?* **We recommend investment in SPIRIT mission-enabling technologies and a realistic, affordable Formulation and Development schedule leading to launch in 2023.**

The questions posed above are among the most compelling questions that have piqued the interest of astrophysicists and the public. A far-IR observatory that offers high angular resolution imaging and spectroscopic capabilities and high sensitivity is an essential tool if we are to succeed in our quest for the answers to these questions. SPIRIT, a 36-meter interferometer with a wide-field Michelson beam combiner, will provide critical spatial and spectral information. No other existing, planned, or proposed facility can offer these capabilities in the information-rich 25 – 400 μm wavelength range. SPIRIT could be in development by the end of the decade, and by 2023 could be providing the data needed by astrophysicists to: (a) learn how planetary systems and habitable planets form; (b) find and characterize exoplanets; (c) learn how galaxies form and change over time; and (d) take advantage of an untapped and promising realm of discovery space to ask and answer questions not yet imagined.



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A number of advances made during the past decade have prepared the ground for SPIRIT. With NASA support we developed and conducted experiments with an optical testbed interferometer that is functionally equivalent to SPIRIT, and demonstrated and gained experience with the wide-field spatial-spectral interferometric technique to be used on SPIRIT. In the UK, the Rutherford Appleton Lab developed a similar testbed that operates at far-IR wavelengths. Japan developed and is ready to fly a balloon-borne far-IR interferometer, and members of the SPIRIT team recently proposed a scientific far-IR interferometry balloon experiment with a SPIRIT-like instrument. We conducted a thorough pre-Phase A mission study. We know how to develop a successful SPIRIT mission. The time has come to embark on the path toward high angular resolution in the far-infrared.

SPIRIT has deep roots in the astrophysics community's strategic plans. The 2000 Decadal Report *Astronomy and Astrophysics in the New Millennium*[1] recommended a "rational coordinated program for space optical and infrared astronomy [culminating in the assembly of] a space-based, far-infrared interferometer." A kilometer baseline far-IR interferometer, widely known as the *Submillimeter Probe of the Evolution of Cosmic Structure* (SPECS), was subsequently added to the NASA Science Plan for astrophysics and studied as a NASA "vision mission"[2] The 2003 *Community Plan for Far-IR/Submillimeter Space Astronomy*[3] recommended SPIRIT, a structurally-connected interferometer, as a practical step on the path leading to the more ambitious SPECS mission. An updated version of the far-IR *Community Plan* prepared for the Astro2010 Decadal Survey[4] recommends technology development for SPIRIT and a formal Phase A study.

A far-IR interferometry mission has consistently remained a high priority of the astrophysics community since 2000.

During the past decade, technology and mission concept development progress was regularly reported in community workshops held in the US, Canada, and Europe.

SPIRIT was selected by NASA for study as a candidate Origins Probe mission.[5] The results of that study form the basis for this activity report.

There is substantial work to be done in the decade ahead, notably technology maturation, commencement of the SPIRIT mission Formulation phase, and telescope and instrument module testbed buildup, integration, and testing. We call upon the Astro2010 Decadal Survey to recommend full NASA support for these activities.

Detailed supporting documentation, including the list of References cited in this paper, is available on the SPIRIT web site, http://astrophysics.gsfc.nasa.gov/cosmology/spirit/.

1.0 KEY SCIENCE GOALS

With SPIRIT we will: (1) learn how planetary systems and habitable planets form; (2) find and characterize exoplanets based on their sculpting effects on protoplanetary and debris disks; and (3) deepen our understanding of the role of mergers in galaxy formation and evolution. Our science objectives in these three areas drove the SPIRIT mission design concept described in ***Section 2***. By providing the measurement capabilities needed to achieve the science objectives, SPIRIT will open an information-rich volume of discovery space, the importance of which is highlighted in at least 15 science papers submitted for review by the Decadal Survey.

1.1 Primary Scientific Objectives of the SPIRIT Mission

1.1.1 Learn How Planetary Systems and Habitable Planets Form

SPIRIT will revolutionize our understanding of the formation of planetary systems and enable us to "follow the water" as these systems develop.

SPIRIT will revolutionize our understanding of the formation of planetary systems and enable us to "follow the water" as these systems develop. To understand how planets form it is essential to study objects in a variety of evolutionary states, from the gas-rich early phase when giant planets form to the later, gas-poor terrestrial planet formation phase. Objects in clusters and in relative isolation should be studied. The early phase of star and planet formation takes place behind a veil of dust, rendering young protoplanetary disks inaccessible to visible wavelength telescopes.

The far-IR light from protoplanetary disks – their dominant emission component – has only been seen until now as an unresolved blur, but SPIRIT will change that. Infrared observations with *Infrared Astronomical Satellite*, *Infrared Space Observatory* (ISO), and *Spitzer*, when interpreted with the aid of models, show evidence of a diverse set of disk features, including flaring shapes, inner holes, settling dust, and possibly gaps, but these features are inferred from spatially unresolved spectral energy distributions.[6,7] The next logical step is to probe finer angular scales observationally, as this is the only way to avoid the simplifying assumptions that contemporary modelers must make, and to detect disk structures and asymmetries that cannot be inferred from spectral information alone.[8] The closest clusters of gas-rich protostars are found in the ρ Oph and Taurus stellar nurseries, at 140 pc. Older, gas-poor developing planetary systems can be observed in the Tuc or TW Hya associations, whose distances are ~50 pc. *The sub-arcsecond angular resolution provided by SPIRIT is needed to resolve protostellar objects at these distances.* The top panel in ***Figure 1*** illustrates SPIRIT's capability to resolve the disks around young stellar objects (YSOs) and more mature systems at a distance of 140 pc. The SPIRIT beam is shown at 28 μm, corresponding to the wavelength of an easily excited rotational transition in the H_2 molecule, one of the most important spectral lines accessible to SPIRIT. SPIRIT will image protostellar and protoplanetary disks to measure their structure and break model degeneracy.

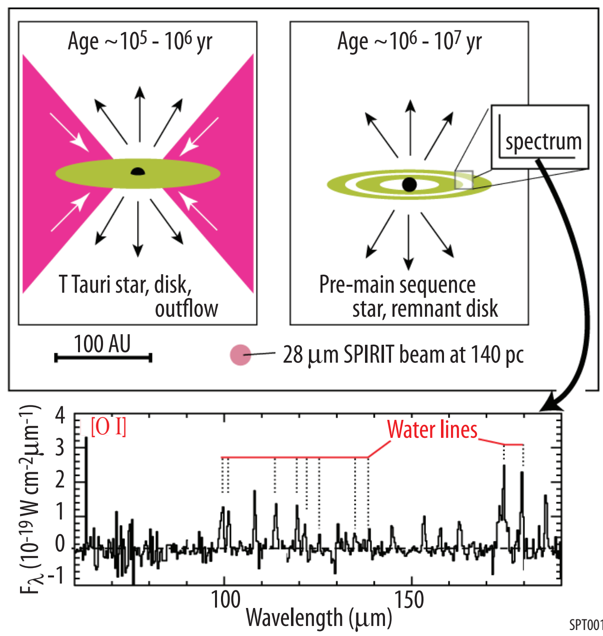


Figure 1: SPIRIT will map the distribution of gas and dust in young and developing planetary systems to test theoretical models and elucidate the planet formation process. SPIRIT will trace the distribution of water in its gaseous and solid states and teach us how our planet acquired its life-enabling oceans.

Spatial resolution alone is not enough. To gain deep physical understanding of planet formation processes SPIRIT will also exploit information available in the spectral domain. Of course, SPIRIT will provide spatial maps of the thermal continuum spectral energy distribution, enabling observers to measure the three-dimensional distribution of dust and map the dust temperature. But more significantly, *SPIRIT will constrain the timescale for gas giant planet formation and the migration of planetary bodies of all sizes by* *measuring the gas contents of planet forming disks of various ages*. Recent observations have begun to detect the rich spectrum of near and far-infrared spectral lines from circumstellar disks and envelopes.[9,10,11] SPIRIT's direct observations of H_2 and HD in the readily excited 28 μm and 112 μm rotational lines will obviate the need for surrogate gas tracers such as CO, which can be photodissociated or frozen onto grain surfaces.

While *Herschel* will be able to observe far-IR lines from hydrides (e.g., CH and OH) and strong fine structure lines of, e.g., [C I], [O I] and [C II], SPIRIT will be able to *map* them. Such line maps, when coupled with models,[9,12,13] will help us to decipher the complex spectra *Herschel* will soon deliver, and contribute to our understanding of the role of chemistry in the planet formation process. For example, SPIRIT observations will be used to derive the C/O ratio as a function of distance from the host star and infer from models[14,15] the composition, surface chemistry, and habitability of planets. SPIRIT will improve on *Herschel's* angular resolution by more than an order of magnitude.

Given its biological significance, water is a critical target molecule.[16] The ISO spectrum shown in the lower panel of ***Figure 1*** [17] shows a small fraction of the spectral range accessible spectroscopically with SPIRIT, but it nicely illustrates the richness of the spectrum and the multitude of water lines present in the far-IR. Most of the volatiles found on the terrestrial planet surfaces are thought to be delivered by impacts of small H_2O rich bodies from the outer solar system. With spectral resolution 10x better than that of the ISO spectrum shown above, *SPIRIT will access the rich gas-phase spectrum of the H_2O molecule, map the water distribution in protoplanetary disks to study the formation of the water reservoir, and search for evaporating water in extrasolar comet trails.*[18,19] *Since water is expected to be frozen in the outer, colder regions of disks, SPIRIT will map the distribution of frozen water by observing the H_2O ice features at 44 and 63 μm*.[20]

1.1.2 Find and Characterize Exoplanets

SPIRIT will find the telltale signatures of exoplanets in spatially resolved protostellar and debris disks.

SPIRIT will study planets in debris disks, young planetary systems in the late stages of terrestrial planet formation. In these disks, young planets perturb the orbits of dust grains via orbital resonances,[21,22] imprinting their signatures on the disk morphology. These patterns, which have been observed at visible to millimeter wavelengths,[23,24,25,26] point the way to extrasolar planets, just as structures in the Saturnian rings have led to discoveries of new moons. SPIRIT's measurements will constrain extrasolar planet masses and orbital parameters. For example, the extrasolar planet directly imaged in the Fomalhaut debris disk sculpts the disk into an eccentric ring whose shape indicates the presence of the planet, and whose extent indicates the planet's mass.[27]

Spatially resolved far-IR images of debris disks can be used to determine the locations, masses, and orbits of exoplanets, including some that might otherwise be overlooked because they produce only weak reflex motions in their parent stars. Multi-epoch observations within the time span of the SPIRIT mission will show motions in the dust concentrations due to planets as slow-moving as Neptune in its solar orbit.

