

Cooling Systems for Far-Infrared Telescopes and Instruments

W. Holmes, T. Chui, D. Johnson, M. Larson, M. Lysek, C. Paine, and J. Rodriguez

Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr., Pasadena, CA 91109

ABSTRACT

NASA will need technology to cool detector systems to sub Kelvin temperatures for its future science program which includes missions such as the BLISS on SPICA, IXO, CMB-Pol, SPIRIT and SAFIR. Building on missions such as Spitzer, Planck, and ASTRO-E and the James Webb Space Telescope (JWST), new cooling technologies offer major advantages including long lifetimes, lower mass, and new capabilities such as cooling a large telescope to 4 K. Instruments on the ground or balloons are valuable, but technical approaches for space are really unique. For example passive cooling to $< 50\text{K}$ is only possible in space. Also, flight-like cryocoolers and optimized thermal support structures are too expensive for ground or balloon based programs since both must be made highly efficient due to strict power limitations on board spacecraft. Furthermore, interactions between passive radiators, multiple active cooling stages, and detectors, as on Planck or JWST, are system specific, which makes ground testing of space instruments technically challenging. Thus, cryogenic mission costs are driven by cryogenic technology readiness. So, it is in the best interest of NASA to support development of space worthy cryogenic technology now to save money later. We outline several key investments in cryogenic technology, including support of a strong US role in the Japanese space mission SPICA, that will enable NASA to achieve future science goals.

Keywords: space cryogenics, cryocoolers

1. INTRODUCTION

Cooling technologies have enabled background limited and high performance spectroscopy from millimeter to nanometer wavelengths. A detector system is cooled to cryogenic temperature to reduce detector noise below the intrinsic background noise or the so-called background limit. This is true for many types of detectors, including doped Si BIBs, bolometers, and coherent superconducting detectors. Generally, the longer the wavelength measured, the colder the detector system must be. For far infrared detectors, the detector systems need to be cooled to sub-Kelvin temperatures. For ground based and sub-orbital observations, the background limit is set usually by the atmosphere, even at wavelengths where the atmosphere is relatively transparent. For infrared observations in space, the background limit would be set by the optical system, which glows with thermal infrared radiation, unless cooled to cryogenic temperatures. Thus, to realize the ultimate sensitivity for a space mission, cooling the optical system is also

