Responses to questions posed by the Astro2010
Decadal Survey's Program Prioritization Panel

to

The Space Infrared Interferometric Telescope (SPIRIT) Team

led by

David Leisawitz
NASA GSFC
David.T.Leisawitz@nasa.gov
(301) 286-0807

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1) If BLISS is built, what further technology development would be required to propose SPIRIT in 2020 with Phase A start in 2021? What are costs of these developments?

I. Comparison of SPIRIT and BLISS Technology Requirements

SPIRIT is an observatory, whereas BLISS is an instrument, so it should come as no surprise that SPIRIT requires a significantly greater technology investment than BLISS. The cost to prepare BLISS technology for space flight application is estimated to be $33M (C.M. Bradford, private communication). The complete technology development program for SPIRIT, outlined below, will cost approximately $137M, less any cost savings that accrue due to investments made for BLISS, JWST, IXO, or other missions, or through NASA's R&A programs.

A detailed, comprehensive technology plan for SPIRIT was among the products of the 2004-05 SPIRIT Origins Probe mission concept study. This plan describes the work breakdown, schedule and cost associated with developing all of the SPIRIT technologies from then-current state-of-the-art through a Validation and Test phase (see NASA Procedural Requirements Document NPR 7120.8 at http://nodis3.gsfc.nasa.gov/npg_img/N_PR_7120_0008_/N_PR_7120_0008__AppendixK.pdf for definition) involving breadboards, testbeds, and protoflight engineering models for the beam combining instrument module and telescope. **In addition to the three key SPIRIT technologies – detectors, the cryo-thermal system, and wide-field double Fourier interferometry – the SPIRIT technology plan prepares for space flight components of the optical, mechanical, and metrology subsystems.**

Appendix A shows the SPIRIT Technology Work Breakdown Structure. WBS elements dominated by basic technology development and maturation are shown in blue, while Validation and Test activities are shown in red. Additional detail is available upon request, including complete descriptions of the work elements, the basis of estimate for the cost of each element, and the phasing plan for funding each element.

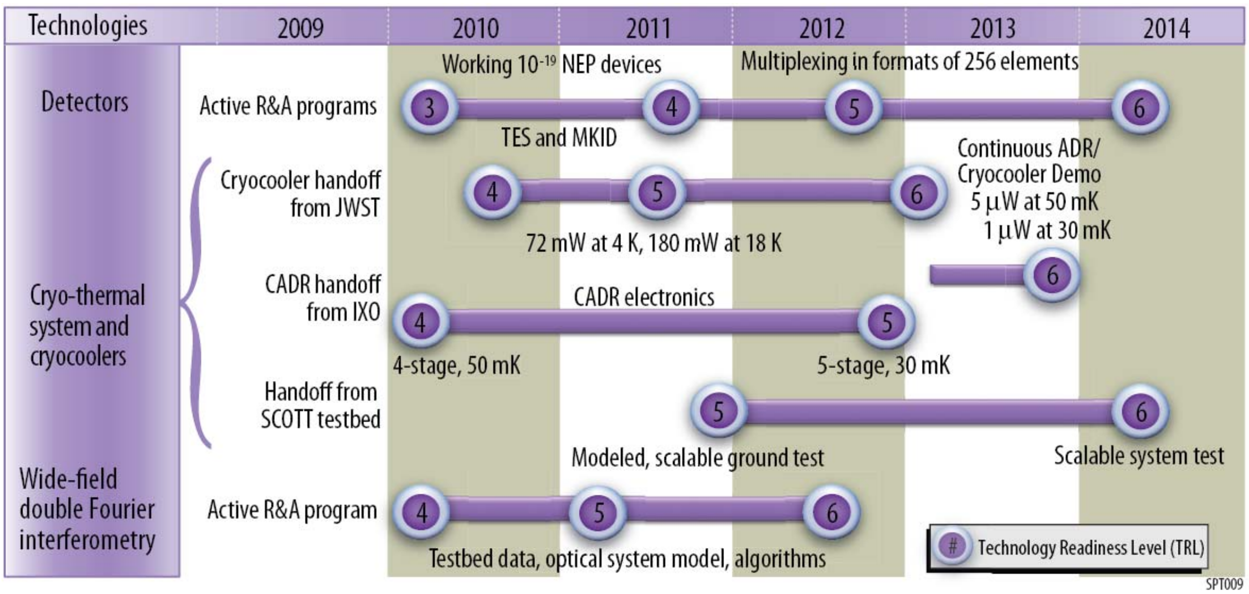
The schedule was given in Figures 9 and 13 of the SPIRIT RFI response (http://astrophysics.gsfc.nasa.gov/cosmology/spirit/). Those figures are reproduced here as Figures 1 and 2, respectively. As indicated in Figure 1, work in all of the key technology areas is underway presently through active R&A programs or would pick up from investments already made for JWST and IXO. Technology maturation would continue through Phase A, and then flow into the Validation and Test phase, which would coincide with Phase B, as shown in Figure 2 (see "Instrument Design" row).

