Integration of a Tactical Cryocooler for 6U CubeSat Hyperspectral Thermal Imager

C.S. Kirkconnell[1], M.A. Nunes[2], I. Ruehlich[3], M.V. Zagarola[4], S.B. Rafol[5]

[1]West Coast Solutions, Huntington Beach, CA 92647
[2]Hawaii Space Flight Laboratory, University of Hawaii-Manoa, 96822
[3]AIM Infrarot Module GmbH, Heilbronn, Germany
[4]Creare LLC, Hanover, NH 03755
[5]Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109

ABSTRACT

All of the usual considerations for spacecraft cryocooler integration, including radiation harness, exported vibration, electromagnetic interference (EMI), and heat rejection, become increasingly challenging as the size of the spacecraft decreases. Small satellites (smallsats) invariably have low power budgets due to the limited volume available for solar panels and batteries, so the thermodynamic efficiency of the cryogenic system (thermomechanical unit and cryocooler electronics) becomes a critical consideration in every design trade. Packaging volume, and to a lesser extent mass, are major drivers, particularly down in the CubeSat range of smallsats. This paper describes how these challenges are being addressed on an ongoing University of Hawaii / Jet Propulsion Laboratory (JPL) led program called the Hyperspectral Thermal Imager (HyTI), which is a 6U hyperspectral spacecraft slated for launch in 2021 to perform a variety of environmental science missions. The HyTI Cryocooler System consists of an AIM SF070 Cryocooler and a Creare Microcryocooler Control Electronics for Tactical Space (MCCE-TS). The selection of this approach and how it is meeting the wide range of integration challenges is discussed.

MISSION STATEMENT

The HyTI (Hyperspectral Thermal Imager) mission, funded by NASA's Earth Science Technology Office InVEST (In-Space Validation of Earth Science Technologies) program has the goal to demonstrate how high spectral, high spatial and high SNR longwave infrared image data can be acquired from a 6U CubeSat platform.

HyTI addresses the need for high spectral and spatial resolution long-wave infrared image data for quantifying the chemical composition and temperature of the Earth's solid surface, its oceans, and its atmosphere. Many important phenomena, including evapotranspiration, volcanic degassing and urban heat pollution rely on such data, and repetitive, global scale measurements are needed to quantify the important physico-chemical processes. Scientists increasingly require these data to be made available with low latency to allow their use in an operational capacity. Such data are currently unavailable to Earth scientists, with sensors such as Advanced

Cryocoolers 21, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

Spaceborne Thermal Emission and Reflection Radiometer (ASTER) [1] nearing the end of their life, and planned Landsat mission offering at most bi-spectral measurements in the long wave infrared (LWIR). The HyTI instrument uses a spatially modulated interferometric imaging technique to produce spectro-radiometrically calibrated image cubes, with 25 channels between 8.0-10.7 µm. The small form factor of HyTI is made possible via the use of a no-moving-parts Fabry-Perot interferometer and JPL's cryogenically-cooled barrier infrared detector (BIRD) focal plane array (FPA) technology. The value of HyTI to Earth scientists will be demonstrated via on-board processing of the raw instrument data to generate L1 and L2 products, with a focus on rapid delivery of precision agriculture metrics.

The HyTI mission will demonstrate a pathway to a future constellation constituting a high temporal resolution, global, LWIR spectrometric mapping mission. To achieve this, HyTI will demonstrate the following three key technologies/capabilities, from a 6U CubeSat platform:

1. A no-moving-parts Fabry-Perot imaging interferometer, which allows LWIR spectral imaging from a low size, weight and power (SWaP) instrument);
2. BIRD focal plane array, which affords high signal-to-noise ratio (SNR), uniformity, and temporal stability even at relatively high operating temperatures); and
3. Onboard processing of payload L0 data using a heterogeneous architecture, which allows for data reduction for the high data rate instrument, and onboard conversion from L0 to L1, and finally L2 science data products, for low latency downlink).