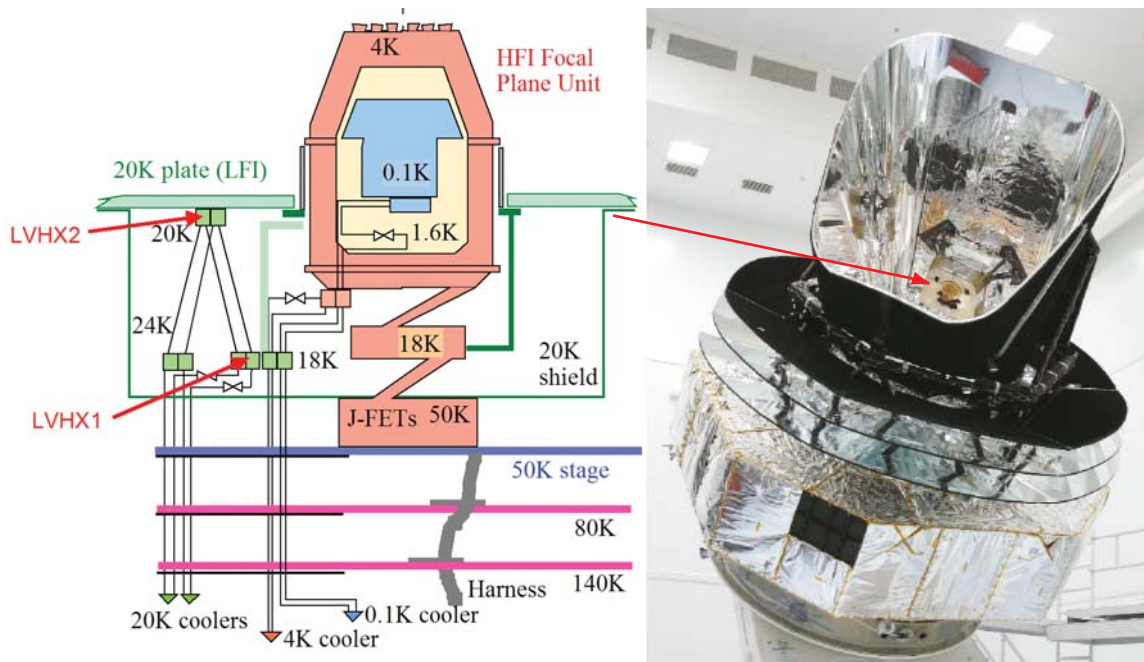


Figure 1. Graphic of the cooling system built for the Planck spacecraft (left) and photo of the completed Planck spacecraft (right).

required. Examples include the liquid helium temperature telescope on Spitzer,¹ cold telescopes on Herschel ($\sim 70\text{K}$), Planck ($< 40\text{K}$), James Webb Space Telescope (JWST) ($< 40\text{K}$), and SPICA ($\sim 5\text{K}$).²⁻⁶ Thus, cooling technology that enables high sensitivity encompasses many parts of the spacecraft and is best viewed as an entire system. An example of such a system is the Planck cooling chain shown Figure 1.

Many cryostats containing stored cryogenics with radiatively cooled outshells have flown in space,⁷ including Spitzer.¹ Herschel² will launch in April 2009. Very soon, spacecraft that employ active cryocoolers in place of stored cryogenics will be launched, including Planck, JWST and SPICA. When active cryocoolers are used, mission life is significantly extended since there are no consumables. This radically improves the scaling of spacecraft mass with lifetime. Very long life missions without a large impact on mass are now possible. Future missions, such as BLISS on SPICA,⁸ IXO, EPIC, CMB-Pol, SPIRIT, CALISTO and SAFIR, can achieve higher sensitivities with larger and colder focal plane arrays compared to previous missions thus expanding the range of achievable science goals. Work is still needed to scale mature technologies used in current missions to those needed for larger missions envisioned for the future.

2. CRYOCOOLERS IN SPACE

When launched in April 2009, Planck, managed by ESA, will be the first spaceborne instrument utilizing only cryocoolers to achieve sub Kelvin temperatures. The cooling chain, Figure 1, consists of V-groove radiators cooling to $< 50\text{K}$, the JPL-built hydrogen sorption cooler⁹ cooling to $< 19\text{K}$, a Rutherford Appleton Laboratory (RAL) cooler cooling to $\sim 4.5\text{K}$ and the open cycle dilution cooler¹⁰ made by Air Liquide in France cooling to 100mK . Planck will be launched

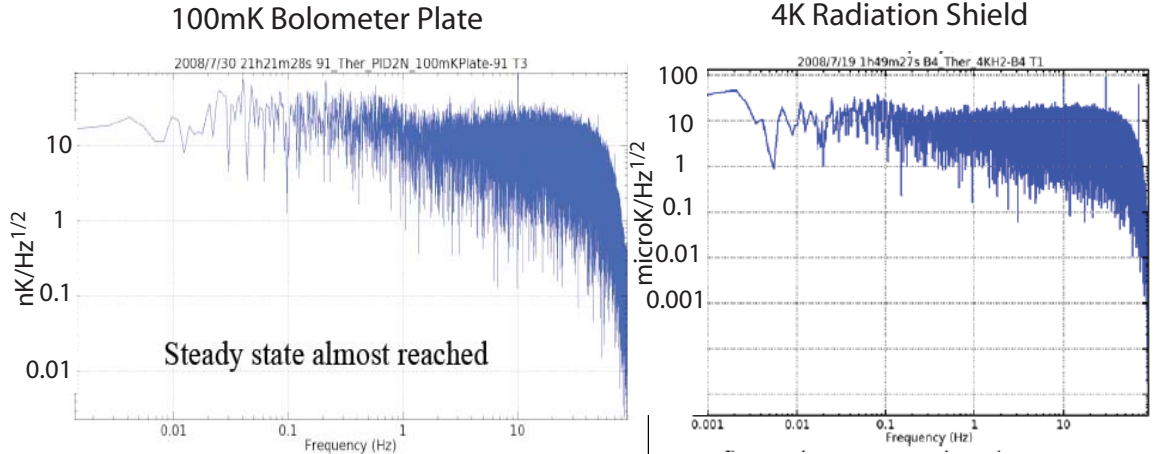


Figure 2. Temperature stability achieved at 4K and 100mK during the Planck spacecraft system tests at CSL. Graphs are courtesy of M. Piat, C. Leroy and J.L. Puget.