Debris disks are brightest and stars are faint at mid to far-IR wavelengths, making these wavelengths ideal for mapping disk patterns caused by planets. ***Figure 2(a)*** shows in false color the predicted 40, 60, and 100 μm emission from the ε Eri debris disk,[22] scaled to illustrate SPIRIT's ability to resolve a similar disk at 30 pc. The dust-trapping planet in these model images, marked with a + sign, is shown at two orbital phases. By comparing the two images, one can easily see that the resonantly trapped dust grains move with the planet. The emission from these dust concentrations, and their contrast relative to surrounding disk emission, will be most pronounced in the mid to far-IR wavelength range covered by SPIRIT. Using this technique to place our solar system in the context of a representative sample of young exoplanetary systems requires a capability to measure 1 AU structures in debris disks out to a distance of ~10 pc, i.e., an angular resolution of the order of 0.1 arcsec. With 6 arcsec angular resolution at 24 μm, *Spitzer* was able to resolve four nearby debris disks.[24] SPIRIT will offer 100x better angular resolution than *Spitzer* and image at least 19 currently known luminous debris disks,[28] as well as many more faint disks.

SPIRIT will similarly study giant planets during their formative stages in younger, protostellar disks. As shown in ***Figure 2(b)***, such planets are predicted to produce "dimples" in these disks, and the shadows they cast will produce their strongest signatures in the 10 – 30 μm range.[29] At 140 pc, where the closest YSO samples are found, SPIRIT will be able to detect the signature of a proto-planet 1/6th the mass of Jupiter at an orbital radius of 8 AU. The *James Webb Space Telescope* (JWST) will operate at the right wavelengths with excellent sensitivity, but its resolving power will be too poor for this project. The *Atacama Large Millimeter Array* (ALMA) will offer superior resolution, but the shadow-induced brightness contrast will be an order of magnitude weaker at the submillimeter and longer wavelengths it covers. SPIRIT may be the first observatory capable of finding newborn Saturn-like planets in the YSO disks in nearby star forming clouds.

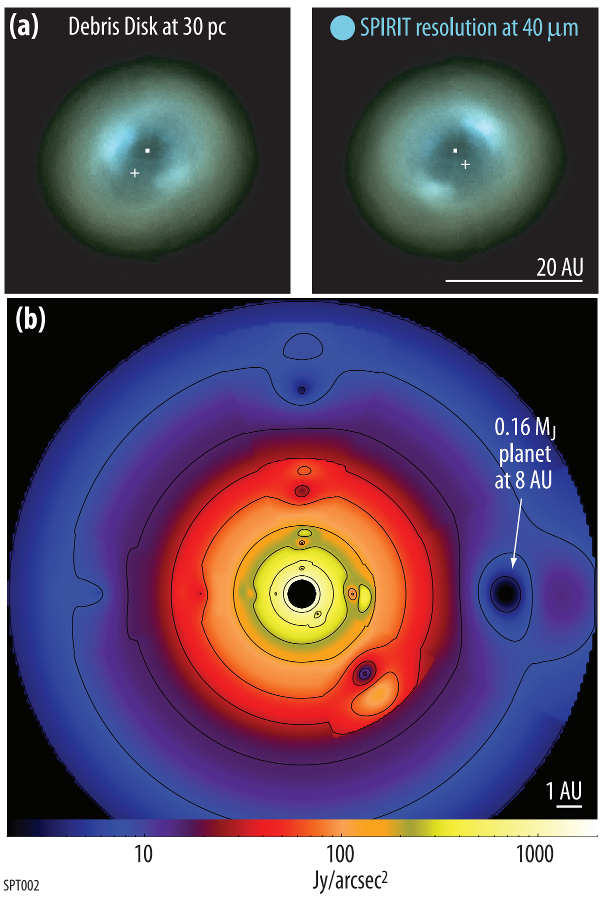


Figure 2: With angular resolution a hundred-fold better than that of Spitzer, SPIRIT will image a large statistical sample of debris disks (a) and protoplanetary systems (b), enabling new discoveries of exoplanets and proto-planets and a great improvement in our understanding of the factors that influence the development of planetary systems.

1.1.3 Learn How Galaxies Form and Change Over Time

> ***SPIRIT will make unique and profound contributions to our understanding of the formation, merger history, and star formation history of galaxies.***

SPIRIT will make unique and profound contributions to our understanding of the formation, merger history, super-massive black hole and star formation histories of galaxies. The cosmic IR "background"[30] bears the signature of a large number of distant, dust-obscured galaxies.[31] While JWST will probe the rest-frame visible/near-IR spectrum in galaxies out to redshifts $z > 10$ and ALMA will make corresponding measurements of the rest-frame far-IR spectrum in objects at redshifts $z > 3$, strong evolution has occurred in galaxies during the time interval corresponding to $0 < z < 3$.[32, 33, 34, 35, 36] *SPIRIT will measure the rest-frame far-IR emission of individual extragalactic sources out to z = 3 for the first time.* ***Figure 3*** compares the angular resolution of *Spitzer* at 160 μm with that of a notional 10 m single-aperture telescope and with SPIRIT at the same wavelength. Although a large cryogenic telescope would provide better sensitivity than SPIRIT, SPIRIT's sub-arcsecond angular resolution is needed to isolate individual objects from others along the line of sight and spatially distinguish the gravitationally bound neighboring galaxies in interacting and merging systems.

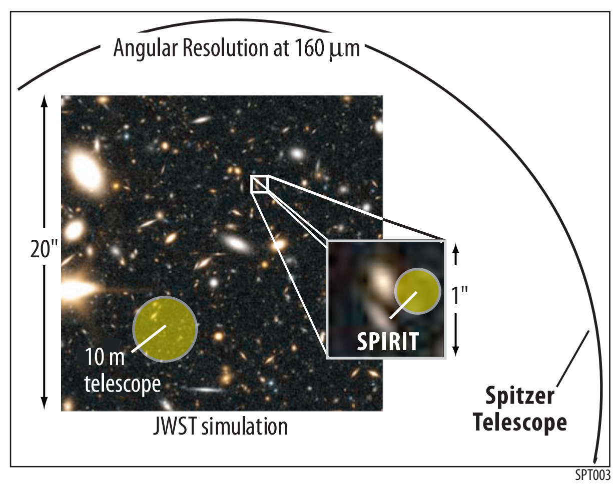


Figure 3: For the first time, SPIRIT will isolate the rest frame far-IR emissions of individual non-local extragalactic objects in the important $z < 3$ redshift range.

The rich rest-frame mid to far-IR spectrum accessible to SPIRIT[31,37,38,39,40] includes fine-structure lines of Ne III, Ne V, O III, O VI, S III, N III, N II, Fe II, Si II, O I, and the luminous C II line at 158 μm, commonly excited transitions of abundant molecules such as H_2, CO, OH, and H_2O, the spectral features of polycyclic aromatic hydrocarbons (PAHs), and thermal radiation from interstellar dust. Spectral lines and their velocity structure will give us detailed information on the co-evolution of accreting black holes and starbursts and the chemical element enrichment history during the important z < 3 period.[36,41,42] For example, SPIRIT observers will use the C II line at 158 µm, O I lines at 63 and 145 µm, and the C I line at 370 µm to obtain an extinction-free measure of the far-UV field strength and measure the rate of star formation. Likewise, the [Ne V] (14.24 µm)/[Ne III] (15 µm) line ratio is sensitive to the ionization parameter in Active Galactic Nuclei (AGN) and will enable SPIRIT observers to determine if the emitting objects are powered predominantly by star formation or by mass accretion onto a nuclear black hole.[43] *SPIRIT will resolve the far-IR merging components in local ultraluminous galaxies and determine the relative far-IR luminosities in distant gas-rich interacting and merging systems of galaxies for the first time.*

SPIRIT will provide integral field R ~ 3000 spectroscopic observations in four bands over the 25 – 400 µm range and simultaneously provide photometric imaging in each band at broad-band resolving power. Adaptive spectral smoothing will be applied to optimize sensitivity to faint sources and to obtain redshifts and spectral line diagnostic information for the brighter sources. Smoothing down to R ~ 1.5 will provide ~3 – 10 µJy level sensitivity in a SPIRIT "deep field" exposure lasting 2 weeks and yield photometric images in each of SPIRIT's four wavelength bands, 25 – 50, 50 – 100, 100 – 200, and 200 – 400 µm. PAH features and strong spectral lines will be detectable in Ultraluminous Infrared Galaxies (ULIRGs) out to at least z = 2, and SPIRIT will measure the continuum spectral energy distributions of galaxies like the Milky Way out to at least z = 3.

1.2 Enabling New Discoveries

SPIRIT will enable a wide array of astrophysical measurements and impact many of the fields of research discussed in science white papers submitted to the Decadal Survey. For example, SPIRIT will: (1) provide critical tests of the unification model for Active Galactic Nuclei;[44,45] (2) image nearby spiral galaxies to better understand the role of large-scale gas compression in the process of star formation;[46,47,48,49,50,51,52] (3) measure temperature and mass structures in "starless cores" to study the earliest stage of star formation;[8] and (4) follow up *Spitzer* and Wide-field Infrared Survey Explorer (WISE) observations of cold objects in the outer solar system to mine the fossil record of our planetary system's formation and evolution.[53,54]

As a case in point, consider mid-IR spectroscopy of giant exoplanets.[55] Many *Spitzer* observations of transiting extrasolar giant planets demonstrate the value of IR spectroscopy as a tool to constrain a planet's temperature structure and probe the composition of its atmosphere.[56,57,58,59,60,61] In addition to exploiting the transiting technique, which favors detections of "hot" exoplanets, SPIRIT, like JWST,[53] will measure the spectra of giant exoplanets at larger orbital distances. As SPIRIT's interferometric baseline changes the planet's fringes modulate while the star produces a stable reference pattern. The modulated interferogram can be extracted and then Fourier transformed to obtain the spectrum of the planet. A typical planet:star flux ratio is of the order of 10^{-4} in the far-IR, so starlight nulling is not required to measure the spectrum of an exoplanet separated by more than 0.1 arcsec (1 AU at 10 pc) from the star. Spectroscopic observations of Jupiter[62] suggest that broad NH_3 bands in the 40 to 100 µm range, and key chemical species such as water and methane, will be measurable in exoplanet atmospheres with moderate spectral resolution, $\lambda/\Delta\lambda$ ~ 3000. *SPIRIT observations of the far-IR spectra of extrasolar giant planets will help us understand the internal structure, formation, and migration of these planets to smaller orbits, and to measure the composition of their atmospheres.*

1.3 Measurement Requirements

The SPIRIT study team developed a detailed Design Reference Mission (DRM) addressing fifteen science "use cases." Each "use case" represents a set of observations that would be made with SPIRIT to address a major scientific goal requiring high angular resolution in the far-IR. The conceived observation sets were characterized by target name or type, desired field of view, number of fields to be observed, angular resolution, wavelength range, spectroscopic resolving power needed, and continuum or line sensitivity and dynamic range requirements. For example, one use case calls for "imaging a deep field to measure the H_2 28 µm line in galaxies at z ~ 3, and the dust continuum from objects at lower z," for which the desired observing parameters are: 1 arcmin field of view, 10 fields, 0.5 arcsec resolution, wavelength coverage from 100 to 500 µm, spectral resolution 2000, 5 µJy continuum sensitivity, and a dynamic range of 100. With emphasis on the goals adopted as the primary scientific objectives of the SPIRIT mission (those discussed in ***Section 1.1***), the SPIRIT team derived from the DRM a set of measurement requirements for the mission. These measurement requirements are summarized in ***Table 1***. The SPIRIT design concept described in ***Section 2*** meets all of these requirements.

