The SPIRIT Thermal System

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ABSTRACT

The Space Infrared Interferometric Telescope (SPIRIT) is envisioned to be a pair of one meter diameter primary light collectors on either side of a beam combiner, all cooled to 4 K or lower. During an observation, the collectors are required to move toward and away from the beam combiner to obtain information at various baselines to simulate a filled aperture. The thermal design of this mission as presented in this paper provides each light collector and the beam combiner with separate cryogenic systems. This allows the boom that attaches the combiner and collectors, the motors and many of the mechanisms to operate at room temperature, thus simplifying ground testing and reducing mission cost and complexity. Furthermore, the cryogenic systems consist of passive radiators and mechanical coolers – a cryogen-free approach. This paper gives a description of the requirements and resulting design for this architecture and some of the benefits and difficulties of this approach. A subscale thermal vacuum test of one of the collector thermal systems was performed. The thermal model and test agreed very well showing the viability of the thermal design and subscale cryo-thermal test approach.

Keywords: Thermal modeling, cryogenic, space telescopes

1. INTRODUCTION

The Space Infrared Interferometric Telescope (SPIRIT) was designed to accomplish three scientific objectives: (1) learn how planetary systems form from protostellar disks and how they acquire their inhomogeneous chemical composition; (2) characterize the family of extrasolar planetary systems by imaging the structure in debris disks to understand how and where planets of different types form; and (3) learn how high-redshift galaxies formed and merged to form the present-day population of galaxies. To achieve these objectives SPIRIT will provide integral field spectroscopy throughout the wavelength range 25 – 400 μm with sub-arcsecond angular resolution and $\lambda/\Delta\lambda = 3000$ spectral resolution in a one arcminute instantaneous field of view. Many of the astronomical targets of interest will be resolved for the first time at far-IR wavelengths. SPIRIT's spatially resolved spectra will break model degeneracy and enable a new physical understanding of forming stars and planetary systems, mature planetary systems, and galaxies.

A single scientific instrument gives SPIRIT its powerful combination of spatial and spectroscopic measurement capabilities. SPIRIT is a Michelson stellar interferometer with a scanning optical delay line for Fourier transform spectroscopy and compensation of external optical path length differences. Following beam combination in the pupil plane, detector arrays multiplex the area coverage, expanding the field of view from the diffraction spot size of the individual light collecting telescopes to the desired arcminute scale. SPIRIT's two telescopes can be moved to sample many interferometric baselines, and therefore 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.

The results of a pre-Formulation Phase study of the SPIRIT mission concept are given in a series of papers, of which this paper is one. The scientific objectives, measurement requirements, and an overview of the design concept are described by Leisawitz et al. (2007).[1] Hyde et al. (2007)[2] summarize system level trades and describe the design concept in greater detail, including the error budget for key design parameters and model-based estimates of the system performance. Wilson et al. (2007)[3] describes the optics and stray light trades. Budinoff et al. (2007)[4] describes the SPIRIT mechanical design and mechanisms and explains how the mechanical design will meet instrument stability, thermal and packaging requirements. Benford et al.

(2007)[5] describe detector requirements, including NEP, pixel count and readout speed, and present the rationale for using small arrays of TES bolometers. Rinehart et al. (2007)[6] update the status of our development of the wide-field imaging interferometry technique applicable to SPIRIT, and Martino et al. (2007)[7] describe a model of the Wide-field Imaging Interferometry Testbed, a model which can be adapted to simulate interferometric data from SPIRIT. This paper focuses on the trades that influence optical system design choices, stray light control, metrology, and optical system performance verification.

To achieve background limited performance in the far infrared-submillimeter portion of the electromagnetic spectrum, a space telescope must be cooled to low temperature. Figure 1 shows the effect of telescope temperature on the emitted noise with an effective telescope emissivity of 0.05 when compared with the sky background. For wavelengths in the range of 100 to 600 microns a 4 K or lower telescope temperature is required.