The total cost of the SPIRIT technology program is $137M in FY09$. (A recently-discovered clerical error in one WBS cost estimate led to an overestimate by $20M in the technology cost reported in the SPIRIT RFI response. Here we have corrected that and accounted for recent advances in the cryo-thermal area.) The total cost is comprised of $46M for basic technology development and maturation and $91M for Validation and Test. Figures 3 and 4 show how these costs break down into the nine top-level WBS elements outlined in Appendix A.

The BLISS RFI response calls for development of Transition Edge Sensor (TES) detectors, superconducting SQUID multiplexers capable of kilo-pixel readout, and focal plane coolers. The similarities and differences between the SPIRIT and BLISS requirements are described below.

SPIRIT requires sensitive (NEP = $0.7 – 1.9 \times 10^{-19}$ W Hz$^{-1/2}$), fast ($\tau \sim 185\ \mu$s) detectors in arrays with pixel counts ranging from 2 x 2 to 14 x 14. As described in several papers cited in the SPIRIT RFI response, and in a technology white paper submitted by Bock et al. to the Astro 2010 Decadal Survey Committee (http://www.ipac.caltech.edu/DecadalSurvey/Bock_scarrays_TEC_OIR_RMS_PSC.pdf), at least two promising detector technologies are likely to satisfy the SPIRIT requirements: TES bolometers with SQUID readouts and "Microwave" Kinetic Inductance Detectors (MKIDs). BLISS is targeting better sensitivity than SPIRIT (NEP = 5×10^{-20} WHz$^{-1/2}$) and requires 10 detector arrays, each having several hundred pixels. However, a detector response time $\tau \sim 100$ ms is fast enough for BLISS. In other words, the SPIRIT detector arrays are smaller and slightly less sensitive, but about 500x faster than their BLISS counterparts. An investment in TES detector technology aimed at meeting the BLISS requirements would build momentum and give a head start to SPIRIT detector development, but the prudent course of action for SPIRIT is to continue investing in alternative detector types (e.g., MKIDs) to reduce risk that one technology path might fail to mature by the time it is needed.

Figure 1. Proposed Schedule for the Development of Key SPIRIT Technologies



The focal plane cooling requirements for both BLISS and SPIRIT can be met with a continuously-operating, multi-stage Adiabatic Demagnetization Refrigerator (CADR). A CADR under development for IXO has already 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. Analysis and modeling indicate that SPIRIT will require cooling of 1.0 µW at 30 mK and will reject a modest 3 mW through an interface to a 5 K stage. Thus, NASA's investment for IXO has already saved SPIRIT several $M. The SPIRIT technology budget covers the cost of advancing the IXO CADR to flight worthy status. The BLISS cooling requirements are somewhat different. BLISS requires cooling of 1.6 µW at 50 mK and can reject up to 5 mW through an interface to a 1.7 K stage. In other words, IXO more than BLISS, helps SPIRIT in the area of focal plane cooling.