Table 1: SPIRIT Measurement Requirements

Wavelength range	25 – 400 µm
Instantaneous FoV	1 arcmin
Angular Resolution	0.3 (λ/100 µm) arcsec
Spectral Resolution	3000
Point Source Sensitivity (5σ, 24 hours)	Spectral line: 10^{-19} W m^{-2} Continuum: 10 µJy
Science Time per Field	24 hours
Field of Regard	40° band centered on ecliptic

The single most critical new capability offered by SPIRIT is the high angular resolution imaging needed to achieve the science goals described above. SPIRIT's resolving power is comparable to that of JWST but at 10 times longer wavelengths (***Figure 4***). *Spitzer*, *Herschel* and the *Stratospheric Observatory for Infrared Astronomy* (SOFIA) are fundamentally limited by a lack of angular resolution; even a notional 10 m telescope cannot resolve nearby young stellar objects (YSOs).

SPIRIT's ability to resolve the objects of interest (***Figure 4***) will allow it routinely to deliver dust continuum images and spectral line maps of the targeted objects. SPIRIT's sensitivity (***Table 1***) will allow it to image low surface brightness debris disks and detect water lines in resolved protoplanetary systems and the major cooling and diagnostic lines in distant galaxies.

2.0 TECHNICAL OVERVIEW

SPIRIT provides integral field spectroscopy throughout the wavelength range 25 – 400 µm with sub-arcsecond resolution and λ/Δλ ~ 3000 spectral resolution in a 1 arcmin instantaneous field of view.

In 2004, NASA selected SPIRIT for study as a candidate Origins Probe. A year of intensive effort by the SPIRIT Origins Probe study team led to the development of a robust mission concept that met all of the measurement requirements (***Table 1***).

2.1 The SPIRIT Mission Design Process

The design concept described below is the third of three studied "point designs" and represents the convergence of an iterative design process that optimized science return within practical (technical feasibility and cost) constraints consistent with a Probe-class mission. The first two point designs

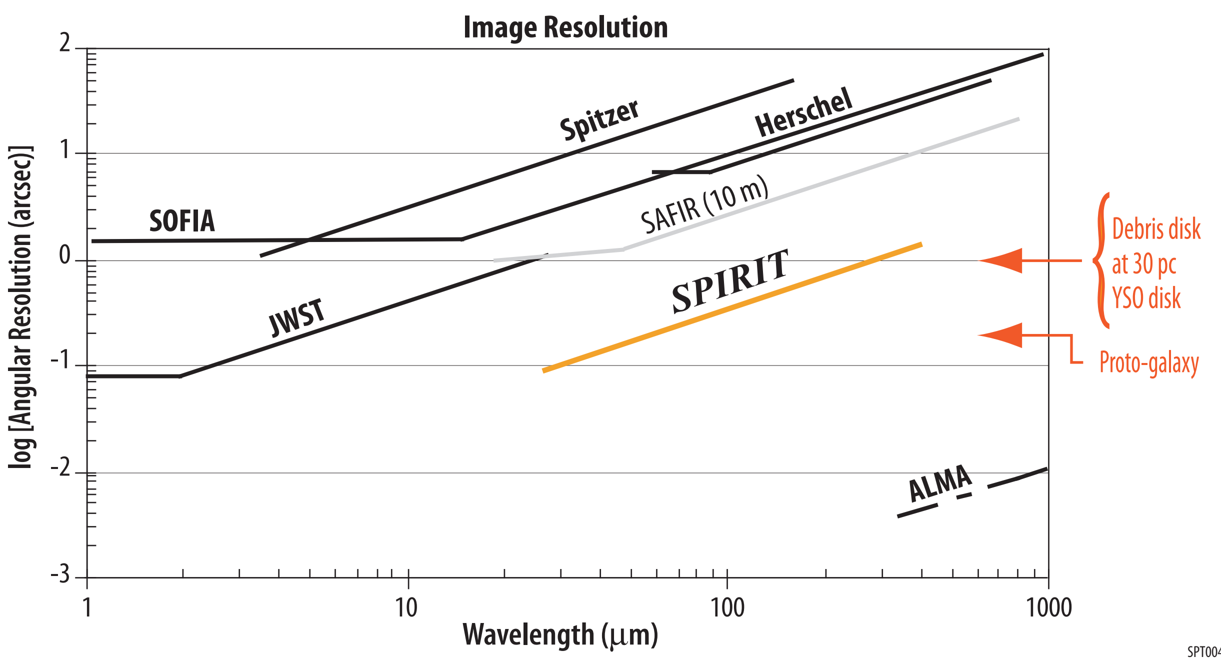


Figure 4: SPIRIT will deliver one hundred times better angular resolution than Spitzer, and resolution comparable to that of JWST, but at ten times longer wavelengths, where protoplanetary disks, debris disks, and some galaxies emit most of their light.

intentionally straddled what seemed likely to be the optimum balance between complexity, affordability, and measurement capability, while the third design cycle aimed to achieve that optimum balance based on the study team's earlier experience. All essential elements of space mission design were addressed, including, e.g., the launch vehicle, packaging and deployment, the spacecraft bus, attitude control, power, flight software, Integration and Test (I&T), and mission and science operations. Each SPIRIT sub-system (thermal, optical, attitude control, instrument control electronics, flight software, etc.) was documented in a detailed ~20-page design report and a corresponding cost spreadsheet. The study team compiled a detailed Master Equipment List. Following each of the three design cycles, system-level integrated analysis studies were conducted and the results were documented. For example, after the third study, 15 major analysis tasks were undertaken, including studies to (a) derive SPIRIT's sensitivity based on system throughput, detector performance, and background and stray light levels; (b) estimate the boom settling time after telescope baseline reconfiguration; (c) derive torque and angular momentum timelines corresponding to a typical observation period; (d) derive bus requirements for power, communication, and reaction wheel sizing; (e) determine the effect of temperature on boom alignment; etc. A robust concept for the SPIRIT mission existed by the end of the third design cycle.

A comprehensive system-level SPIRIT performance model was developed by an experienced systems engineer, Tupper Hyde, in collaboration with Instrument Scientist Stephen Rinehart and detector scientist Dominic Benford, and reflects contributions from 31 discipline engineers on the SPIRIT team. The SPIRIT model includes a budget for alignment and pointing errors, a fringe visibility error budget, a sensitivity calculation, and detailed spreadsheet tabs for Dynamics, Attitude Control, Operations, Optics, Electronics, Detectors, Structures, Mechanisms, Metrology, and Throughput, all of which play together to predict system performance and demonstrate compliance with design tolerances. The most interesting aspects of the SPIRIT design concept were reported in a series of papers (***Table 2***) and presented to the community at several AAS and SPIE meetings, workshops, and seminars. These papers can be downloaded from the SPIRIT web site, http://astrophysics.gsfc.nasa.gov/cosmology/spirit/.

The SPIRIT study team identified technologies needing further maturation and formulated a comprehensive technology development plan using a detailed work breakdown structure (WBS). The cost of each WBS element was estimated, and the plan and cost estimate were documented.

Table 2: Papers Describing the SPIRIT Design Concept

Topic	Authors	Ref.
SPIRIT scientific objectives, measurement requirements, mission study methodology, and overview of Origins Probe design concept	Leisawitz et al.	5
Detailed description of the SPIRIT design concept, with summary of system level trades, including error budget for key design parameters and model-based estimates of system performance	Hyde et al.	63
Optical system design trades and choices, stray light control, metrology, and optical system performance verification approach	Wilson et al.	64
Mechanical design and mechanisms, explaining how the mechanical design will meet instrument stability, thermal, and packaging requirements	Budinoff et al.	65
Thermal design concept, thermal modeling results, and cooling power requirements, explaining how cryocoolers will be used to meet the requirements	DiPirro et al.	66
Detector requirements, including NEP, pixel count, and readout speed, presenting TES bolometers as a possible design choice	Benford et al.	67

2.2 The SPIRIT Mission Design Concept

To achieve the scientific objectives described in ***Section 1***, SPIRIT provides integral field spectroscopy throughout the wavelength range 25 – 400 μm, with sub-arcsecond angular resolution and $\lambda/\Delta\lambda$ ~ 3000 spectral resolution in a 1 arcmin instantaneous field of view.

SPIRIT's innovative design allows all of the science objectives to be met with a single instrument. SPIRIT is a Michelson stellar (i.e., spatial) interferometer with a scanning optical delay line for Fourier transform spectroscopy and compensation for external optical path length differences across the field of view. ***Figure 5*** illustrates this "double Fourier" technique.[68, 69] Following beam combination in the pupil plane, detector arrays multiplex the “primary beam,” expanding the instantaneous field of view from the diffraction spot size of the individual light collecting telescopes to the desired 1 arcmin scale. We have demonstrated this wide-field double-Fourier technique on a laboratory prototype of SPIRIT, the Wide-field Imaging Interferometry Testbed.[70] SPIRIT’s two telescopes (***Figure 6***) can be moved to sample many interferometric baselines, and therefore to measure spatial structure on all of the angular scales necessary to produce high-quality far-IR images. The image resolution, 0.3 (λ/100 μm) arcsec, is determined by the maximum baseline length, 36 m.

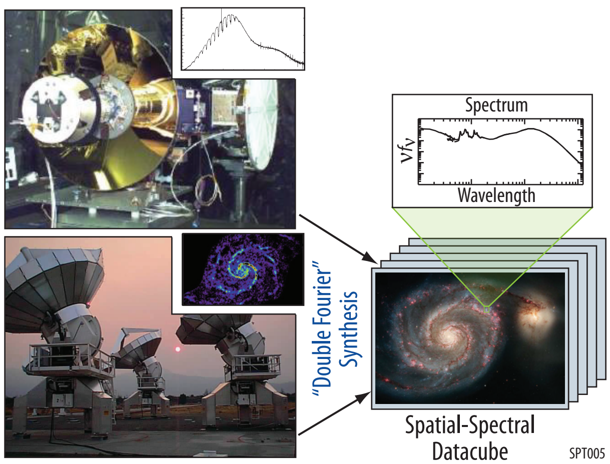


Figure 5: SPIRIT combines the capabilities of an imaging interferometer with those of a Fourier Transform Spectrometer to produce spatial-spectral data cubes.