The first two of these three key technologies are directly enabled by the AIM-Creare Cryocooler System described in the sections to follow.

SCIENCE IMPLEMENTATION

The HyTI imager is a novel, no-moving-parts hyperspectral imager that was originally developed using funding from DARPA and NASA. A prototype of the instrument (Fig. 1) has already been developed at the University of Hawaii with previous grant-based projects and flight tested in a light aircraft [2-4]. The instrument collects light from the scene through a refractive lens focused on a Fabry-Perot interferometer mounted directly above the focal plane array and ROIC within the integrated dewar cooler assembly (IDCA). The Fabry-Perot interferometer consists of two pieces of germanium (AR coated), with a sloped air-gap between.

Forward motion of the instrument in the CubeSat platform allows interferograms of targets on the ground to be reconstructed, as each ground target is imaged at a succession of optical path differences as the fixed interference pattern is pushed along the ground in the in-track flight direction. Fig. 2 illustrates the process. After co-registration of the image frames, standard Fourier Transform techniques are used to produce a spectro-radiometrically calibrated image cube. Reflection, transmission and eventual recombination of the light rays that traverse the interferometer gap produces interference that can be sampled at the array. The slope ensures that optical path difference (hence fringe period) varies linearly across the gap. Note in Fig. 2 the broad dark vertical stripe in the images, which denotes the point at which the pieces of Ge are contacted, where no modulation takes place.

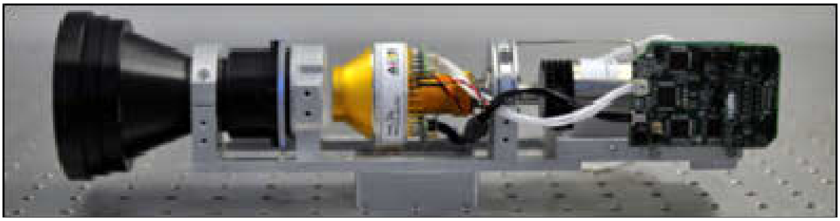


Figure 1. HyTI imager prototype.

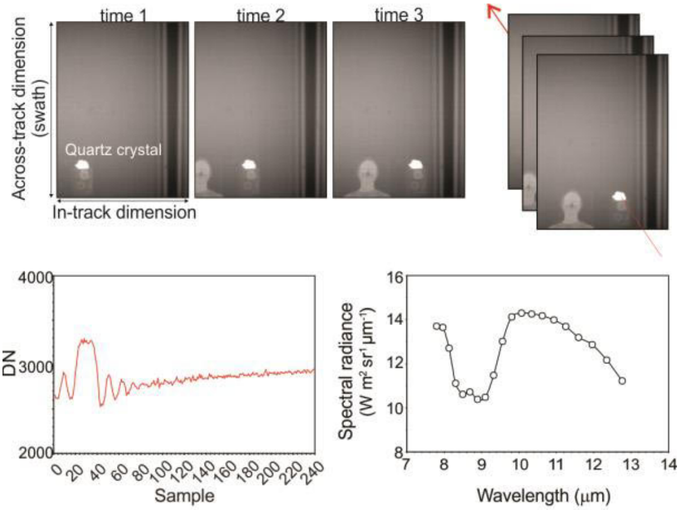


Figure 2. HyTI imaging approach.

HyTI produces high spatial and spectral resolution LWIR imaging by combining the multiplex advantage common to all interferometers with the sensitivity of JPL's BIRD FPA technology. Based on III-V compound semiconductors, the BIRD detectors offer a breakthrough solution for the realization of low cost, high-performance FPAs with excellent uniformity and pixel-to-pixel operability. To achieve acceptable dark current levels, the FPA must be maintained at a temperature of 68 K and therefore the critical importance of the SF070 cryocooler. The spectral sensitivity for the HyTI instrument is in the LWIR range of 8-10.7 µm, with a quantum efficiency of 35%. An FPA of 320 × 512 elements running at 139 Hz is used (320 detectors used to define the field of view or the swath). From a ~400km orbital altitude the ground sampling resolution is ~60 m. To achieve this resolution a multi-element refractive lens is used, with an IFOV of 0.15 mrad, and an f-number of 3.44. The HyTI performance model indicates narrow band noise equivalent temperature (NET) of <0.3 K for source temperatures in the range 0-50 ºC. The HyTI science data is then processed on-board to generate L1 and L2 science products, with a focus on low latency to deliver of precision hyperspectral data to Earth Scientists. This is made possible with a dedicated high performance, heterogeneous payload computer and specialized algorithms being developed at UH.