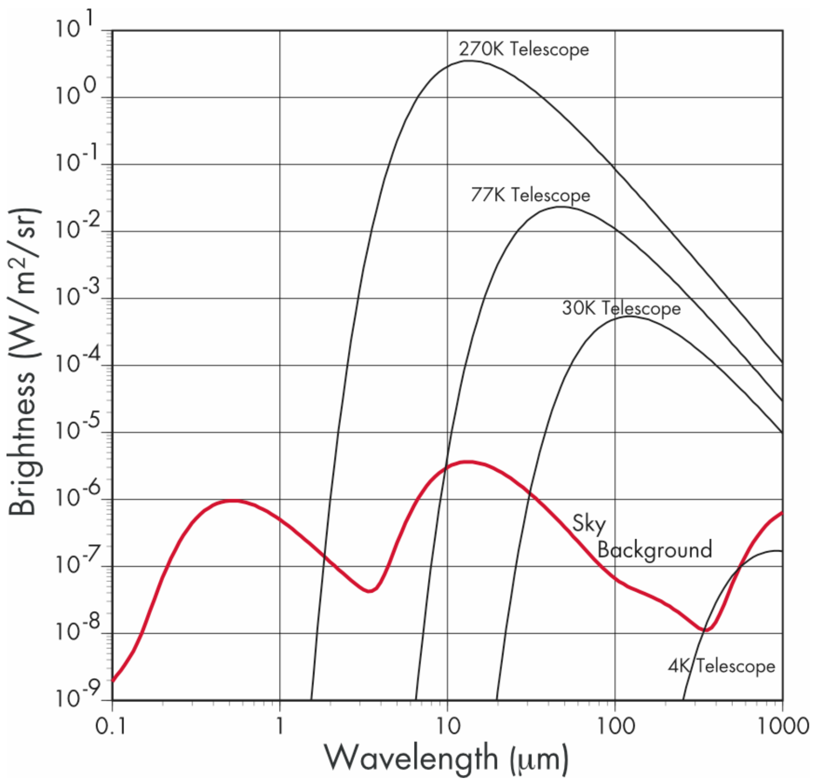

Figure 1. A space telescope must be cooled to 4 K to achieve background limitied performance in the far infrared/submillimeter por.tion of the spectrum.

To reach the angular resolution required[2] an interferometric technique was chosen which gives excellent mass and stored volume performance. The technique employs two collector telescopes mounted on a truss and moveable such that they are separated by approximately 7 to 36 m. Between the two collectors is a beam combiner which takes the light beams from the two collector telescopes and interferes them using the double Fourier technique[1]. The thermal system must therefore provide 4 K temperatures to widely spaced - and moveable - optical subsystems. In addition, the assembly must be spun about the optical axis to fill in the u-v plane[1] and must be able to achieve at least a 40° field of regard (FoR). This again puts limits on the design of the thermal system.

The beam combiner, which must also be cooled to at least 4 K, also houses the single SPIRIT instrument, a Double Fourier spectrometer. This instrument contains mechanisms that will be cooled to 4 K to take advantage of the low dissipation of superconducting motors. It also has detectors that must be cooled to 50 mK to achieve the required performance[2].

2. THERMAL SYSTEM DESIGN

2.1 Initial Trades

In the past, flight instruments requiring 4 K have used liquid helium, a consumable with limited life and cooling capacity and a dewar system that presents I&T and launch operations challenges. As a result, low temperature mechanical coolers have been developed under the Advanced Cryocooler Technology Development Program (ACTDP). These coolers will simultaneously provide 30 mW of cooling at 6 K, 150 mW of cooling at 18 K and 0.5 W at 45 K for an input power of less than 200 W at end of life[8]. See Figure 2. For comparison, the Spitzer Space Telescope uses the boiloff ^{4}He gas from a 360 liter liquid helium dewar to cool a 850 mm diameter telescope down to 5.5 K absorbing 6 mW at 5.5 K and 26 mW at 24 K. Since 137 kg was the liquid helium dewar, a cryocooler system (~2 kg mass at 4 K and 40 kg total mass) will save mass and improve thermal margins. The cooling requirements of SPIRIT are expected to be much higher than Spitzer making a helium dewar much more massive. SPIRIT will therefore use mechanical cryocoolers rather than stored cryogens to produce 4 K.

There are three general ways to cool the collecting telescopes and combiner to the required 4 K: a) cool the entire payload including the connecting truss to 4 K; b) cool the truss passively to 40-50 K, and spot cool the collectors and combiner; or c) provide a separate cooling system on each collector and the combiner while leaving the truss at room temperature or slightly below. Option a) requires a very large cooling power over a very large area so would consume an extraordinary amount of power. b) requires central compressors to be connected by coilable plumbing to the collector coolers so that the compressor heat can be dumped to the warm side of the shields while the collector telescopes move back and forth along the truss. This would still result in a large parasitic heat to the cold stages of the compressors do to parasitic heat into the log coils. Option b) also requires a sunshield of the order of the JWST sunshield in size and performance. Option c) removes the need for coilable plumbing or wires between the moving platforms. In addition, confining the areas to be cooled results in a smaller, lighter weight system that will be easier to verify on the ground. On the negative side, option c) means that the collectors and combiners will have to be carefully shielded both thermally and from stray light from several warm components like the support truss. Option c), three independent subsystems, with the collector telescopes likened to "dancers-on-a-stick", was chosen for this study.