Key SPIRIT engineering design parameters are shown in ***Table 3***. SPIRIT 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 (***Figure 6***). The afocal, off-axis telescopes direct clean 10 cm diameter collimated beams toward the beam combiner. The 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.[71] 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, of at least 3000 at the geometric mean wavelength in each band. Details of the multi-pass, multi-output delay line optics and mechanism are given by Wilson et al.[64] and Budinoff et al.,[65] respectively.

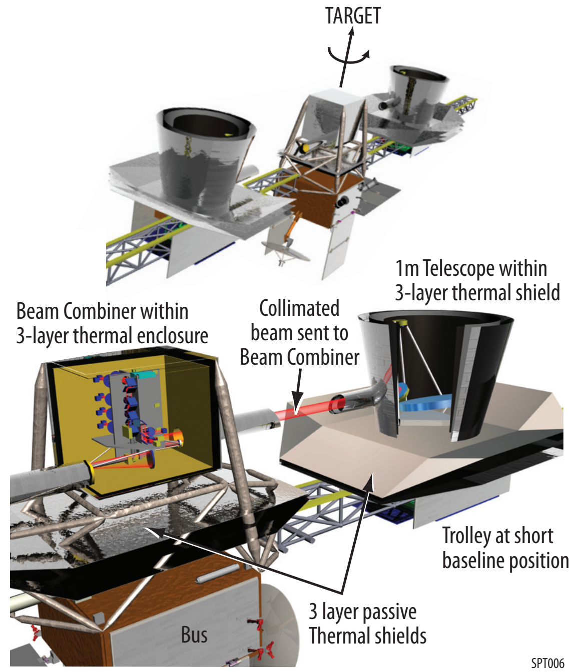


Figure 6: Major components of the SPIRIT observatory are two movable afocal off-axis telescopes and a single beam-combining instrument.

The SPIRIT telescopes are mounted on trolleys, which 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), as well as the interference fringe pattern corresponding to the spatial Fourier component sampled by a single interferometric baseline. 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 “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 3***.

The SPIRIT design provides natural background photon noise-limited sensitivity. SPIRIT will have low-noise detectors,[67] baffles to shield

Table 3: 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 resolution¹	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 resolution¹	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, V¹	0.98, $V = (I_{max} - I_{min})/(I_{max} + I_{min})$
Typical time per field	29 hours (24 hours for science)
Point Source Sensitivity¹ (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 rate¹	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)
¹Derived quantity	

against stray thermal radiation,[64] and cryogenic optics.[66] *Table 4* summarizes the main detector requirements. The detector Noise Equivalent Power (NEP) requirement allows the detectors to contribute 10% to the total system noise, with dark sky photon fluctuation power dominating, except in the longest wavelength channel where noise due to telescope thermal emission is comparable to that of the cosmic microwave background. The sky model includes contributions from zodiacal emission and scattering near the plane of the ecliptic, Galactic cirrus, extragalactic sources, and the cosmic microwave background. The pixel count is required to Nyquist sample the 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. In addition to the requirements shown in *Table 4,* the detectors must be fast enough to measure 4 samples per fringe during an optical delay scan (34 seconds), which implies a time constant $\tau \sim 185$ μs, and the dynamic range (ratio of sky brightness to noise) must be at least 2500. SPIRIT has two identical detector arrays in each wavelength band, one for each of the two complementary output ports of the Michelson beam combiner. This maximizes the signal-to-noise ratio and reduces risk.

Table 4: SPIRIT Detector Requirements

Band (μm)	NEP (10^{-19} W Hz$^{-1/2}$)	Pixels
25 - 50	1.9	14 x 14
50 - 100	1.1	7 x 7
100 - 200	0.7	4 x 4
200 - 400	1.8	2 x 2

SPIRIT could use superconducting Transition-Edge Sensor (TES) bolometers cooled to 30 mK, with SQUID amplifiers for readout or "Microwave" Kinetic Inductance Detectors (MKIDs).[67, 72] Both detector types are likely to be able to meet the SPIRIT requirements. A Continuously-operating Adiabatic Demagnetization Refrigerator (CADR)[73] will be used 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[66] (*Figure 7*) 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 which 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.

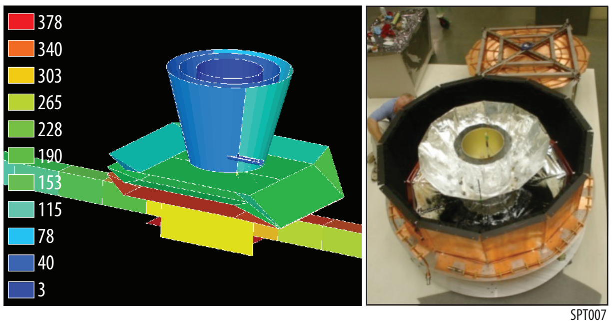


Figure 7: (Left) Heat loads and cryocooler requirements were based on a 106-node thermal model. (Right) Subscale cryo-thermal testing in a LHe shroud validated the model.

SPIRIT uses JWST-type cryocoolers with ^{3}He as the working fluid. Each telescope is equipped with a co-moving cryocooler. Two cryocoolers are used to cool the beam combiner, one to handle the conducted and radiated parasitic and the other to cool the instrument. The 4 K cryocooler stage will serve as a heat sink for the upper stage of the CADR. The total bus power required to operate the cryocoolers is 304 W at each telescope and 576 W at the instrument module. The cryocooler compressors use back-to-back pistons for vibration cancellation.

To validate the SPIRIT thermal model and pave the way for future thermal balance testing, an 18% scale model of a SPIRIT telescope was built and tested in a LHe cooled shroud inside a LN_2 cooled thermal vacuum chamber (***Figure 7***, right). The test results were in excellent agreement with pre-test thermal model predictions.[74]

After accounting for photon background noise, source photon noise, system throughput (18%), and quantization noise, the calculated SPIRIT sensitivity is that shown in ***Table 3***.

Hyde et al.[63] describe how the SPIRIT visibility requirements flow down to subsystem allocations for optics, sensors, controls, mechanisms, and structures, and they report the rolled up system performance based on the actual component performance reported in subsystem design documents. Two factors drive the interferometric error budget: the need to achieve fringe visibility (standard definition, see ***Table 3***) V > 0.90 at science wavelengths, and V > 0.25 at 2 µm. Near-IR light from a guide star in the science FOV is monitored by a Zero Path Difference Sensor, which enables a pathlength compensation mechanism to maintain fringe stability to 0.1 µm, a small fraction of the SPIRIT science wavelengths. The near-IR fringe visibility requirement dominates the error budget, and SPIRIT satisfies this requirement while tolerating 200 nm pathlength errors due to each of the following wavefront matching terms: uncompensated piston error, wavefront tilt, and wavefront error. Some of the sources of visibility loss are mitigated through the use of controls, while mechanisms cannot compensate for others (polarization, polarization shift, and optical surface errors). The SPIRIT error budget allocates 1 arcmin to telescope pointing (estimated performance 13 arcsec), 3.05 mm to beam alignment at the combination plane (estimated performance 2.56 mm), 0.23 arcsec to wavefront tilt on the sky at the combiner (estimated performance 0.13 arcsec), and 200 nm to uncorrected OPD error (estimated performance 143 nm). In each case the estimated SPIRIT performance meets or exceeds the budgeted performance. Based on estimated component level performance, the total wavefront matching error will contribute an estimated 0.5% to the visibility loss at SPIRIT's shortest science wavelength, 25 µm. Pupil area overlap will contribute 1.7%, while polarization and polarization shift matching at the point of beam combination will each contribute about 0.1% visibility loss. Amplitude mismatch will be negligible. The net result (RSS of all error terms) is an estimated V = 0.98 (i.e., 2% instrumental visibility loss) at 25 µm. This excellent performance is attributable, in part, to the need to provide V > 0.25 in the near-IR, and in part to SPIRIT's long science wavelengths.

A metrology subsystem[64] provides the necessary measurements to meet the SPIRIT requirements for control and knowledge of pointing, baseline length and optical path difference, to maintain alignment between the optical beams from the two arms of the interferometer, and to provide an absolute phase reference. Laser metrology is used to measure the optical path difference between the two arms of the interferometer in real time to 0.5 µm accuracy as the delay line scans. Pathlength control to within 1 mm keeps the zero path difference point well within the capture range of the scanning optical delay line. Sources in the science field of view serve as phase references for image reconstruction. The same techniques are employed in our laboratory testbed interferometer.

The SPIRIT spacecraft bus has standard subsystems and is similar to, but smaller than, the JWST bus. It consists of a box structure approximately 1.5 m on a side with electronics and propellant tank mounted inside and deployables and thrusters mounted outside. The attitude control system (ACS) consists of six reaction wheels of 100 Nms each, providing a slew rate of 1 deg/min, and supports an average data collection rotation rate of 0.63 rot/hr. Star trackers and gyros provide sensing for the coarse ACS control of 5 arcsec. This puts guide stars on the instrument's angle sensor, which provides finer accuracy. The communication system uses Ka-band for high data rate (100 Mbps) link and S-band for a contingency low data rate link. The electrical power system (EPS) consists of a solar array, battery, and power management electronics. The EPS supports the spacecraft systems and provides 1081 W for the instrument module. Separate power systems on the collector telescopes have their own fixed solar arrays.

The SPIRIT design supports a direct trajectory insertion into a large amplitude Sun-Earth L2 Lissajous orbit on an EELV with a 5-m medium-length fairing (***Figure 8***). Orbit station keeping maneuvers are performed infrequently (every few months). The SPIRIT field of regard is a 40° wide swath of sky around the ecliptic plane, within which all the astronomical targets required to satisfy the science objectives are accessible.