MISSION IMPLEMENTATION

HyTI will be launched to orbit via the NASA CubeSat Launch Initiative. The 6U CubeSat is planned for deployment from the ISS into a 51.6° ~400 km orbit on a late 2021 launch. The baseline mission includes a 3-month mission life with possible extension to 1-year goal. The Hawaii Space Flight Laboratory at the University of Hawai'i at Mānoa is the lead system integrator and JPL is Co-Prime, primarily responsible for the enabling focal plane array (FPA) technology. West Coast Solutions is lead on the Cryocooler System Engineering; AIM is providing the Cryocooler Thermo Mechanical Unit (TMU) and Creare/WCS is providing the Cryocooler Control Electronics (CCE), including an Input Ripple Filter to reduce extreme currents oscillations on the spacecraft bus.

SPACECRAFT BUS

HyTI will use a 6U bus with subsystems provided by Innovative Solutions In Space (ISISpace), CubeSpace, Syrlinks and other space-qualified components vendors for CubeSats. Fig. 3 shows a conceptual rendering of the HyTI spacecraft with the spacecraft configuration shown in Figs. 4 and 5. The payload uses 3.5U of the 6U available which includes the IDCA (provided by American Infrared Solutions; https://www.go-airs.com/), the cryocooler (AIM SF070; https://www.aim-ir.com), the multielement refractive lens (provided by New England Optical Systems; http://www.neos-inc.com/), and the payload on-board computer (Unibap Deep Delphi iX5; https://unibap.com/). The Fabry-Perot interferometer is provided by LightMachinery (https://lightmachinery.com/). Payload data downlink will be via a Syrlinks X-band. (S-band redundant) with S-band uplink (S-band redundant), as well as a Globalstar transmit/receive capability.