The collectors each have a one m diameter primary, but the beam that exits toward the collector is compressed to one tenth that. Having a smaller beam means that a smaller penetration into the cold, thermally sensitive, volume of the collectors and instrument. The beam is 100 mm in diameter at the collectors and 150 mm at the combiner due to beam spreading at the largest separation.

The collector is shown schematically in Figure 2 and the combiner in Figure 3.

2.2 Passive Shields and Radiators

To limit the cooling requirements on the cryocooler, SPIRIT uses passive shielding against both the sun and warm parts of the spacecraft. The L2 orbit allows shielding for both the spacecraft and sun to be in the same direction, and allows maximum view to deep space for radiative cooling. As mentioned above, each of the three subsystems – the two collectors and one combiner – has its own cryo-thermal system of passive and active cooling. Five shields were chosen as a compromise between performance and complexity and weight. Three of the shields are strictly passive: shielding the telescope/instrument from the sun and warm spacecraft while cooling radiatively out the v-grooves in the perpendicular direction. The two coldest shields are partly cooled by radiation and partly cooled conductively by attachment to the cryocooler's 45 K and 18 K stages. It has been shown that the shields may be made of a very lightweight material, double aluminized kapton (DAK) for instance, and still have good performance as long as the relatively large conductive loads from structure and wires are removed by a cryocooler[9].

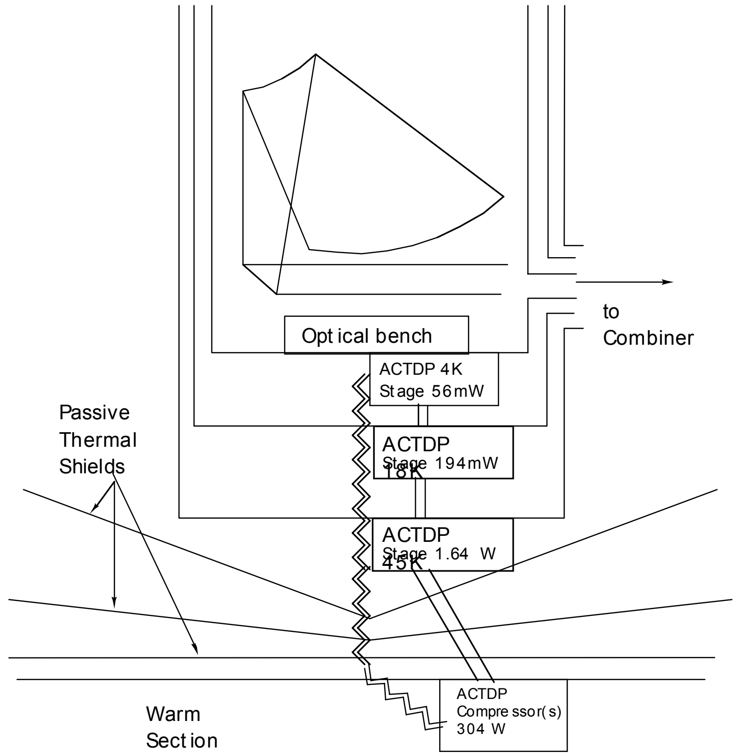

Figure 2. Schematic of the thermal system for each of the two collector telescopes.