warm. It will first cool radiatively. Then, the active coolers will be started in sequence, with the highest temperature cooler first all during cruise to the L2 lagrange point. Shortly after arrival at L2, all elements of Planck will be at the operating temperature and ready to observe. The temperature stability achieved at 4K and 100mK in the full spacecraft system tests at the Centre Spatial de Liège (CSL) facility in Liège, Belgium, shown in Figure 2, is remarkable. The measured bolometer noise during the CSL tests is at the design value and is free from interference and low frequency ($1/f^\beta$) noise over the signal bandwidth, 16mHz to ~ 40 Hz. In addition to the thermal design and control of Planck, systematic design and test of the electronic grounding scheme and cabling for the entire spacecraft contributed significantly to the near absence of electromagnetic interference as measured in the detector systems.¹¹ Future missions designed with a warm launch and a similar cooling chain are clearly feasible based on the experience with Planck.

The first US-led large astronomical mission with radiative cooling and active cryocoolers in place of a solid hydrogen or liquid helium cryostat is the James Webb Space Telescope (JWST) shown in Figure 3. The Mid-InfraRed Instrument (MIRI) is one of 4 instruments on JWST. Unlike the other instruments on JWST, which cool passively to 40K, the MIRI optics and focal plane require cooling to near 6 K. The active cooling is provided by a dedicated three stage Stirling-cycle pulse-tube to precool a circulating helium flow loop, with a Joule-Thomson expansion stage to provide continuous cooling to 6.2 K to a single point on the MIRI optical bench. Significant development of the cryocooler occurred as part of the Advanced Cryocooler Technology Development Program (ACTDP) prior to selection as the flight cryocooler for MIRI.

Preliminary work has been done to extend the MIRI cooler architecture to lower temperature.¹² A MIRI-type cooler using a modified compressor configuration has reached < 4.5 K with nearly unchanged system efficiency. However, more work is needed. Additional development is expected to increase the heat lift and efficiency. Further modifications are expected to achieve temperatures near 2K.¹² A cryocooler with ~ 10 mW lift at 1.7K has been demonstrated by Sumitomo Heavy Industries, and is currently baselined for cooling the instruments on JAXAs