II. Does an Investment in BLISS Reduce the Cost to Develop SPIRIT Technology?

The technology requirements for SPIRIT and BLISS overlap up to a point, but they diverge when the technology reaches readiness level (TRL) 4 due to unique design details driven by different mission and instrument requirements. **All of the SPIRIT technologies except detectors have reached or surpassed TRL 4; the detectors are currently at TRL 3.**

The SPIRIT and BLISS detector requirements partially overlap, yielding an opportunity to leverage investment up to TRL 4. If f_B represents the fraction of technology investments made for BLISS, we estimate that $f_B \sim 30\%$. That is, **an investment in BLISS technology would save approximately $10M for SPIRIT.**

Figure 2. Proposed Schedule for Technology Validation and Test, and SPIRIT Development

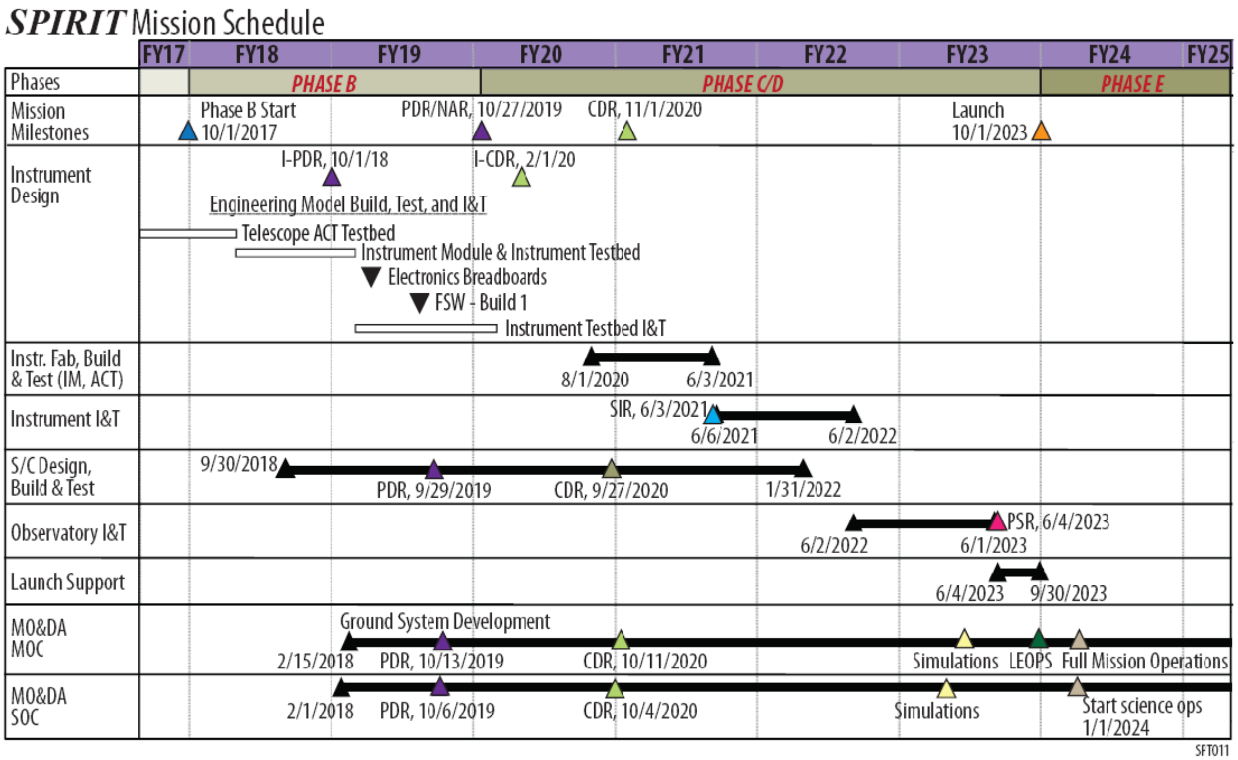


Figure 3. Distribution of Funding ($46M) for Technology Development and Maturation. Detectors dominate the cost of basic technology development for SPIRIT.