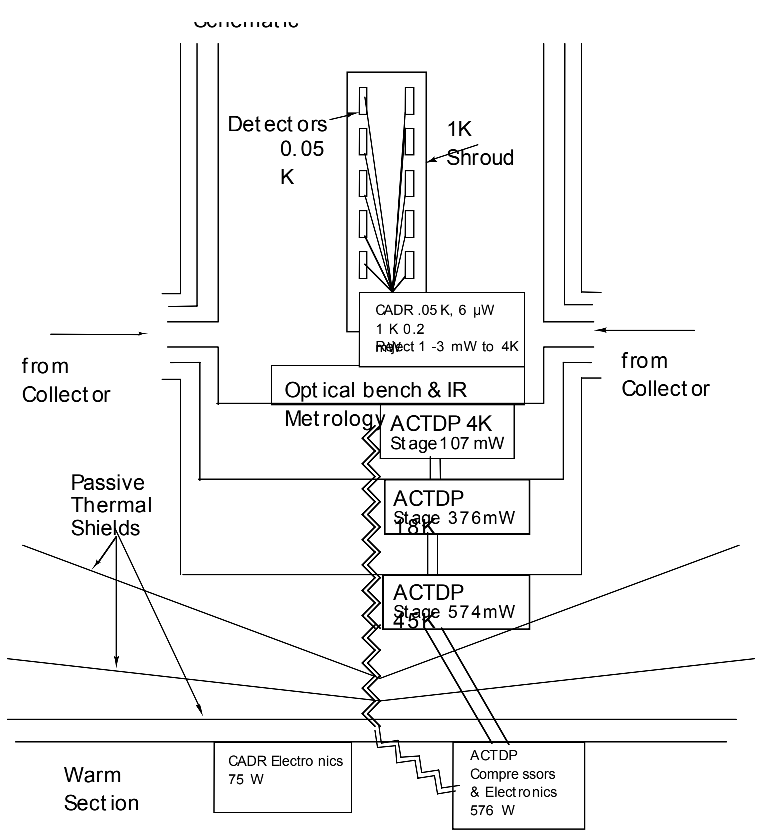

Figure 5. Cryogenic system schematic for the combiner telescope. Heat loads are twice the predicted values.

The configuration of the shields is partly governed by maintaining a 40° FoR while totally blocking sunlight and radiation from each of the outer shields in turn. The more open the geometry, the better the performance, which is why the "tulip" shape is preferred. A small trade study was done that shows that nested cone shaped shields are more effective at lowering parasitics than nested cylindrical shields. In contrast to a large telescope such as JWST, the overall shield size is small enough to be fixed – no deployment after launch is necessary – with a one m diameter primary and a FoR limited to 40°.

The configuration and preferred emissivity of the shield components is also crucial to blocking stray thermal energy from entering any of the beam combining ports on the collectors or combiner. To limit this parasitic the higher temperature shields are dropped down in the direction facing the combiner or collector to present a colder surface to the aperture. In addition, concentric baffles are used on both the collectors and combiner with the inner baffle being at the lowest temperature (4 K) and the outer baffle at 45 K. The facing surfaces are all made with low emissivity (ε) material to limit the heat input, while the deep space viewing surfaces are black to increase the radiative cooling. The inside of the 4 K surfaces are black. Finally, the size of the skirts facing the combiner/collectors sets the minimum approach distance which ideally is zero. In this case there is a minimum separation of 7 m.

The Afocal Collector Telescopes (ACT) have five thermal shields: two nested cones and three flatter warmer thermal shields roughly parallel to the connecting truss structure. See Figure 3. The shields are numbered one through 5 starting with the warmest. Building on the James Webb Space Telescope (JWST) sunshield design, these shields can be fabricated out of thin kapton covered with vapor deposited aluminum (VDA). Inside the innermost shield (Shield #5) is a sheet metal cylinder housing the off-axis primary, secondary and tertiary mirrors. This cylinder is black and maintained at the same 4 K temperature as the optics. Each shield is mounted to a hub to which the supporting structure and wiring is mechanically and thermally connected. The Shield #5 hub is cryocooled to 18 K and the Shield #4 hub is cryocooled to 45 K. The three outermost shields and hubs are completely passively cooled.

There is one Collector Steering Mirror that operates at 100% duty cycle at 4 K in each telescope. This mechanism has a dissipation budget of 8mW. As a point of comparison, the Spitzer Space Telescope has an average instrument dissipation of 3 mW. The baseline is to use normal copper wire for this mechanism. A Superconducting coil may be used to reduce the dissipation to less than 1 mW.

All other mechanisms will be located on the warm side of Shield #1. The cryocooler compressor will also be located on the warm part of the ACT and will be the largest source of heating. Radiators will be positioned below the truss and sized at a total area of 4.6 m^2 to operate at no higher than 30°C.

The Instrument Module (IM) thermal system will be conceptually similar to ACTs with 3 passively and 2 actively cooled shields surrounding a 4 K enclosure. Larger beam combiner ports, more mechanisms and CADR operation to cool the detectors will result in a larger cooling requirement for the three cryocooled stages. The main spacecraft bus lies below the IM and houses its electronics and cryocooler compressors. Together with the spacecraft functions the heat is rejected by two fixed radiators at 2 m^2 each and two deployable radiators that deploy below the fixed radiators at 2.9 m^2 each. The radiators are sized to dissipate all of the heat from the boxes mounted to them with 20° incident sun angle at end of life with maximum solar flux. The maximum temperature the radiators are designed to are 15°C, which allows for a 15°C temperature delta between the box and the radiator.

The mechanisms are allocated 8 mW to dissipate at the 4 K interface. There are four mechanisms on the bench with 100% duty cycle. These mechanisms are two combiner mirror steering mechanisms, a pathlength compensation mechanism, and an optical delay line scan mechanism. Use of superconducting coils would lower the parasitic level to below 1 mW.