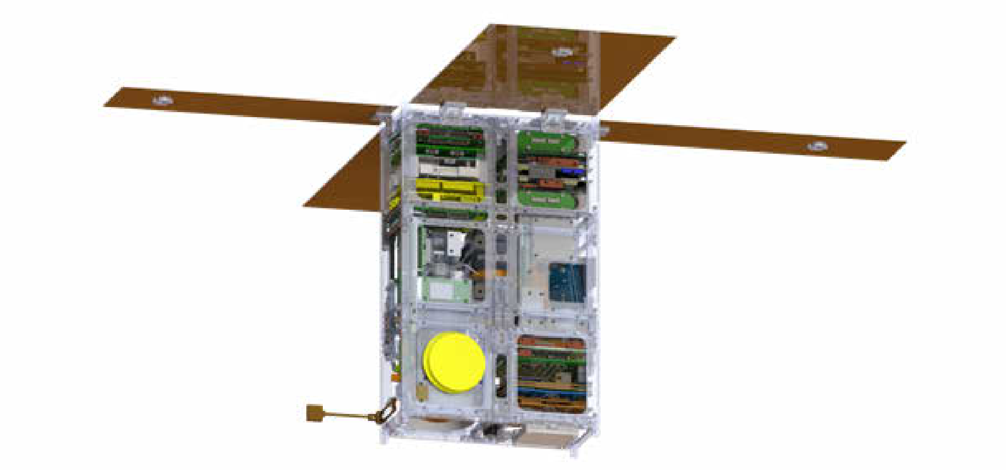


Figure 3. 3D rendering of the HyTI bus configuration as of October 2020

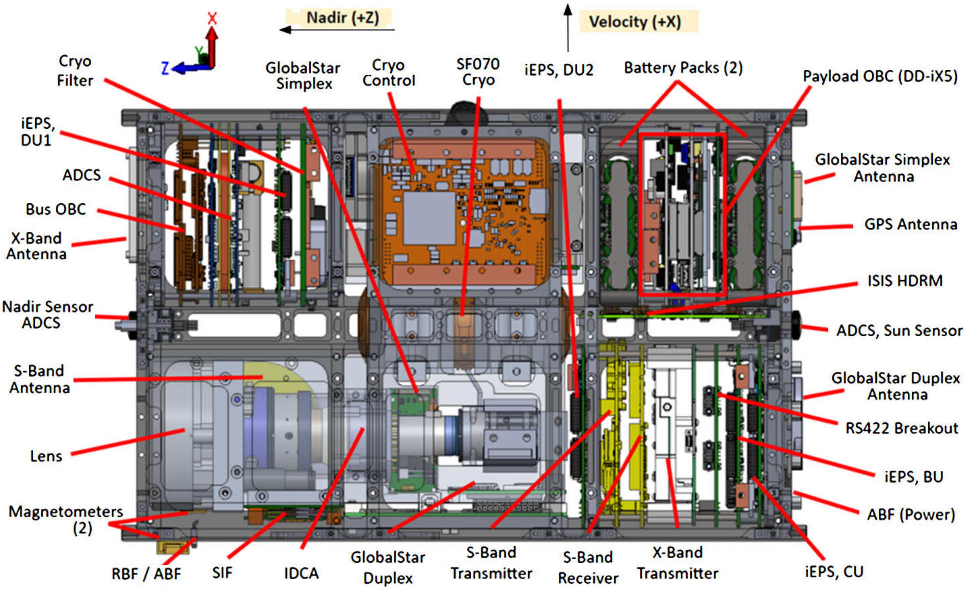


Figure 4. HyTI configuration. -Y face.

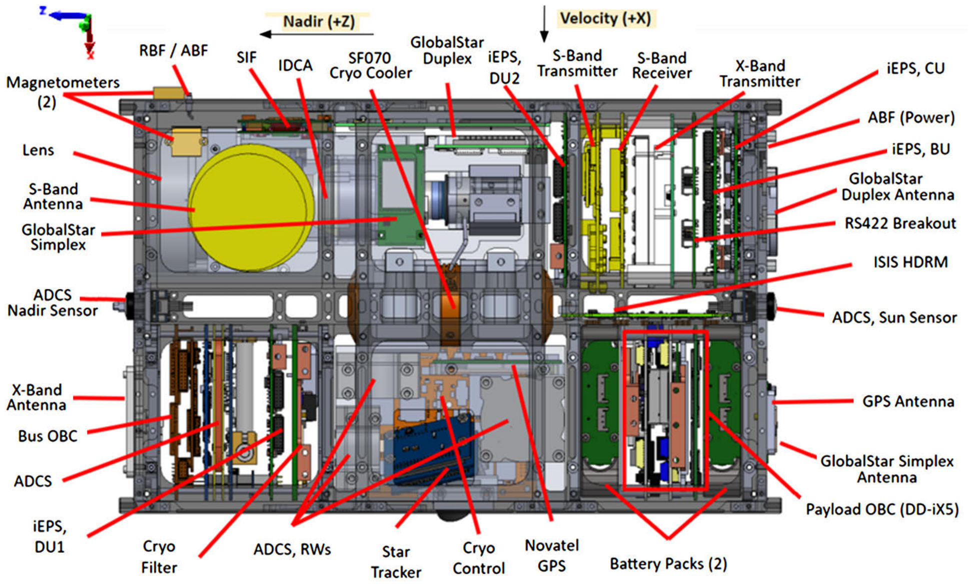


Figure 5. HyTI configuration. +Y face.