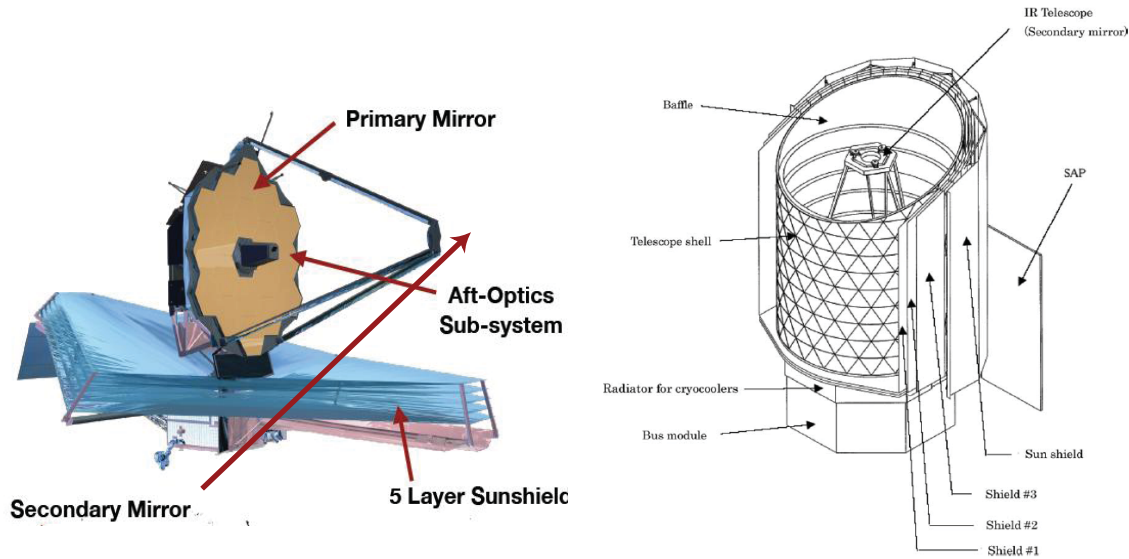


Figure 3. Graphics of the JWST⁴ (left) and SPICA⁶ (right) spacecrafts.

SPICA mission.^{6,13} For instruments operating in the mid-wave IR of $\sim 30 - 40\mu m$, cooling to $\sim 2K$ is likely to be sufficient; the enhanced MIRI-type cooler would provide this cooling directly, eliminating the need for an additional separate cooling system such as an adiabatic demagnetization refrigerator (ADR) staging from the 4 to 6K cryocooler cold head. For the far-IR capabilities of SPICA and similar future missions, 2K provides an ideal staging temperature for sub-Kelvin cooling. For example, staging at 2K replaces the less mass-effective warmer ADR stages which would otherwise be required to operate up to 4 to 6 K with reliable and proven mechanical pumps in the warm part of the spacecraft.

The requirement for far-IR telescopes to be cooled to $\sim 4K$ for background suppression is well-documented. The Japanese SPICA mission,^{5,6} Figure 3 with a 3.5m telescope cooled to 4.5K, will fill a scientific niche in the far-IR between the capabilities of Spitzer and JWST. Future missions such as CALISTO and SAFIR with primary mirror diameters of 610m have been considered. Mirrors this large are too large to launch monolithic, and 4K cannot be achieved by passive cooling. Thus active cooling of each segment of a deployed multi-segement mirror will be necessary. By deploying a small heat exchanger and a fluid flow system along with each segment, shown in Figure 4, the mass penalty of heat straps is eliminated, and automatically load-balanced cooling can be delivered to each individual mirror segment. Deployment of a single cold head, of single-phase helium operation, is an essential component of the cryocooler developed under the ACTDP for MIRI on JWST. With experience gained in the design and testing of the two-heat-exchanger, two-phase hydrogen cold end design of the Planck cooler (to launch in April 2009), and utilizing the designs developed under ACTDP for compression, precooling, and recovery of the helium working fluid, techniques for multiple, individual, two-phase helium heat exchangers to be deployed along with the mirror segments, to provide automatically load-balanced cooling at a fixed temperature to all mirror segments will be developed.

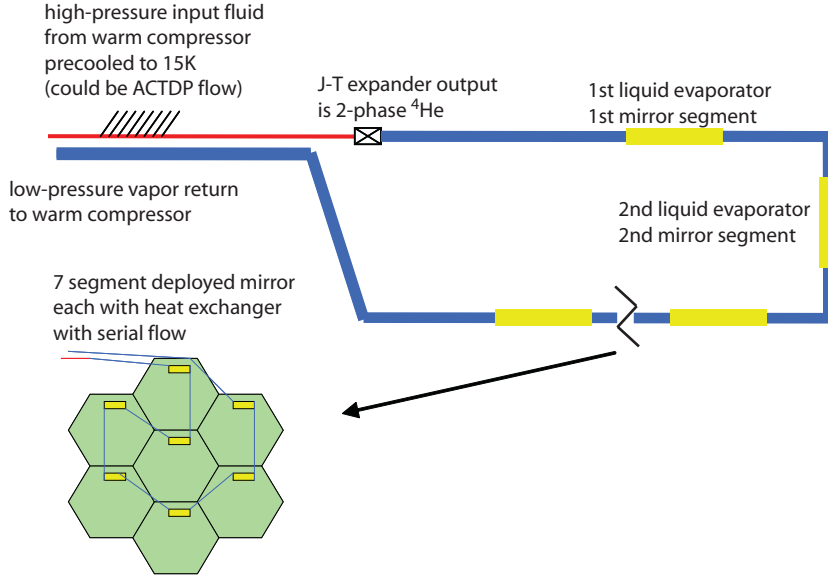


Figure 4. Graphic representation of a deployed multi-point cooling system on a segmented mirror.