Two sets of three nested thermal baffles for the combiner are located at the top of the IM 45 K enclosure and inside the passive box. The inner baffle is 150 mm in diameter. There is an outer 45 K tube with an 18 K and 4 K tube inside. The 18 K and 4 K baffles are black and the 45 K baffle is low emissivity. The baffles are approximately 500 mm long.

The truss cross section is 500 mm x 500 mm. The anti-sun facing side of the truss is covered with VDA (facing in and out). The other three sides of the truss are silvered Teflon facing out and VDA facing in. This enclosure of the truss eliminates the glint of sun that may have been possible off of individually wrapped members. The silvered Teflon lowers the temperature of the truss in the sun and the VDA provides a low emissivity surface for the cold IM and ACTs to view.

2.3 Mechanical Cryocooler

The cryocoolers developed under ACTDP (Figure 4) have been improved. In particular, JWST required a cryocooler with more cooling power at 6 K than the ACTDP specification, so has furthered the technology development of one of the cooler designs to provide 60 mW of cooling at 6 K and 75 mW of cooling at 18 K. In addition, cooling at lower than 6 K has been demonstrated in a straightforward way by substituting ^{3}He for ^{4}He as the working fluid. The baseline therefore assumes the ACTDP/JWST cryocooler will fill the needs of the SPIRIT mission, using one cryocooler at each of the collectors and two cryocoolers at the beam combiner.

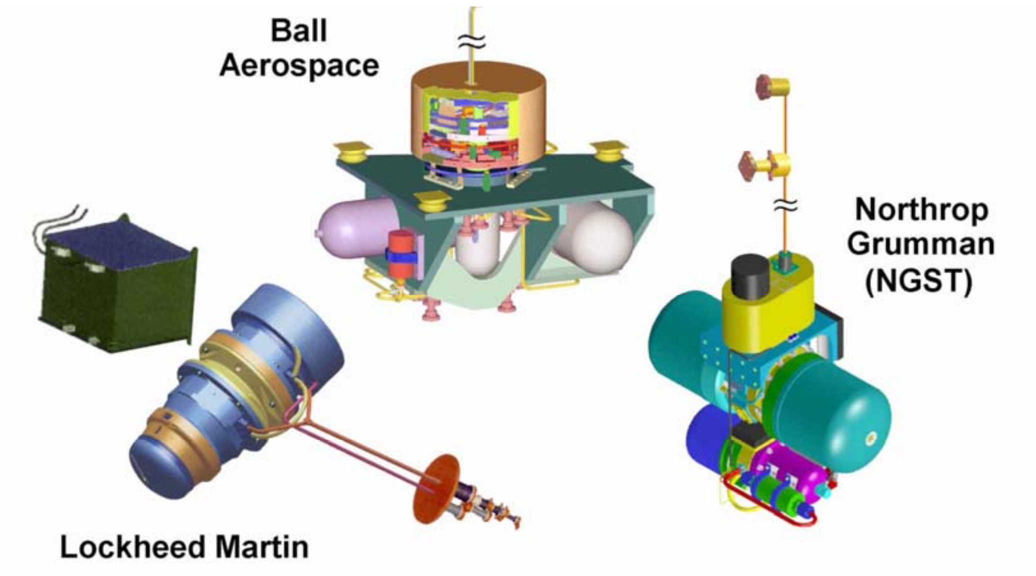

Figure 4. The three cryocoolers for 6 K and lower operation developed under ACTDP.

Each cryocooler consists of a 4 K cold head and 2 higher temperature stages of cooling. 2 of the 3 ACTDP designs use a separate compressor system to power the 4 K stage in which the cooling is provided by Joule/Thompson expansion. The other ACTDP design uses a single compressor system. All of the compressors are designed using back to back pistons for vibration cancellation. The tubing connecting the compressors to the lower temperature stages is small and flexible (1 to 20 meters), allowing remote location.

The cooling required at each ACT can be provided by one ACTDP/JWST type cryocooler while the IM will use one cryocooler to handle the conducted and radiated parasitics and the other to cool the instrument. The total bus power required by the cryocoolers is 304 W at each ACT and 576 W at the IM.

A benefit of operating at 4 K and below is that the operating temperature need not be any more stable than staying below the target temperature. The coefficient of expansion of almost all solids is nearly zero at this temperature, and the background radiation emitted is small relative to any signal.