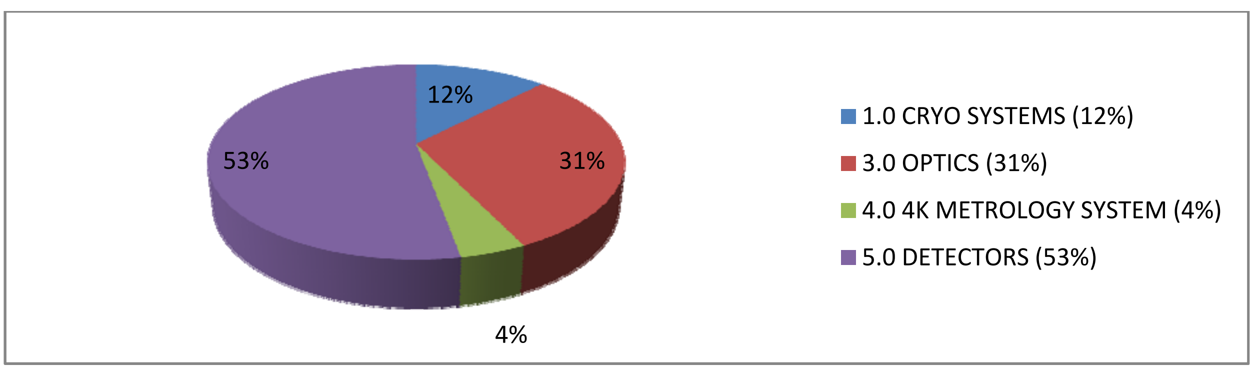
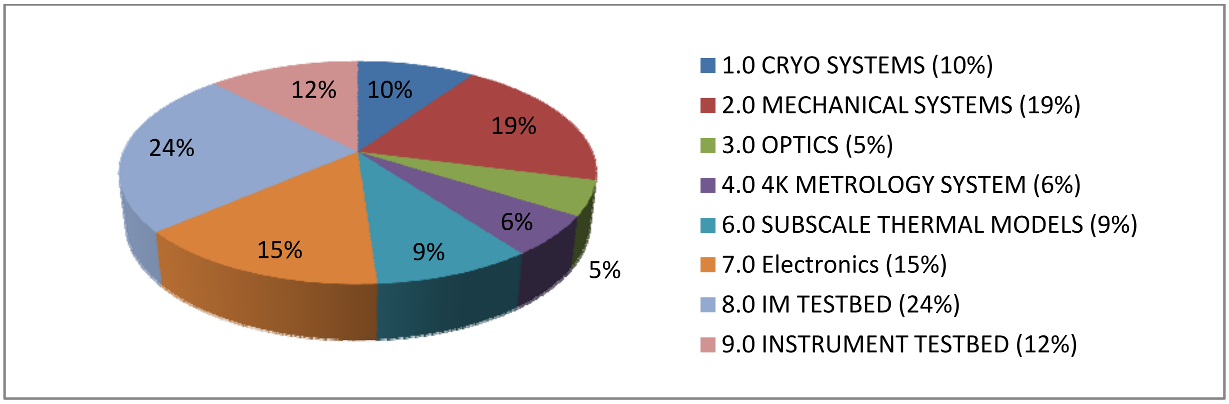


Figure 4. Distribution of Funding ($91M) for Validation and Test



Perhaps equally important, **an investment in detector technology for BLISS will build momentum for a larger-scale investment in SPIRIT technology, continuing a trend that began with past projects, such as COBE and Cassini/CIRS, and includes future missions such as JWST and IXO, and already-funded R&A projects. This momentum is expected to reduce start-up costs for SPIRIT technology development.** To be useful on the Japanese mission SPICA, the BLISS technologies will have to be demonstrably flight worthy by mid-2012. This time constraint could motivate additional near-term investment in detectors, the longest lead-time SPIRIT technology, while contributing to the vitality of critical detector development and characterization facilities.

The entire suite of SPIRIT mission-enabling technologies can be advanced to TRL 6 (system/subsystem model or prototype demonstration in a relevant environment) on the schedule shown in Figures 1 and 2, leading to SPIRIT transition to Phase B as early as 2017, with 2 years of margin before Phase B start.

2) What is the science yield for SPIRIT after three to five years of operations? How many of what objects can be observed to what sensitivities, and how this will address the mission's science goals?