3. SUB-KELVIN COOLING

The detector systems for far-IR and mm-wave focal planes require cooling to sub Kelvin temperatures. To achieve these temperatures (50-300mK), single shot coolers have been used in instrument for ground or suborbital telescopes (BICEP, ACBAR, Python, Boomerang, MAXIMA, ZSPEC, Spider) and have been flown in space (IRTS,¹⁴ XRS¹⁵, and Herschel (300mK sorption pumped ^3He , all at TRL 8 or 9). Single shot cooling is adequate, although not best, for most space borne applications because there is usually some other factor that limits observing time, such as the time to repoint a spacecraft, or down time while another instrument is observing. Thus, the requirement on the single shot system is that it be recycled, very quickly, during the non-observing time. The instruments proposed for future mission, however, are significantly more massive and actively dissipate more power at the operating temperature (50-100mK). Scaling the high TRL single shot systems to cool these massive instruments results in a sub-K cooler that is prohibitively massive. Also, the heat load on the cold head of an active cooler during the short recycle period would be so high that a heat absorber would be needed, increasing the system mass further.

A technological step towards a sub-Kelvin cooler that can be operated without the limitations of single shot coolers is the open cycle dilution cooler (OCDR).¹⁰ The OCDL will cool the Planck High Frequency Instrument (Planck HFI) to 100mK in space continuously for 2-3 years. Thus the OCDL is at TRL 8 and will soon be at TRL9. The OCDL requires a continuous heat lift at $< 5\text{-}6\text{K}$ in the mW range, well within the capabilities of existing mechanical cryocoolers. It has a low cryogenic mass ($< 1\text{kg}$), does not generate ElectroMagnetic Interference (EMI), and most of the sensitive components are located in the warm spacecraft bus which is relatively easy to service. The OCDL is not single shot, but requires tanks of high pressure ^3He and ^4He gas that are expendable similar to the stored cryogen in cryostats. Thus, an OCDL design for the needs of future missions will require more massive storage tanks that scale similarly to the mass

of a storage cryogen system. Additionally, the amount of ^3He needed for Planck was significant compared to the global supply. The amount of ^3He needed for future longer duration missions with higher heat load at 50-100mK simply might not be available at any price.

A closed cycle version of the Planck OADR (CCDR) was recently demonstrated in Alain Benoit's lab in Grenoble with a base temperature of 39mK and several microW of lift at 100mK.¹⁶ The sub-Kelvin performance of this laboratory demonstration model are very close to the heat lifts needed to cool instruments for BLISS, EPIC and IXO. The cooler requires a mechanical pump, similar to those already in use for the MIRI and SPICA coolers, to circulate ^3He and a ^4He phase separator which dissipates a few mW at $< 2\text{K}$. A space qualified $< 2\text{K}$ cooler with sufficient heat lift for this intercept is already available,⁶ but may be engineered into the CCDR system using the circulating ^3He for use with a higher temperature (4-6K) intercept. The CCDR is already at TRL 4. Advancement to higher TRL requires operation with flight model pumps, system engineering and design of a CCDR for specific flight applications, and operation of the CCDR with a ground based instrument.