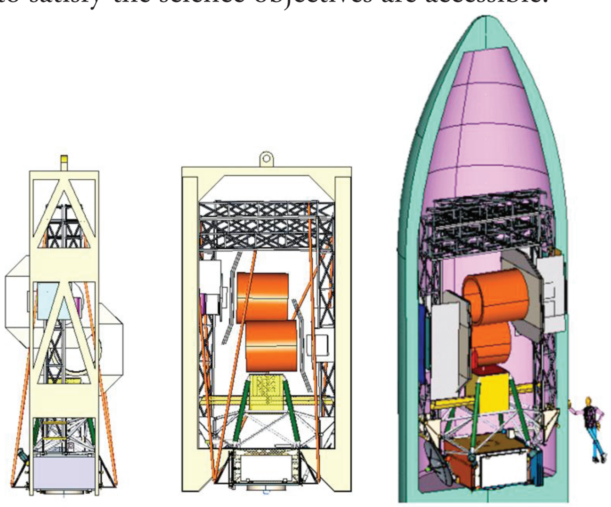


Figure 8: SPIRIT and its expendable launch support structure (left, two views), when stowed for launch, are 8.7 m tall and fit into an EELV 5 m medium-length fairing dynamic envelope.

During the Origins Probe study, we developed a realistic and affordable Integration and Test (I&T) program; during Phase A, we will apply lessons from the JWST, *Spitzer*, *Herschel*, and *Planck* experiences to improve this plan. In Phase B, end-to-end imaging will be demonstrated with full-scale test units and non-flight detectors. Also during Phase B, a flight equipment test program with maximum fidelity will be developed. The feasibility of far-IR double Fourier interferometry has already been demonstrated in the lab, at GSFC and in the UK. During I&T, the major components of the SPIRIT observatory – the telescopes and the instrument module – will be tested as they will fly. These payload elements individually fit into existing test facilities. Collimated light from a single source will be delivered via flat reflectors to the beam combining instrument in thermal-vac to demonstrate instrument functionality and measure performance in a space-like environment. Since the SPIRIT telescopes will direct collimated beams toward the beam combiner, an end-to-end functional test with closely spaced telescopes (i.e., short interferometric baselines) will verify the essential aspects of integrated system performance. This test will be conducted in Chamber A at the Johnson Space Center, which will soon be prepared for JWST testing. Analysis and model verification will complement the SPIRIT experimental I&T program and build confidence in the flightworthiness of the system. The already existing high-fidelity model of our laboratory testbed interferometer will be adapted to model the performance of SPIRIT for comparison with test results obtained during I&T.

3.0 TECHNOLOGY DRIVERS

The technical feasibility of SPIRIT derives, in part, from the current maturity level of its technologies. All of the SPIRIT technologies except detectors have reached Technology Readiness Level (TRL)[75] 4 or higher. A schedule for advancing the three most challenging SPIRIT technologies is given in ***Figure 9***. According to experienced technologists on the SPIRIT team, the entire suite of SPIRIT mission-enabling technologies can be advanced to TRL 6 in four years.

3.1 Detectors

The detector technology needed for SPIRIT is discussed in a technology paper submitted to the Decadal Survey by Bock et al.[72] SPIRIT detector NEP, pixel count and time constant requirements were given in ***Section 2***. At present, the most mature technology that could meet the SPIRIT requirements is leg-isolated superconducting transition edge sensor (TES) bolometers (***Figure 10***).

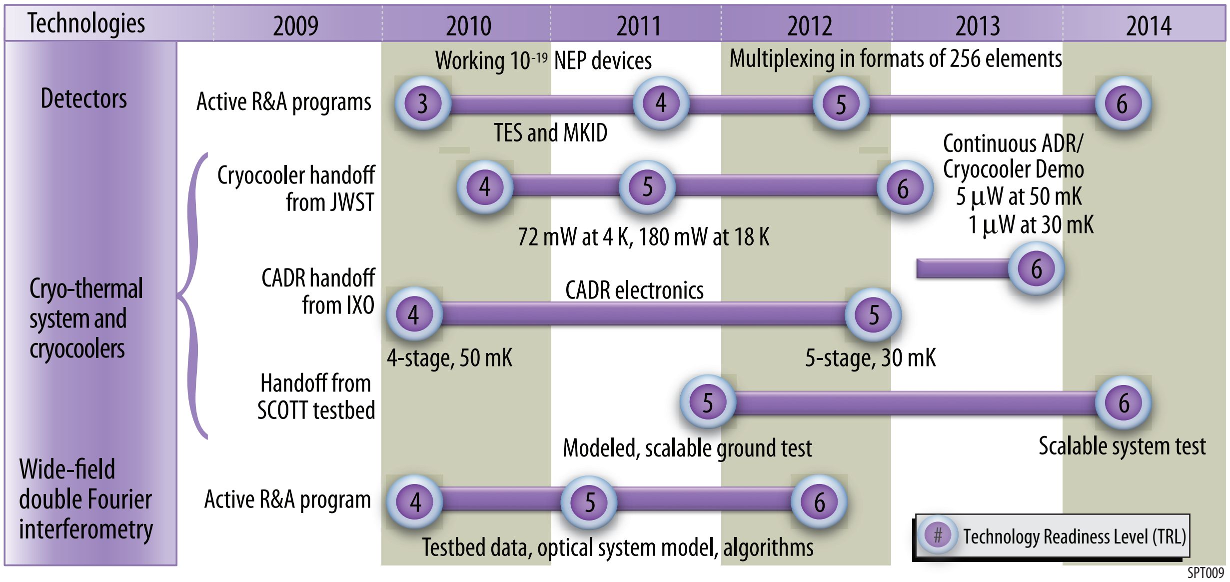


Figure 9: The technology development plan for SPIRIT builds on existing heritage and past investments to mature all the mission-enabling technologies from their present state to TRL 6 in four years.

Single-pixel TES bolometers have already met the SPIRIT sensitivity requirements, but fall short of the response time by a factor of 2000.[76] However, scaling from present performance suggests that the existing technology can meet SPIRIT's sensitivity, array size, and possibly also time constant requirements by operating at 30 mK. [67,77] Further, new measurements of TES bolometers that use electron-phonon decoupling demonstrate that these detectors can meet all of SPIRIT's requirements.[78,79] Other detector technologies may also be suitable for SPIRIT. Kinetic Inductance Detectors[80,81,82] also have the potential for high performance, and multiple research groups have made significant progress with these devices in recent years.

Prudence calls for early investment in parallel competing detector technologies, leading to down-selection to the one detector type that exhibits the greatest promise at an appropriate time. This approach worked for JWST and will assure the timely delivery of detectors for SPIRIT. At the present time, detector research efforts are slowly advancing the state of the art through NASA's ROSES/APRA program. A modest increase in support would allow multiple research groups to target detectors needed by SPIRIT and other far-IR missions. A robust and focused effort is needed to bring these detectors to TRL 6. This could be achieved within the next 5 years, with a technology program cost of ~$12M.

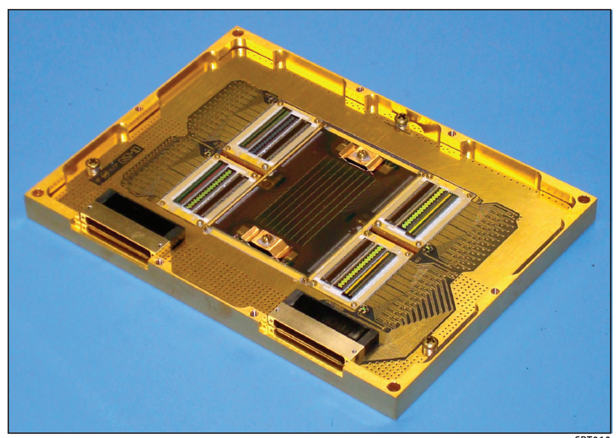


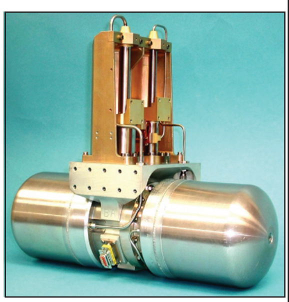
Figure 10: This 8 x 16 array of close-packed TES bolometers saw first light at IRAM in 2007.[83] This was the first fielded array with backshort-under-grid architecture, a technology developed to enable and mature versatile, space-qualifable kilopixel TES arrays with NIST large-format SQUID multiplexers.

3.2 The Cryo-Thermal System and Cryo-Coolers

The technological challenges are: (1) upgrading the JWST cryocooler to enable higher power cooling to 4 K; (2) upgrading the *International X-ray Observatory* (IXO) Continuous Adiabatic Demagnetization Refrigerator (ADR) to enable detector cooling to 30 mK; and (3) integrating the coolers into a functional cryo-thermal system and demonstrating system performance.

The JWST cryocooler (*Figure 11*, left) was required to provide 60 mW of cooling at 6 K and 75 mW of cooling at 18 K. Cooling to ~4 K can be achieved by substituting ^{3}He for ^{4}He as the working fluid in the lowest temperature stage. This demonstration will advance the TRL to 5.

The CADR (*Figure 11*, right) under development for the IXO can be adapted to meet the SPIRIT focal plane cooling requirements.[66] To achieve TRL 6 for SPIRIT, the CADR, when interfaced with a mechanical cryocooler operating at 4-6 K, must demonstrate the capacity to lift 5 μW of heat at 50 mK or ~1 μW at 30 mK. Already, the CADR has demonstrated continuous cooling of 6 μW at 50 mK and 1.5 μW at 35 mK starting from a heat sink temperature of 5 K, nearly meeting the SPIRIT requirement. To progress to TRL 5 the CADR development program will take about three years, resulting in a brassboard, demonstrating an integrated CADR/cryocooler system capable of satisfying the SPIRIT focal plane cooling requirements. The CADR for SPIRIT will have 4 stages operating between roughly 5 K to 1.2 K, 1.2 K to 0.3 K, 0.3 K to 0.05 K and a stage that operates continuously at 0.05 K. A fifth stage will operate continuously at about 1.2 K to provide a low thermal emission environment surrounding the detectors to eliminate stray thermal radiation and to provide a stable cooling stage for detector amplifiers. The nominal input power varies between 30 and 80 W, depending on the cooling power required. The CADR will reject approximately 3 mW to 4 K, a very modest cooling power for the current suite of TRL 4-5 cryocoolers.



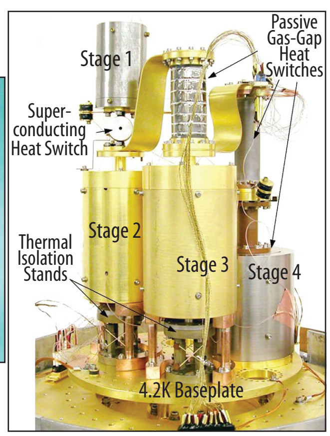


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Figure 11: With straightforward modifications, the JWST cryocooler (left) and the IXO CADR (right) will reach TRL 6 for SPIRIT.