As noted in the RFI response, SPIRIT could be developed as a "PI-led" mission or as a facility-class observatory. In either case, we expect that a large fraction of the mission will be dedicated to the three main science goals that guided the development of the SPIRIT design concept, namely:

- revolutionize our understanding of the formation of planetary systems and enable us to "follow the water" as these systems develop;
- find and characterize exoplanets based on their sculpting effects on protoplanetary and debris disks; and
- make unique and profound contributions to our understanding of the formation, merger history, and star formation history of galaxies.

As described below, **in 3.5 years SPIRIT will address an array of compelling scientific questions in these areas, such as: *How do planetary systems form from protostellar disks, covering 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 envision that **an additional 1.5 years will be dedicated to a wide variety of follow-up and exploratory measurements prioritized by peer review** of solicited observing proposals.

Our performance model adopts realistic estimates of the system throughput and observing efficiency and predicts the continuum or line sensitivity achieved in a given amount of time as a function of selectable measurement parameters, including field of view size, spectral resolution, and density of u-v plane coverage. 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 covering the desired field of view, and a third spectral dimension with the desired spectral resolution. Longer exposures, lasting up to about 16 days, are used to satisfy the most demanding sensitivity requirements.

Table 1, based on the Design Reference Mission (DRM) assembled at the beginning of the SPIRIT Origins Probe Mission Concept Study in 2004, describes a set of measurements that could be made to achieve the primary goals of the mission. These observations are intended to be representative. Further analysis during Phase A will optimize the observing program and strive for appropriate balance among the major science themes. **Each row of Table 1 describes a type of observation (i.e., target type, number of target fields, field of view, angular resolution, wavelength range, spectroscopic resolving power), and the continuum or line sensitivity achieved in the specified amount of observing time (days per field). The number of fields observed in each mode is set to capture all the data needed to address a science question relating to one of the major science themes.** To illustrate this point, Table 2 shows the relationship between three measurement sets, or "use cases," and the science topics they address. Suitable target fields are available in sufficient numbers within the SPIRIT field of regard.

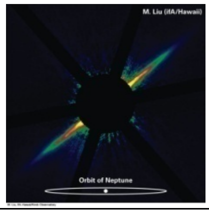
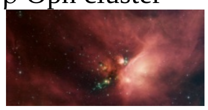
The achieved continuum sensitivity shown in Table 1 meets or exceeds the required sensitivity specified in the DRM in all cases; the line sensitivities, while not ideal, are adequate to accomplish the objectives. According to Table 1, approximately 1 year would be spent on exoplanet and related studies; three-fourths of a year would be spent on star and planetary system formation; and 1.2 years would be spent on studies of the formation and evolution of galaxies. The entire program would be executed in 3.5 years, assuming an 83% average observing efficiency.

In conclusion, **a five-year mission lifetime will generously allow for the accomplishment of the mission's primary science objectives and a large number of follow-up and exploratory goals.**

Table 1. Notional Allocation of SPIRIT Observing Time

Topic Area	Subject		FOV (arcsec)	Number of Fields	Spectral Resolution ($R=\lambda/\Delta\lambda$)	Average Days per field	Min wavelength	Max wavelength	Achieved Line Sensitivity	Achieved Continuum Sensitivity	Total Number of Days
							μm	μm	W/m^2	μJy	
Exoplanet Studies	Image debris disks, searching for structures induced by planets		15	80	50	1	25	100		2.8	80
	Spatially resolve gas/dust emission from protoplanetary disks to learn about planet formation, planetary migration, and delivery of volatiles. Follow the water	Shallow Survey	15	100	3000	1	25	200	1.42E-18	30.5	100
		Deep Survey	15	10	3000	14	25	200	3.80E-19	8.2	140
	Obtain the FIR spectra for extrasolar giant planets		10	20	50	1	25	50		1.8	20
	Study outer solar system objects to better understand the formation and evolution of the Solar System		10	20	500	1	25	200		12.5	20
											360
Star and Planet Formation	Directly observe, and resolve, the youngest star-forming cores		60	40	100	1	25	400		7.0	40
	Resolve and obtain spectra for young (~1 Myr old) stars in dense clusters		60	24	100	2	25	400		4.9	48
	Study binary stars to learn how binarity impacts disk formation and evolution		30	50	100	1	25	400		6.6	50
	Image brown dwarfs to study their photospheres and surrounding disks		20	75	100	1	25	300		6.5	75
	Wide-field images of nearby star-forming clouds to study evolution of protostellar disks		60	30	50	1	25	300		5.4	30
	Study star formation in nearby galaxies to better understand global processes		20	30	500	1	25	400		14.0	30
											273
Formation and Evolution of Galaxies	Deep field observations		60	5	1000	16	100	400	9.97E-20	5.0	80
	Resolve FIR emission from ultra-luminous infrared galaxies		10	100	3000	1	25	400		34.1	100
	Molecular hydrogen absorption, linking rest-UV absorption line objects with molecular gas		30	10	500	0.5	25	100		11.8	5
	Isolate FIR emission within star forming galaxies at z~1-5		10	100	3000	1	150	350		34.1	100
	Separate emission from AGN and starburst regions in nearby IR-luminous galaxies		10	15	1000	10	40	400	2.60E-19		150
											435