CRYOCOOLER SUBSYSTEM

Instrument Requirements

Based on the above, the following were identified by NASA and the HyTI Program Office as the key payload requirements. As indicated by the bold and italics text below, half of these key requirements had a direct influence on the selection and/or integration features of the Cryocooler Subsystem:

- Ground Sampling Resolution 60 m on LWIR.
- 25 spectral bands.
- FPA operation set point at 69-72 K for good quality SNR.
- Cryocooler expander warm end must be < 40ºC to prevent thermal runaway. Higher heat reject temperature both increases required cooler power and increases dewar parasitic heat load, further increasing power and potentially leading to a thermal runaway condition.
- Lens temperature must be stable and less than 50ºC.
- Pixel blur must be less than 10% to preserve image integrity.
- Based on the blur requirement, active vibration cancellation not required. Vibration mitigation was addressed by selecting low vibration coolers and placing the compressor close to the spacecraft center of mass.

Additional derived requirements also have a strong influence on cryocooler selection, including:

- Cost sensitivity. Specific component allocations were not assigned, but ultimately a space cryocooler system was architected as described below for <<$1M.
- Radiation hardness for Mission Assurance. Although the short mission life was not a driver for total ionizing dose (TID), concern over an unrecoverable single event effect (SEE) drove the need to look beyond COTS cryocooler electronics.
- Bus compatibility. With all instruments necessarily tied to a single bus on the small 6U spacecraft, conducted emissions became a concern, especially for a linear cryocooler which inherently creates several amps of AC bus current if not mitigated.

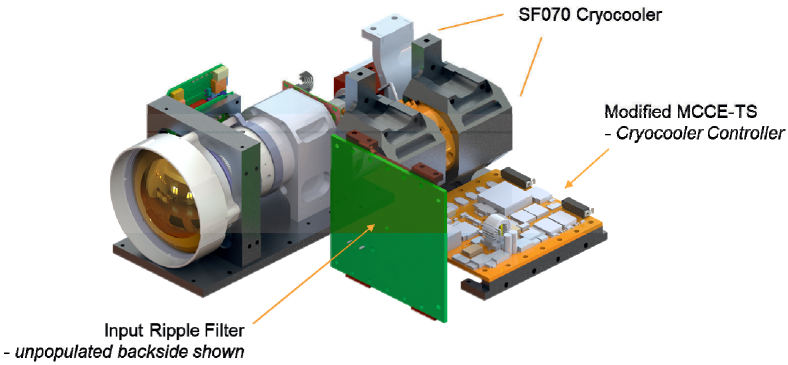


Figure 6. HyTI Cryocooler System. The three key elements, namely the SF070 Cryocooler, MCCE-TS, and CARF, shown together with the IDCA and main lens in their actual spacecraft orientation.

To achieve these requirements, the Cryocooler Subsystem shown in Fig. 6 consisting of the following key components was selected:

- AIM SF070 Cryocooler. Single-stage Stirling cryocooler with a dual-opposed piston compressor, providing high SWaP efficiency at 69K and adequately low vibration.
- Creare Microcryocooler Control Electronics for Tactical Space (MCCE-TS). Optimized for a balance between cost and radiation tolerance, and physically sized to package is a standard CubeSat frame. Modified to a single output drive circuit for HyTI.
- Creare / West Coast Solutions Active Ripple Filter (CARF). Low risk adaptation of prior Creare/WCS design optimized for the SF070/MCCE-TS combination to provide required bus compatibility.

Each of these components is described further in the sections to follow.

Mechanical Cryocooler – AIM SF070

AIM has been fabricating dual opposed piston linear Stirling coolers for military and commercial applications since 1996. In the beginning, linear compressors featured contact seals and moving coil motors. The mean time to failure (MTTF) of such coolers was initially about 4000 hours and was improved to more than 10,000h through material and process improvements. To further increase MTTF life, the first flexure bearing moving magnet compressor in the OWL (One Watt Linear) class was developed in the early 2000s and started serial production in 2006 [5]. Key advantages of the moving magnet motor designs are placement of the coil outside helium vessel to eliminate outgassing material from coil and coil potting, elimination of moving wire and an electrical feedthrough into the helium vessel.