Thermal system verification is challenging because the thermal balance test will contain warm, ~300 K, and cold, 4 K, components. Test chamber non-idealities can dominate the results. For example, the *Spitzer* thermal balance test showed a measured heat leak of 52 mW into the instrument when the on-orbit value turned out to be only 6 mW. To improve this situation, we conducted an experiment using an 18% scale model of a preliminary SPIRIT telescope design, the Subscale Cryo-thermal Testbed (SCOTT) (*Figure 7*).[74] The test results agreed remarkably well with pre-test thermal model predictions, proving out the design and giving us confidence that SPIRIT's telescopes and instrument module can be cooled with JWST-like cryocoolers.

3.3 Wide-Field Double-Fourier Interferometry

Experiments conducted with a lab testbed functionally equivalent to SPIRIT, and an analytical model of the testbed interferometer will enable us to optimize the SPIRIT design.

With ROSES/APRA support we developed the Wide-field Imaging Interferometry Testbed (WIIT) to demonstrate wide-field double Fourier interferometry and learn the practical limitations of this technique. WIIT is functionally equivalent to SPIRIT, but it operates at 100x shorter (visible) wavelengths and accesses 100x shorter interferometric baselines. Three key features of SPIRIT are demonstrated in the testbed: (1) an injected laser metrology system is used to measure the path lengths of the two interferometer arms; (2) camera exposures are triggered based on the measured optical path difference while the delay line is scanned; and (3) control software maintains co-alignment of the baseline mirrors (corresponding to the SPIRIT telescopes) based on information in the science field of view. WIIT operates in the Goddard Advanced Interferometry and Metrology (AIM) Lab under flight-like conditions, with data quality limited by the instrument instead of the environment.

Our experimental approach,[84] shown in *Figure 12*, combines SPIRIT-like data acquired with WIIT, independent measurements ("truth images") of the spatial-spectral scenes observed with WIIT, a high-fidelity computational model of the testbed which generates synthetic interferometric data[85] and can be adapted to model SPIRIT, and algorithm and code development to enable synthesis of spatial-spectral data cubes

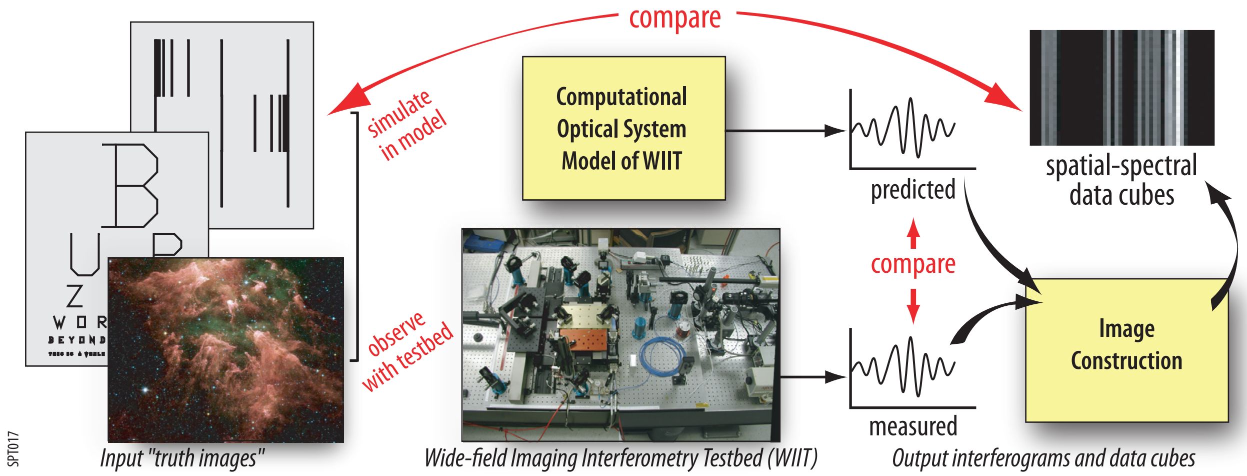

Figure 12: WIIT, a laboratory testbed functionally equivalent to SPIRIT, and a high-fidelity model of the testbed, are giving us practical experience with the wide-field double-Fourier interferometric technique to be used on SPIRIT.

from the interferometric data[86] to advance Wide-field double Fourier interferometry to TRL 6. The technique has matured beyond the proof-of-concept stage[70] to about TRL 4, and TRL 6 can be attained by 2012. WIIT routinely yields full u-v data sets with delay line scans sampled in the time domain by ~30 x 30 detector pixels. Increasingly complex test scenes will be observed in the coming year. The WIIT analytical model can be used to understand instrumental error sources, and it will enable well-informed SPIRIT design choices (e.g., optical system tolerances). Interferometric data sent to the ground from SPIRIT will be transformed into spatial-spectral data cubes using software which is already under development.

Complementary research efforts are underway elsewhere around the globe. A Japanese group developed a far-IR balloon-borne interferometer with a Fizeau beam combiner and has a first technology demonstration flight scheduled in 2009.[87] The Rutherford Appleton Lab in the UK has assembled a double-Fourier testbed that operates at far-IR wavelengths, in part to test quasi-optical metal mesh components (dichroic filters and beamsplitters) supplied by the Cardiff group and suitable for use in the SPIRIT beam combiner.[88] The RAL testbed will yield its first data in 2009. A Canadian group has proposed to develop efficient software to process the data (i.e., synthesize spatial-spectral data cubes) from double-Fourier interferometers.[89]

Based on the WIIT, RAL, and balloon interferometry experiences we will know how to assemble a high-fidelity instrument testbed for SPIRIT long before the mission enters the Development Phase. This advanced testbed is a keystone in the SPIRIT team's technology development plan (see *Section 5*).

3.4 Leveraging Past Investments

NASA investments made in wavefront sensing & control and cryocooler technology for JWST, focal plane cooling for the International IXO, and European investments in far-IR filter technology for *Herschel* have already reduced cost and risk for SPIRIT. Mechanisms similar to those used on SPIRIT have flown successfully on past NASA and ESA missions. For example, cryogenic delay lines have been used in COBE/FIRAS and Cassini/CIRS. The Dutch company TNO has developed a precision delay line for Darwin.[90] Metrology system components developed for the *Space Interferometry Mission* (SIM) vastly exceed SPIRIT requirements. A small additional investment can be made to realize cost savings associated with greatly relaxed tolerances. The SPIRIT telescope transport vehicle could be similar to the trolley-on-rails device used in the Mobile Transporter on the International Space Station, and again cost savings can be realized because ISS-related human safety factors will not pertain to SPIRIT.

4.0 ACTIVITY ORGANIZATION, PARTNERSHIPS, AND CURRENT STATUS

SPIRIT could be developed by the US alone or in collaboration with international partners whose constituents are eager to be involved.

The notion of a space far-IR interferometry mission grew from an informal conversation in

1998 between John Mather and Harvey Moseley at GSFC into a global collaborative effort in which more than one hundred highly-motivated individuals have been directly engaged. The early concept for a kilometer maximum baseline interferometer known as SPECS was embraced by the far-IR community during a 1999 workshop held at the University of Maryland, and then it was presented to the 2000 Decadal Survey, which endorsed the idea as a long-term objective and called for appropriate technology investment by NASA. A second community workshop held in 2002 gave rise to the *Community Plan for Far-IR/Submillimeter Space Astronomy*[3] which recommended SPIRIT as a less technically challenging, less expensive step toward SPECS. In 2004, SPIRIT was selected by NASA for study as a candidate Origins Probe.[5] The study was conducted by the team shown on the front cover of this paper, with David Leisawitz as PI. The SPIRIT mission design concept was presented to the SPIRIT Advisory Review Panel (also shown on the cover), which made technical recommendations, some of which have been implemented and others of which will be subjects for future study. Many additional people, also shown on the cover, have contributed ideas to and participated in white papers on SPIRIT. SPIRIT team members have come from three NASA Centers – GSFC, JPL and MSFC – the Naval Research Lab, four domestic industrial partners, academic institutions around the world, and European space research organizations.

Since the SPIRIT Origins Probe study was completed in 2005, SPIRIT detector, cryocooler, double Fourier interferometry, and metrology technology development has progressed through JWST, IXO, and SIM project investments and ROSES/APRA-funded R&A projects. SPIRIT team members have written white papers, such as the one submitted to the ExoPlanet Task Force.[91]

SPIRIT could be developed by the US alone or in collaboration with international partners whose constituents are eager to be involved. With its sights set on the post-*Herschel* mission era, the European far-IR community convened workshops in 2003, 2005, 2006, and 2009, the first three of which culminated in the conclusion that a far-IR long-baseline (~1 km) interferometer is the logical successor to *Herschel*. This European concept, known as FIRI, was proposed to ESA's Cosmic Visions program. The proposal received excellent marks for science but was rejected because the technology, including formation flying, was not mature enough. The 2009 workshop focused on technical preparation, and a SPIRIT-like mission was recognized as a practical step toward FIRI. A mission bearing a striking resemblance to SPIRIT was studied by ESA in 2006.[92] In the UK, RAL developed a double Fourier interferometry testbed that operates in the far-IR. The Canadian space astrophysics community held an informal workshop in November 2006, organized by the CSA, and a far-IR interferometer was the only project clearly identified as the highest priority by the majority of the participants. The Japanese balloon-borne Far-Infrared Interferometric Telescope Experiment (FITE) will be ready for its first (technology demonstration) flight in 2009. Scientists around the world have recognized the need for a mission like SPIRIT, suggesting the possibility of a fruitful partnership between NASA and its sister agencies ESA, CSA, and JAXA.

5.0 ACTIVITY SCHEDULE

We recommend a call for NASA to invest in SPIRIT and adhere to a schedule that leads to launch in 2023.

A SPIRIT launch in 2023 is achievable if the technology development program is funded robustly beginning in 2011 and an ideal funding profile is maintained. In this scenario, Phase A would start in 2016 and Phase B would start in 2017, consistent with the time all of the technologies are matured to TRL 6. The period from Phase B start to launch would last six years, which includes 10 months of schedule margin.

The key, underpinning technology development and funding activities will need strong advocacy and action by NASA and/or the international community if a 2023 SPIRIT launch is to become reality. A Decadal Survey recommendation would substantially boost the prospects for near-term activation of a dedicated technology development program.