Table 2. Relationship between Use Cases in the DRM and the SPIRIT Mission's Science Goals

Use Case (a "Subject" in Table 1)	Representative Target Field	Addressing a Science Objective
Spatially resolve gas/dust emission from protoplanetary disks to learn about planet formation, planetary migration, and delivery of volatiles. "Follow the water."	AU Mic 	Measure the spatial distribution of dust and gas in disks spanning a range of ages, and surrounding stars of various spectral types and metallicity values. Map the distribution of water in the vapor and solid states in these disks to locate the water reservoirs and learn how the water distribution evolves over time.
Wide-field images of nearby star-forming clouds to study evolution of protostellar disks	ρ Oph cluster 	Study structure in the disks around young stars in nearby clouds (<200pc). Resolve disks to measure density and temperature spatial distributions and check to see if the inner part of the disk (<5AU) is cleared of material. Survey 30 clusters to understand the range of behavior.
Resolve FIR emission from ultra-luminous infrared galaxies	NGC 7469 	Resolve the far-IR emission from the most luminous high-redshift galaxies, identified as powerful dust emitters in Spitzer, WISE, and ground-based observations. Sub-arcsec resolution will allow internal and merging structure to be resolved. Image the galaxies in fine-structure line emission, PAH features in emission, and Si in absorption at rest frame ~10 μm.

Appendix A. SPIRIT Technology Development Program Work Breakdown Structure

WBS 1.0 Cryothermal Systems

- Design a flight worthy version (TRL-5) of the CADR. Fabricate parts and perform functional tests. Includes structural and electromagnetic considerations.
- Design the test apparatus for, and structurally test the CADR.
- Research and develop a new lower temperature stage to reach 10 μK for the CADR.
- Integrate the new 10 μK stage into a fully functional CADR operating down to 10 μK. Includes design, fabrication, assembly, test and analysis of the 10 μK CADR.
- Integrate TRL-5 CADR with engineering unit ACTDP cryocooler and test the combination. Includes design, fabrication of test parts, assembly, test, and analysis of results.
- Switch working fluid in ACTDP cryocooler and perform tests to demonstrate performance at 4K.
- Design and procure a development unit higher capacity compressor and cold head for the ACTDP cryocoolers.
- Design and Procure/Fabricate all parts necessary to upgrade cryocooler test facilities for SPIRIT technology verification.

WBS 2.0 Mechanical Systems

- Analyze, design, fabricate, assemble, test, and document end-to-end demonstrations of the SPIRIT trolley and active boom hinge subsystems, which shall consist of a short section of tracked boom and the trolley drive, and a single active hinge mechanism. The activity is planned to go through several functional prototypes, and vibration & thermal vacuum testing.
- Analyze, design, fabricate, assemble, test, and document a 4K cryogenic dry lubricant evaluation test.
- Analyze, design, fabricate, assemble, test, and document several 4K cryogenic actuators for application to SPIRIT 4K mechanisms.
- Analyze, design, fabricate, assemble, test, and document 4K cryogenic scanning devices for application to SPIRIT Instrument and life-testing.