2.4 Detector Cooling to 50 mK

The state-of-the-art space cooler for providing temperatures below 0.1 K is the adiabatic demagnetization refrigerator (ADR). An ADR has no moving parts and achieves cooling performance at close to Carnot efficiency. An ADR was developed for XRS-2 instrument launched on the on the Japanese Astro-E2 mission. This ADR is a single shot device with a 24 hour cooling cycle and 96% duty cycle. It has a cooling capacity of 0.5 Joules at 0.06 K and rejects its heat to a superfluid helium tank at 1.3 K. For the larger arrays with higher dissipation required for SPIRIT and to be able to reject heat at higher temperatures more compatible with cryocoolers, a continuously operated ADR (CADR) has been invented and developed at GSFC. See Figure 5. This device has more cooling power (6 microwatts at 0.05 K, 31 microwatts at 0.10 K have been demonstrated[10] while having less mass (<8 kg vs. 15 kg for the XRS ADR) than the XRS-2 ADR. It also can reject its heat to as high as 5 K with a Carnot efficiency of 25-50%. 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. In addition, 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 overall size of the CADR is 150 mm in diameter and 200 mm tall, but the packaging of the modular components is flexible. The nominal input power varies between 30 and 80 W, depending on cooling power required. The CADR will reject approximately 3 mW to 4 K or 4 mW if operated at 5 K. The cold end stability is limited mainly by thermometer resolution at 0.05 K and is approximately 10^{-6} K rms.

To improve the efficiency of the system, a CADR upper stage may be used to provide the 4 K cooling, rejecting its heat to a higher cryocooler temperature (10 K for instance[11]). Because of the high thermodynamic efficiency of an ADR the input power required may be significantly lower[12].

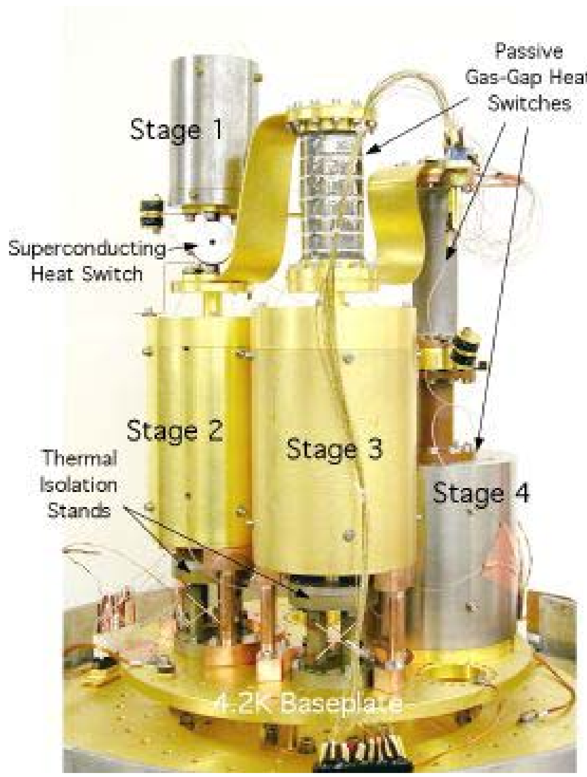

Figure 5. The multi-stage, modular CADR is shown with all components necessary to achieve 0.05 K from a starting temperature of 5 K. The overall height is 250 mm.

3. THERMAL SYSTEM MODELING

Several thermal cases were considered when analyzing the thermal design: closest approach, furthest separation, nominal anti-sun pointing and 20° off nominal pointing (edge of the FoR). The titling relative to the sun angle did not perturb the cryogenic system very much. Figures 6 and 7 show the modeled configuration.

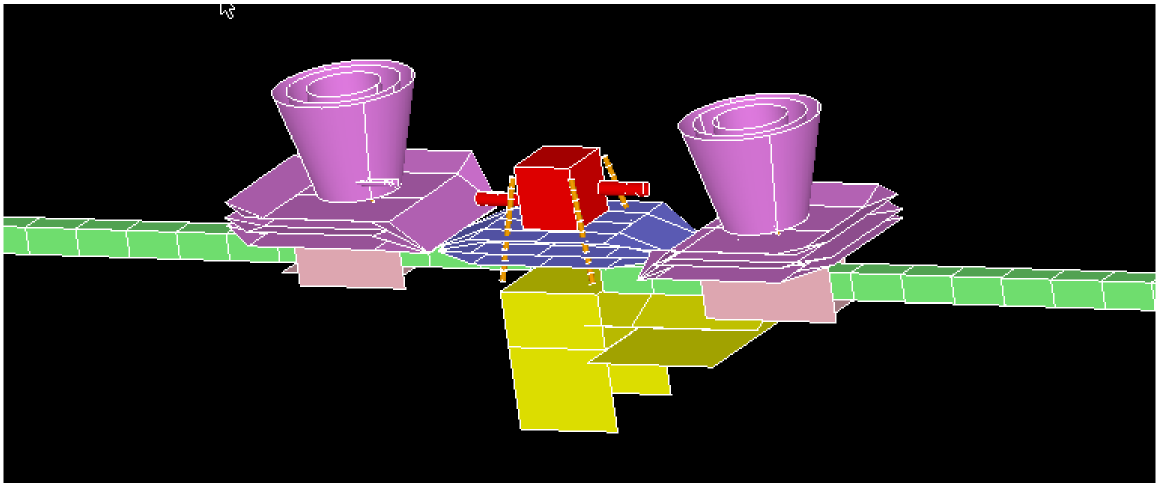

Figure 6. At closest approach of the collectors the middle shield is the only thermal contributor to the baffled beam apertures.