An alternative method to provide continuous cooling is a continuously cycling adiabatic demagnetization refrigerator (cADR).¹⁷⁻¹⁹ The cADR works by coordinated cycling of several single shot ADRs, using heat switches, to produce a fixed temperature at the detector and heat intercept stages. The cADR is unique for space borne missions since many sub-K cooling systems are available for ground based applications that cannot be adapted for space flight applications. A prototype cADR has been demonstrated in the laboratory so it is at TRL 4. Many of the technologies for the cADR have been adapted from the TRL 9 XRS single shot ADR.¹⁵ Three technologies needed for a space-qualified cADR require development. These are reliable heat switches with on/off switching ratios > 1000 and operated at temperatures as low as 50mK, magnetically shielded, high field (4-6Tesla) magnets with quench protection, and low thermal impact high temperature superconducting cable harnesses to carry the 1-15A of current needed to drive the magnets and possibly the heat switches. In addition to individual component development, system level testing of the cADR with prototype instruments is very important. There are many examples of single shot ADR coolers working with bolometric systems¹⁵ and superconducting electronics in laboratory tests at NIST, JPL, GSFC and at Universities. However, the detectors in these systems are not operated when any magnet is at peak field. For a cADR, the risk of EMI from the magnet drive and the presence of cycling magnetic fields nearby the sub-Kelvin instrument that is likely to contain superconducting electronics is higher than that of a single shot ADR. Thus system level testing with engineering model instruments will mitigate risk prior to flight build and reduce mission cost.

The size of proposed kilopixel bolometric detector systems operated at 100mK is unprecedented even for ground-based systems. For example, some instrument design concepts consist of several focal planes distributed over a one meter diameter cryogenic space. Materials to distribute cooling to the point of use are extremely limited due to the physics at low temperatures. Examples where thermal distribution is over distance of 1 meter or larger include ground based systems such as Cold Dark Matter Direct Detectors and the SCUBA II sub-mm detector array, and balloon borne systems such as the Cosmic Microwave Background Polarimeter SPIDER. These systems incorporated many kilograms of pure copper, to distribute heat from the detec-

tors to the point of cooling. Besides heat (or rather cold) distribution, no system of this size $> 10\text{kg}$ of mass and operated at $< 100\text{mK}$ has been designed to withstand rocket launch. The increased sensitivity requirements also drive an improvement in long term (many hours) temperature stability to $< 10\text{nK}$ as compared to previous ground based efforts. So there are two main thrusts of the sub-Kelvin structural and thermal engineering effort. First, demonstrate the required base temperatures at the detector focal plane with a light weighted mounting structure. Second, achieve a $\sim 10\text{nK}$ temperature control over a focal plane $\sim 2\times$ larger diameter and $\sim 10\times$ more massive than have been fielded to date. This sub-Kelvin thermal engineering effort is unique to NASA programs since ground based instruments do not require significant attention to light-weighting. Also, the very low sensitivity achieved only by flying in space requires tighter temperature control of the focal plane assembly compared to measurements from ground or sub-orbital platforms. Technological advances that could reduce the mass of the temperature control system include the on-wafer Normal metal-Insulator-Superconducting (NIS) coolers^{20,21} and liquid helium filled sub-Kelvin heat pipes.

Demonstration of a CDDR and a cADR sub-Kelvin with an instrument in the next 3-5 years would easily advanced them to TRL 6. Support of a strong US role in the Japanese space mission SPICA, including full funding of the flight sub-Kelvin cooler, would advance a sub-Kelvin cooler to TRL 9 before 2020 and will enable NASA to achieve future science goals.

4. EXECUTIVE SUMMARY

NASAs next generation of space telescopes will measure at the background limit of the observable universe in the far-IR and sub-mm bands, discovering the first generation of stars, and probing dark matter and dark energy back to the era of inflation. The observatories making these measurements require cooling the optical system as well as the detectors to achieve ultimate performance. The telescope surfaces must be cooled to $\sim 4\text{ K}$ to suppress thermal radiation directly into the optical train to well below the zodiacal contribution. Additionally the environment external to the telescope, that is the structure and shielding which isolate the optical components from the spacecraft, must not source radiation which scatters into the optical beam; trying to observe in the far-IR in a hot environment is like observing with a sensitive telescope from inside a brightly-lit room. Low-emissivity surfaces at $\sim 15\text{ K}$ will reduce the straylight from the surroundings to acceptable levels. The radiative thermal shielding to achieve this is the first line of defense against light from the sun and thermal radiation from the spacecraft; active heat interception from the structure, to assist the passive radiation shields, is also required. Both cooling capabilities, i.e. on the telescope and on the environment, must be extended about a factor of 10 beyond what is currently being developed for JWST. Developments based on existing ACTDP-type cooler technology, the soon-to-launch Planck Sorption Cooler, and other laboratory developments point the way for these capabilities to be realized. The MIRI/JWST cryocooler has demonstrated $< 6.5\text{ K}$ in TRL 6 configuration; the addition of a second compression/recovery stage has been shown to lower this close to 4 K , and $< 4\text{ K}$ has been achieved in similar systems by changing the working fluid from ^4He to ^3He . Developmental cooler work in Japan for the SPICA mission has demonstrated $< 2\text{ K}$ with additional pump stages; but all of these developments have provided only a single point of cooling. Cooling a large aperture telescope, most likely one composed of deployed segments, requires heat extraction from a number