As envisaged by the SPIRIT study team, funding for the SPIRIT technology program described in ***Section 3*** would ramp up by 2011 and flow seamlessly into a testbed and protoflight unit development phase beginning in 2017. The pace of technology development could be up to two years slower than the realistic schedule shown in ***Figure 9*** and still support a transition to the engineering model buildup phase by 2017. Starting in 2017, the SPIRIT team will build a telescope testbed. This will be followed in the next year and a half by the buildup of a beam-combining instrument module. Functional and performance tests

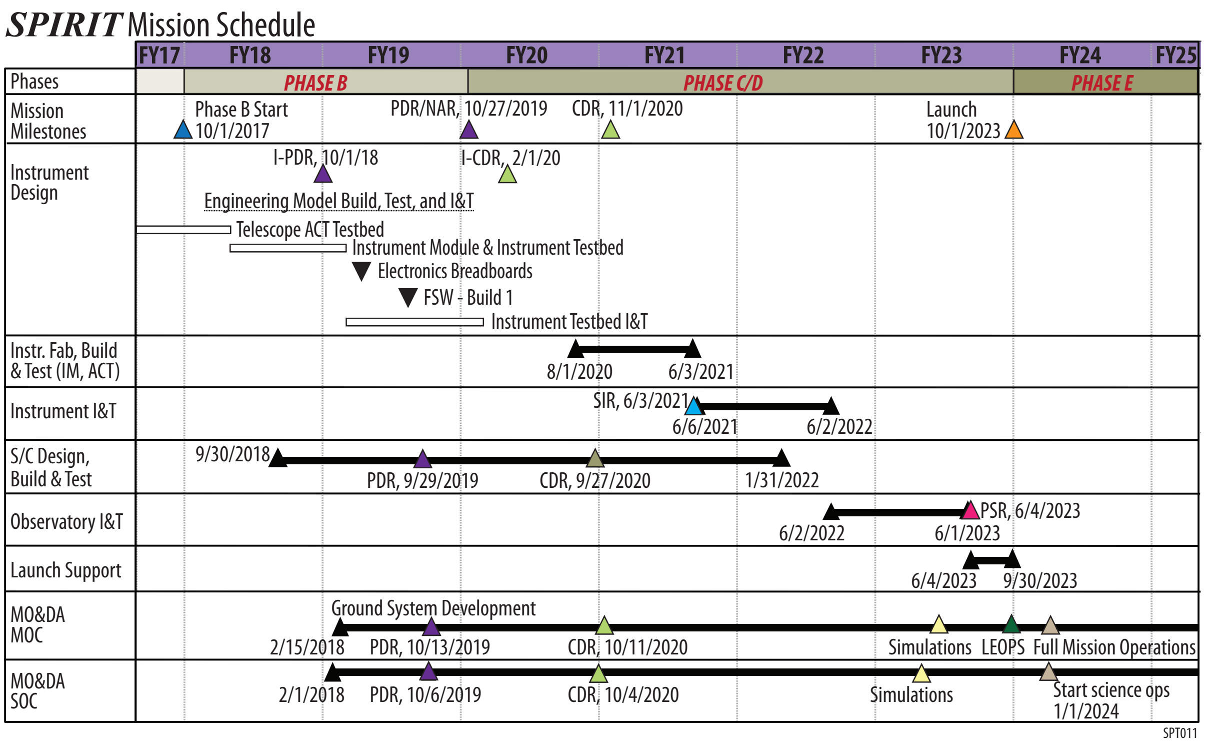

Figure 13: The SPIRIT development schedule allows 10 months of slack during a 72-month Development Phase from Phase B start to launch.

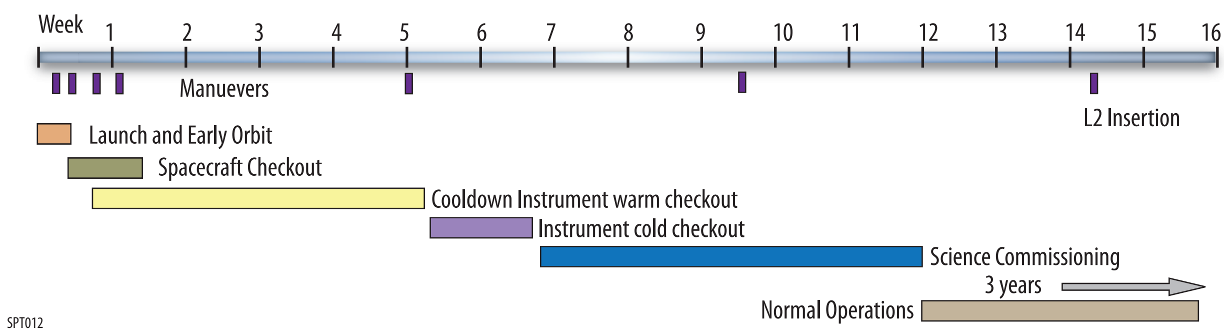

Figure 14: SPIRIT will arrive at L2 fully commissioned and already engaged in normal science operations.

will be conducted with these Engineering Models individually, and then they will be integrated into a full Instrument Testbed, which will be subjected to further functional and performance tests. The test program runs concurrently with Phase A, extends into Phase B, and yields a refined, implementable instrument design. ***Figure 13*** presents a realistic, affordable schedule for the SPIRIT mission, from Phase B start through the end of science operations. The SPIRIT commissioning phase, beginning at launch and lasting 12 weeks, is shown in expanded detail in ***Figure 14***. SPIRIT is deployed and warm components are checked during a 5-week cool-down phase, followed by cold instrument checkout and science commissioning, all during the observatory's 14-week journey to L2. An animation depicting the SPIRIT deployment sequence is available at http://astrophysics.gsfc.nasa.gov/cosmology/spirit/.

Figure 15 shows a typical week of normal SPIRIT science operations, during which six science target fields are observed. A typical observation begins by slewing to the new target, typically 10 degrees away, in less than 2 hours. Calibrations and alignments take a few minutes. The target is observed for a half-revolution, and then the telescope trolleys move to a new position (while the observatory continues to spin). Trolley spacing is dependent on desired u-v plane coverage but typically consists of 31 positions with baselines from 6 to 36 m. SPIRIT's rate of rotation ranges from 2.8 rev/hr at the shortest baseline

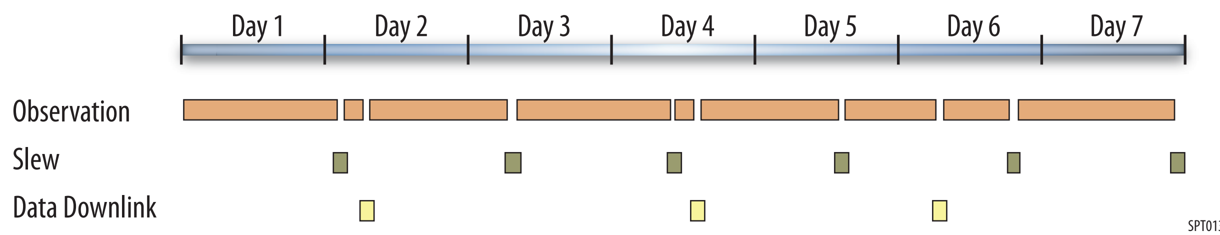

Figure 15: SPIRIT operates with 85% science efficiency.

to 0.5 rev/hr at the longest baseline. Downlinks interrupt science observations. During integration, the delay line is continuously stroked over the full range during the time the collecting telescopes have moved one half of a diameter tangentially due to spacecraft rotation. If necessary, the detectors will be calibrated between consecutive delay line scans by cycling illuminators on and off without interrupting the scanning motion. The illumination response would be used to transfer calibrations from standards to unknown sources. Images are read from the 8 detector arrays (2 each, in 4 wavelength bands), which creates an on-board data set with baseline length, rotation angle, and delay line position per image read. This results in a total uncompressed raw science data rate of 5.4 Mbps. Onboard loss less compression would effectively reduce this rate by about a factor of 2. Momentum dumps are scheduled during slews. Total integration time depends on the desired sensitivity but typically is 24 hours of detector integration in 28.2 hours (29 hours with margin) total observation time. In other words, SPIRIT operates with 85% science efficiency and visits approximately 0.85 target fields per day.

During an observation, in addition to the science data, SPIRIT would accumulate 1.4 Gb of engineering and housekeeping data. The data are stored onboard for two days and then delivered to the ground in a 2 hour period at 100 Mb/s via the Deep Space Network.

Variations on the typical 29-hour observation cycle are possible. Occasional "deep" exposures may last up to 2 weeks. And SPIRIT can be commanded to sample the u-v plane less densely if warranted by the science objective (e.g., rotations at two long baselines would be sufficient to obtain the spectrum of a giant exoplanet).

The double Fourier interferometric data are post-processed on the ground to create an integral field spectroscopic data set with high spatial and spectral resolution.

The total mission lifetime will be at least 3 years, with a goal of 5 years. As discussed in *Section 6*, the impacts on mission design and the incremental flight system cost associated with a longer Phase E (5 years of science operations, with a goal of 10 years) are modest.

6.0 COST ESTIMATES

SPIRIT will be less expensive than a typical facility-class observatory.

The SPIRIT Origins Probe mission concept study team's grass-roots estimate for the cost of the entire mission was $986M in FY04 dollars. Of this total cost, $140M was the estimated cost of technology development, and $846M was for Formulation, Implementation, and Operation for three years. Tasks were organized according to the standard NASA Work Breakdown Structure and grass roots cost estimates were developed to at least the second, and in some cases the third WBS level, in all cases with assumptions and the basis of estimate documented. The cost estimates were linked with the master schedule.

The SPIRIT technology development program methodically retires risk by maturing technologies from their current maturity levels through to the design, buildup and testing of proto-flight models, all in the context of a managed program with appropriate systems engineering support. Nine technology tasks were identified, assigned WBS numbers, and their costs estimated to the same fidelity as the mission tasks. Seventy percent of the technology investment value was assumed to convey exactly to protoflight units, and 30% was assumed to require re-work either due to requirements changes or unmet performance goals.

Parametric modeling was used to develop an *independent* cost estimate (ICE) for comparison with the study team's grass roots estimate. PRICE-H was used, and the ICE was developed by Bill Lawson, nominee for the 2009 NASA Cost Estimator of the Year Award. The SPIRIT payload parametric model was based on a detailed Master Equipment List. Standard GSFC full-cost Global Parameters were used, and appropriate complexity factors were applied. The SPIRIT PRICE-H model includes Engineering Test Unit and Flight Unit design, system engineering, project management, production, I&T, labor for environmental testing, and grass roots flight software development cost, but does not include special purpose GSE, environmental test facilities, launch vehicle I&T or the cost to develop technology to TRL 6. The payload ICE was $306M. A PRICE-H spacecraft bus model developed for a similar observatory provided the SPIRIT bus ICE, $156M, and the ICE for payload/bus I&T was $5M. These numbers compare favorably with the study team's corresponding grass roots cost estimates: $181M for the bus (16% higher than ICE, for understood reasons: different development schedules, labor rates, and design details between the analog bus and the SPIRIT bus in the ICE), and $318M (2% higher than ICE) for the payload plus I&T. The SPIRIT Independent Cost Estimates give us confidence in the "advocacy" cost estimates developed by the project managers, engineers and scientists on the SPIRIT team.