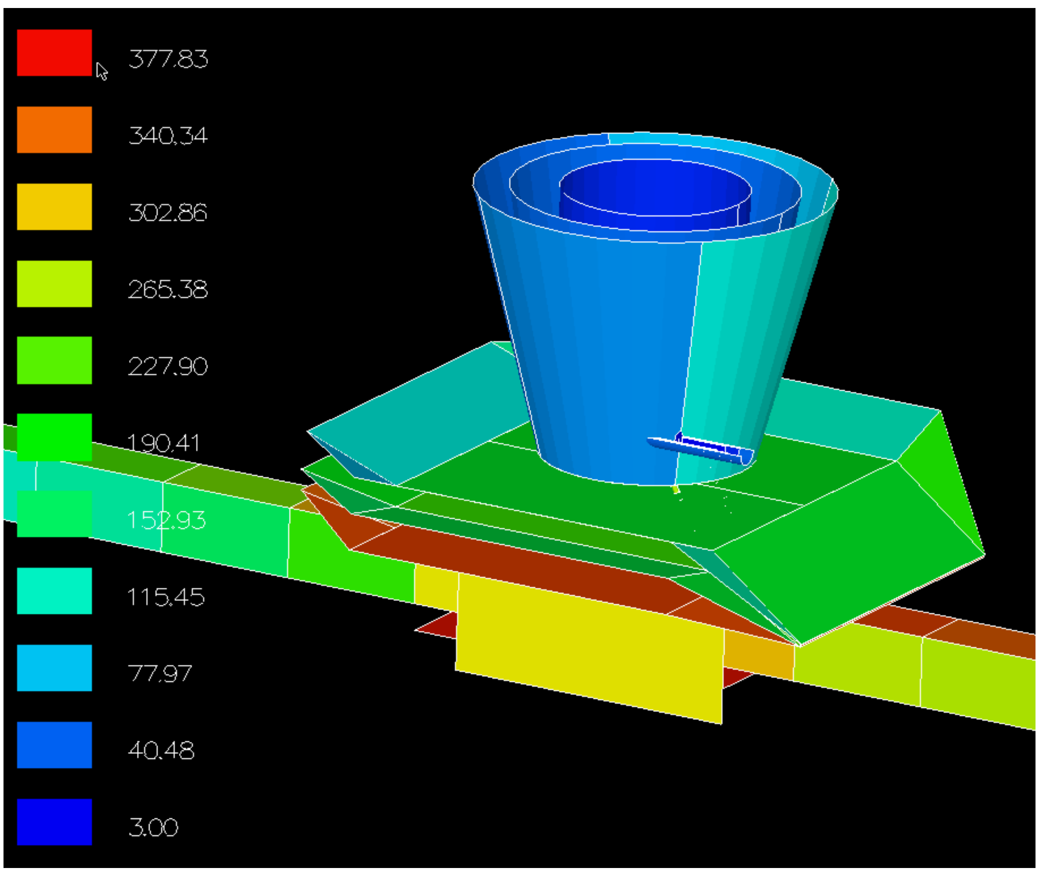

Figure 7. The thermal model results for one of the collector telescopes.

Table 1 summarizes the heat loads for the collector telescopes and combiner. The cryocooler is sized to handle twice the predicted load for a margin of confidence.

Table 1. Heat Load Summary. The cryocooler cooling requirement carries a factor of 2 over the predicted heat loads.

	Conductive (strut+wire)	Radiative	Mechanism Power	Cooling Needed From Cryocooler
Telescope				
4K	2mW + 15mW	11 mW	8 mW	72 mW
18K	17mW + 9mW	0 mW	N/A	52 mW
45K	0.223 W + 0.147 W	0W	N/A	0.74 W
Instrument Module				
4K	2mW + 12mW	44 mW	8 mW + 3mW from CADR	138 mW
18K	17mW + 7mW	156 mW	N/A	360 mW
45K	0.223 W + 0.773 W	0.228 W	N/A	2.448 W

4. THERMAL SYSTEM VERIFICATION

As mentioned above, the cryogenic architecture of cooling only the collector telescopes and combiner instrument allows easier verification of the cryo-thermal system. The warm truss and warm mechanisms can be tested outside of a thermal vacuum chamber. The individual ACTs and IM can be tested in smaller, cheaper, more common helium cooled thermal vacuum chambers. In fact these items are small enough that one could envision a performance test using small chambers for each of the three subsystems transmitting beams through windows between the collectors and combiners.