WBS 3.0 Optics

- Examine optical figure errors and other behaviors for aluminum, glass, and silicon carbide mirrors (spheres)
- 1 meter off axis parabola, to SPIRIT specs (null lens test), at ambient; secondary and tertiary mirror components fabricated and tested at ambient; design and specification of optic and mounting structure (includes opto/mechanical/thermal)
- 1 meter off-axis parabola, to SPIRIT specs (null lens test), at 4K; secondary and tertiary mirrors - optical figure test for each mirror at 4K; design, analysis, and drawings for large cryo chamber; Other direct costs are for telescope mount and secondary/fast steering mirror mounts
- Test of one fully assembled 1.0 m telescope at 4K. Secondary mechanism may be part of collector optical system test in latter part of test
- Generate a design for each of the SPIRIT metal mesh dichroic filters and beamsplitters, and provide breadboard results of transmission and reflection at 4K

WBS 4.0 4K Metrology System

- Design and test of fiber interface to carry light from the Path Length Sensor source optics, in a warm region, to the Path Length Sensor optics in a 4K region. This includes optical, thermal, and mechanical design of the interface, and testing in a liquid helium dewar.
- Development of a wavelength-stabilized laser diode for the path-length sensor. Includes breadboard development of the locking optics and electronics, and development of a complete opto/electro/mechanical package that passes environmental testing.
- Breadboard effort for the bearing/distance sensor. Demonstrate ability to make measurements with the required precision using catalog parts.
- Design, build, and test a bearing/distance sensor source/receiver and target that passes environmental testing. Design, build, and calibrate necessary test equipment
- Build a breadboard, using catalog parts on an optical table, of the ZPD and angle sensors. Specifically, this would cover the parts after the dichroics that separate the 2 μm light from long IR.
- Design, build, and test ZPD and angle sensor assemblies that can pass environmental tests. Design, build, and calibrate necessary test equipment
- Develop a breadboard version of the path length sensor, using catalog parts on an optical table and breadboard electronics.
- Design, build and test a version of the path length sensor that can pass environmental tests. Design, build, and calibrate necessary test equipment

WBS 5.0 Detectors

- Develop individual detector of required sensitivity (NEP=$7\cdot10^{-20}$ W/√Hz). Develop multiplexed readout technology for arrays up to 14x14 in size. Develop flight-like electronics for detector control and readout. Develop flight software for detector control and readout. Test subsystem components in relevant environment. Produce flight-like detector subsystem.

WBS 6.0 Subscale Thermal Models

- Includes all design, fabrication, assembly, T/V chamber support, thermal modeling and test support to perform a subscale test of the beam combining IM. This includes simulation hardware for ACT and coupon tests for the critical thermal areas. This WBS also includes all of the preparatory work leading up to the initial testing and modeling to prove the viability of the subscale test concept.
- Includes all design, fabrication, assembly, T/V chamber support, thermal modeling and test support to perform a subscale test of the ACT. This includes simulation hardware for the IM and coupon tests of critical areas in the thermal system.

WBS 7.0 Electronics

- Design, build, integrate and test the Instrument Control Electronics. These costs include ICE power conversion, electrical interfaces, command and data handling, signal processing, EGSE, and test and verification with instrument and spacecraft interfaces. Costs include instrument electrical packaging leadership and EEE parts procurement and testing for both the ICE and MDE.
- Design, build, integrate and test the metrology electronics. These costs angle sensor, path length sensor, zero path delay sensor, and bearing sensor electronics, power conversion, electrical interfaces, command and data handling, signal processing, EGSE, and test and verification with instrument and spacecraft interfaces.
- Design, build, integrate and test the Breadboard CADR Control Electronics. These costs include CACE power conversion, electrical interfaces, command and data handling, signal processing,

EGSE, and test and verification with instrument and spacecraft interfaces.

WBS 8.0 Instrument Module (IM) Testbed

- Analyze, design, fabricate, assemble, test, and document 4K IM testbed. GSE for flight IM testing, including dewar and mass.

WBS 9.0 Instrument Testbed

- Build up full scale SPIRIT instrument testbed consisting of the Instrument Module (beam combining instrument) and one collector telescope. The second collector will be simulated. Provide end-to-end ambient performance demonstration of optical and metrology systems and their supporting mechanisms and electronics.
- Provide overall project management and all science and engineering oversight for the SPIRIT technology development efforts.