of spatially-separated components, ideally with constant temperature for changing heat loads. Conductive heat strapping is prohibitively massive, especially in a configuration which would allow deployment with mirror segments. Building on the Planck Sorption Cooler designed and delivered by JPL, which supplied cooling at constant temperature two separate instruments, and using experience from the JPL-managed MIRI cryocooler development of the deployable cold head, we will develop deployable multi-cold-head assemblies which are bolt-on extensions of the existing or in-development mechanical cryocoolers.

Sub-Kelvin coolers are needed for future far-infrared astronomy missions. Flight qualified single shot coolers used for flight instruments are not scalable to meet the needs of the much larger focal planes needed in the future. Continuously operating sub Kelvin coolers, capable of lifting several μW of instrument load at 50-100mK such as a closed cycle version of the dilution cooler used for Planck (CCDR) and the continuous cycle adiabatic demagnetization refrigerator (cADR), have been demonstrated in the laboratory but the technology readiness needs to be advanced from TRL 4 to TRL 6. Furthermore, the CCDR and cADR will need to be engineered for and operated with real flight prototype instruments to mitigate electromagnetic interference before flight design and build phases when it is cheap to do so. These prototype sub-Kelvin instrument system tests will jump start design and test of light-weight support and thermal distribution hardware needed to stabilize the temperature of the massive instruments at 50-100mK.

Specific demonstrations with prototype or flight hardware, as discussed previously is itemized below.

- Modify MIRI-like cryocoolers to demonstrate cooling at $< 2K$.
 - Lower pressure (few torr) recovery of helium
 - Multistage flight worthy pumps to compress lower pressure (few torr) gas
- Multi-point deployable fluid cooling loop
 - Zero-g heat exchangers
 - Automatic load balancing demonstration on meter scale hardware.
- Closed cycle Planck-like dilution cooler (CCDR) TRL advancement
 - Component and system development and optimization
 - Flight-worthiness such as reliability testing
 - Field a CCDR in a ground or sub-orbital instrument
- Continuous Adiabatic Demagnetization Refrigerator (cADR) TRL advancement
 - Flight worthy 50 mK heat switches engineering and test
 - Prototype electronics board build with sequencing and control software

- High Temperature Superconductor (HTS) high current leads in a flight-worthy wiring harness
- Field a aADR in a ground or sub-orbital instrument
- 50-100mK Focal Plane Thermal Engineering
 - Demonstrate NIS coolers on wafer sized detector arrays
 - Liquid helium heat pipe development
 - Demonstrate $< 10\text{nK}$ temperature control over 1 meter sized focal plane mock up.
- Support a US role in SPICA, including build and test of a sub-Kelvin cooler.

The level of effort estimated for this work is as follows. Over the next 3 years, $\sim 5M\$$ per year is needed to raise the TRL of sub-Kelvin coolers, thermal engineering of 50-100mK systems, and prototype instrument and cooler tests so that the technology is ready for opportunities such as SPICA. Subsequently, a $\sim 4M\$$ per year program through 2020 will focus on extending the MIRI cooler technology and demonstrating deployable fluid cooling loops on large scale structures. Completing these cryogenic technology tasks in the next decade will enable many future NASA missions, will reduce cost to NASA by maturing the technologies prior to the flight design phase, and will provide the greatest programmatic flexibility to partner with other space agencies such as ESA and JAXA.

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