The estimated total cost of the SPIRIT mission in FY09 dollars is given in ***Table 5***. The standard inflation factor 1.153 was applied to adjust from FY04 to FY09. As noted, most of the quoted costs are the SPIRIT team's inflated grass roots cost estimates. Safety and Mission Assurance costs during development were assumed to equal 40% of the Mission Systems Engineering cost. The technology development costs were folded into WBS 2.0 for Science, but these costs are shown on a separate line for clarity. This line includes, for example, the CADR brassboard development cost, approximately $4M for CADR electronics development, 4 K cryocooler development, detector development costs not currently covered by ROSES/APRA, and all the funding needed to implement the SPIRIT technology development plan shown in ***Section 5***. A science operations program lasting three years was assumed. Reserves based on 43% of payload cost plus 30% of flight systems and 10% of all other mission cost elements are shown in ***Table 5***. Launch vehicles have increased in cost faster than the rate of inflation, so ***Table 5*** shows the current estimated cost for an EELV 5 m medium launch vehicle. The total lifecycle cost of the SPIRIT mission, including technology development, is estimated to be $1.25B in FY09 dollars.

Several factors moderate the cost of SPIRIT. **First, investments already made by NASA** to develop wavefront sensing and control and cryocooler technology for JWST, focal plane cooling for) and IXO, cryogenic mechanisms for COBE, *Cassini*, and *Aura*, to support ongoing Research & Analysis projects on far-IR detectors and wide-field imaging interferometry, as well as ESA investments in cryogenic mechanisms for *Darwin*, reduce costs and risks for SPIRIT. Second, **a single scientific instrument on SPIRIT delivers all the required data**. Third, instead of massive, voluminous cryostats with expendable cryogen, **SPIRIT uses cryocoolers, which enable the use of a launch vehicle with a medium-length fairing instead of a larger, more expensive EELV**.

With only minor changes to the flight system, SPIRIT could have an operating lifetime of 5 years extendable to 10 instead of the assumed 3 years extendable to 5. The only expendable is hydrazine for orbit maintenance at Sun-Earth L2. A larger hydrazine supply could be accommodated within mass and volume constraints of the assumed EELV (the specs of an Atlas V 531 were adopted for the sake of mission design). Volume is a bigger driver than mass in the case of SPIRIT. Mechanism lifetime testing and other risk management strategies would have to satisfy more stringent conditions, but the incremental cost of a longer mission would be a negligible fraction of the overall mission cost.

One might also wish to consider the cost of a substantially augmented science operations program. SPIRIT could be developed as a facility-class observatory with a Guest Observer program along the lines of those established for NASA's Great Observatories. Scaling from the cost to develop and archive data products and documentation, support guest observers, review observing proposals, plan observations, and fund research grants for *Spitzer*, we estimate that an analogous SPIRIT science operations program would cost approximately $300M integrated over 5 years of science operations.

Figures 16 and ***17*** illustrate the depth to which the SPIRIT costs are understood. The grass-roots payload costs (WBS 5.0) are broken down into payload components in ***Figure 16***. The cost of the most expensive payload component, the instrument module, is further broken down to show the itemized fractional costs of its sub-systems in ***Figure 17***.

Table 5: Estimated Mission Cost (FY09 M$)[1]

Cost Element	Phase A	Phase B[2]	Phase C/D	Develop. Total	Phase E	Mission Total	Cost Methodology[3]
Project Elements:							
1.0 Project Management	N/A	5.5	11.0	**16.5**	5.5	**22.0**	Grass roots
2.0 Mission Sys Engr	N/A	2.6	4.9	**7.6**	0.0	**7.6**	Grass roots
3.0 Mission Assurance	N/A	1.1	2.0	**3.0**	0.0	**3.0**	Fraction of system engineering
4.0 Science	63.8	103.1	12.7	**179.5**	21.1	**200.6**	Science and Technology Development
4.1 Technology Dev	62.6	100.2	N/A	**162.8**	N/A		Grass roots
4.2 Science	1.2	2.9	12.7	**16.7**	21.1		Grass roots
5.0 Payload	0.2	163.3	165.6	**329.1**	1.4	**330.5**	Grass roots
6.0 Flight Systems	6.3	45.9	156.6	**208.8**	0.0	**208.8**	Grass roots
7.0 Mission Ops	N/A	N/A	3.0	**3.0**	17.2	**20.2**	Grass roots
9.0 Ground System	0.0	3.0	9.0	**12.0**	N/A	**12.0**	Grass roots
10.0 System I&T	N/A	9.2	27.5	**36.7**	N/A	**36.7**	Grass roots
Sub total	**70.3**	**333.6**	**392.3**	**796.2**	**45.1**	**841.3**	
Reserves	N/A	96.4	125.2	**221.6**	5.0	**226.6**	Fraction of other elements[4]
Sub total w/reserves	**70.3**	**430.1**	**517.5**	**1017.8**	**50.1**	**1067.9**	
Elements w/o contingency:							
8.0 Launch Vehicle	N/A	N/A	178.0	**178.0**	N/A	**178.0**	EELV, 5m, medium[5]
11.0 E/PO	0.2	0.8	1.0	**2.0**	0.5	**2.4**	Fraction of other elements[6]
Mission Total:	**70.5**	**430.9**	**696.5**	**1197.8**	**50.6**	**1248.4**	

Notes:
[1]The original SPIRIT grass roots cost estimate was $986M (FY04 dollars); spacecraft bus and payload costs were validated by independent PRICE-H parametric cost models. Grass roots and PRICE-H estimates agreed to within 16%.
[2] Mission costs assume a 72-month schedule from Phase B through on-orbit verification.
[3] All grass roots cost estimates from SPIRIT Origins Probe Study (FY04 dollars inflated to FY09).
[4] Reserves are calculated as 43% of Payload cost, 30% Flight Systems, and 10% of all other elements.
[5] Launch vehicle cost increased faster than inflation; a current estimate of the cost is used.
[6] E/PO is calculated as 0.25% of mission cost (before reserves and launcher) during Development, 1% in Phase E.

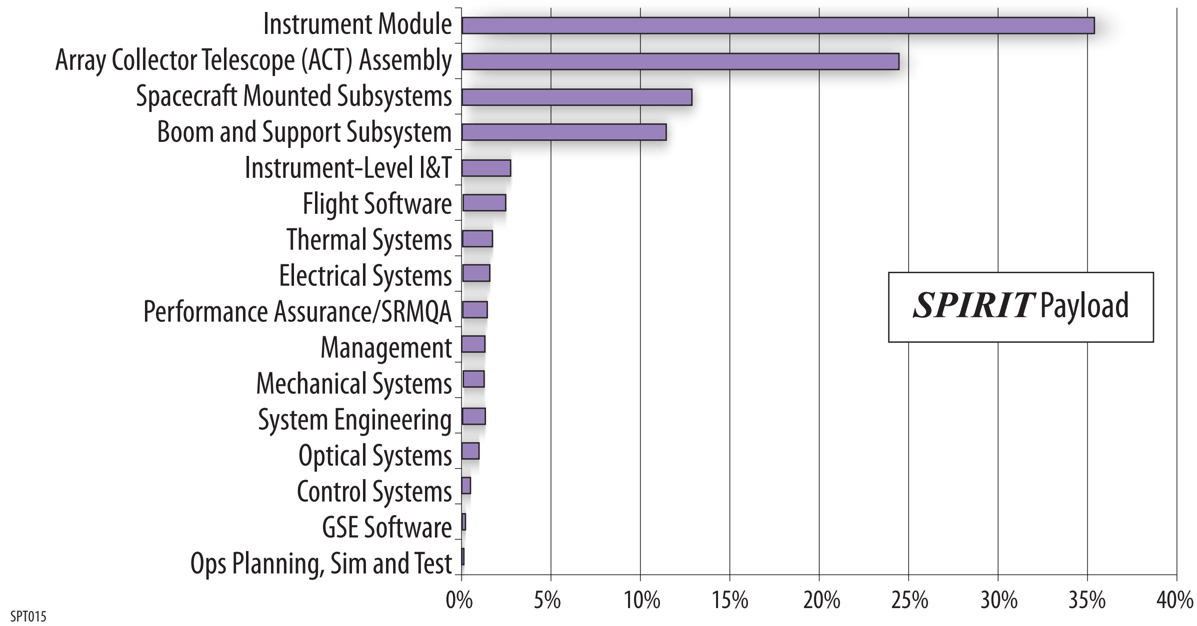

Figure 16: The SPIRIT Payload cost breakdown shows that 35% of the cost is in the instrument module.

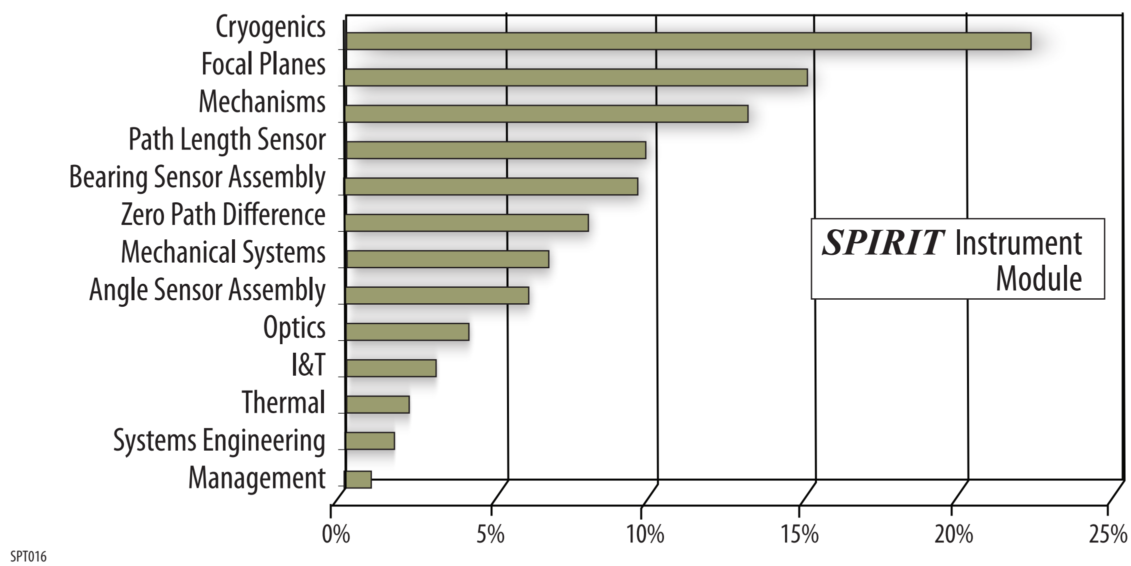

Figure 17: The SPIRIT team's grass-roots cost estimate can be organized to show cost categories at a fine level of detail.