A thermal balance test that contains warm, room temperature, and cold, 4 K, components is an extremely challenging one. Chamber non-idealities which would not be present in space, such as reflections off the not-perfectly-black walls, can dominate the results when the heat loads differ by 6 orders of magnitude or more. 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 6 mW. To improve this situation a program for a subscale test was layed out during the early SPIRIT design phase. An 18% scale model of one of the collector telescopes in an earlier design was built and tested using a low cost, custom built, liquid helium cooled shroud in a LN_2 cooled thermal vacuum chamber[9]. See Figure 8. The cryocooler stages were simulated with temperature controlled straps to the liquid helium shroud. The test results agreed remarkably well with the pre test thermal model predictions, thus proving out the radiatively cooled design as well as the test techniques to limit stray thermal heating.

The results of this subscale test also demonstrate that very lightweight shield material may be used with no degradation in performance. In this subscale test the shields, even the lowest temperature one that operated at 20 K, were made of 25 micron thick double aluminized kapton with a standard 100 nm thick aluminum coating on each face. Thus a low emissivity thermal shield, even at 20 K, can radiatively cool itself when it has a view to deep space and is protected by a properly designed shield set. The higher temperature stages of the cryocooler are present only to remove conductive parasitic heat from the support structure and wiring.

5. SUMMARY

The SPIRIT cryo-thermal system consists of active cooling using mechanical cryocoolers and a CADR aided by passive cooling using thermal shields. Due to the moveable collectors and the size of the system, each collector is self contained relative to power, heat rejection, and cooling. This improves the efficiency and lowers the mass of the cryogenic systems and enables a more complete system verification by leaving the long truss and many mechanisms at room temperature. The passive shielding technology, mechanical cryocooler technology, and thermal verification schemes have been developed to the point where confidence has been achieved in the conceptual design.

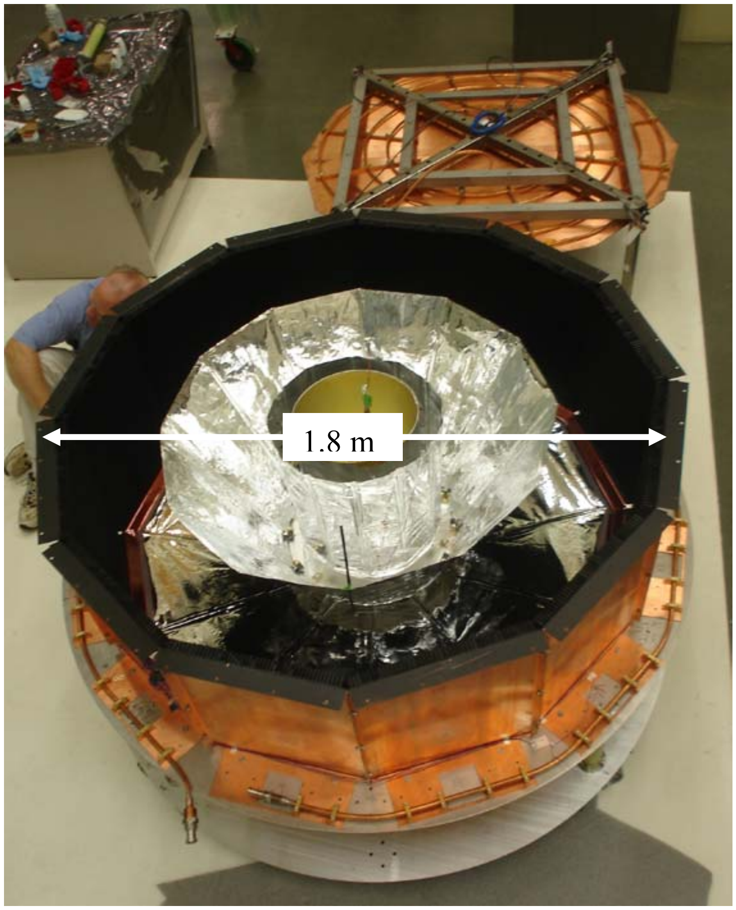

Figure 8. A subscale version of an earlier SPIRIT thermal shield design in a helium shroud. The cover is in the background.

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