Besides outgassing, the second major life limiting factor for linear compressors is the wear-out of the piston coating. Flexure bearing support on both sides of the driving mechanism is well-known from the Oxford class space cryocoolers to eliminate the wear out rubbing mechanism of the piston/sleeve assembly. AIM has developed and implemented a flexure suspension system using a computerized alignment process.

To extend the high life time potential of this technology towards more compact coolers, the SF070 compressor was developed as second member of the AIM flexure bearing moving magnet family [6]. The SF070 compressor weight is 850g, and it has a diameter of 44mm and a length of 113mm. Figure 7 shows the SF070 compressor with a 6mm Stirling coldfinger, while typical performance curves are provided in Fig. 8. The SF070 is rated for > 30,000h MTTF. This is well in excess of the HyTI stretch goal of 1 year (8765h), but more importantly, is a strong indicator of the high quality of this cryocooler and thus its support of the Mission Assurance objectives.

Figure 7. SF070 compressor with 6mm coldfinger, which is the HyTI configuration.

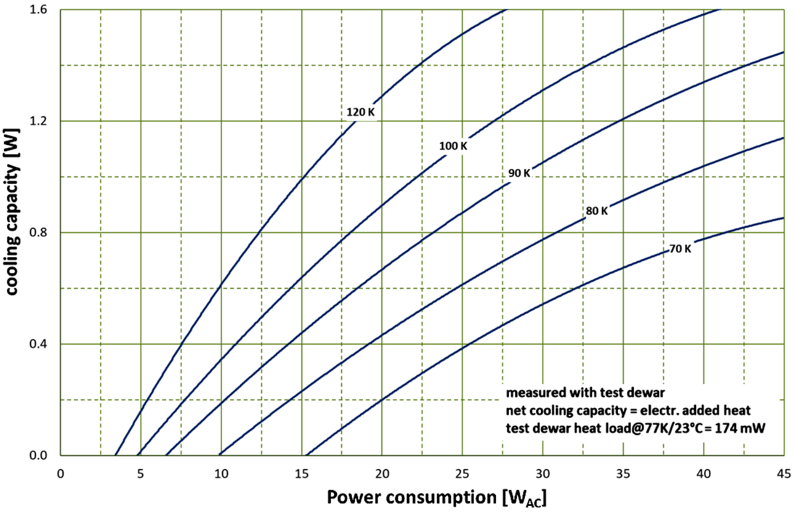


Figure 8. Performance of SF070 w/ 6mm coldfinger at 23°C.

For past programs where exported vibration was a concern, the motors halves have been matched to achieve low exported vibration. By using this method for the substantially larger SF400 compressor (~3kg weight, up to 120W input power), which is in operation on the KompSAT 3A satellite, exported vibration less than 1N at the drive frequency has been achieved, without the benefit of either active vibration cancellation or a passive balancer.

Given the cost sensitivity of HyTI, a different approach was taken. Instead of pairing motor halves, the compressors were down selected from the regular serial production line. The specified cooling performance of 300mW added load at 65K at a reject temperature of 40ºC was experimentally verified in parallel with vibration measurements. The first criterion used for a pre-selection was cryogenic performance. In the first step, 10 coolers were selected for good performance out of serial production, representing the best 40% of the coolers. In a second step, the 10 selected compressors were characterized for exported vibration while operating the cooler at fixed power of $40W_{AC}$. Based on performance and exported vibration, two compressors were selected, with the primary criterion being the lowest vibration. Regenerator (i.e., coldfinger) selection was bases on performance characterization with the selected compressors. The two best out of ten regenerators were chosen. Finally, the selected compressors and regenerators were assembled and tested for their combined performance.

After selection, exported vibration of both units was measured on a Kistler Dynamometer. The results are shown in Fig. 9. Exported vibration in the compressor axis is plotted vs.

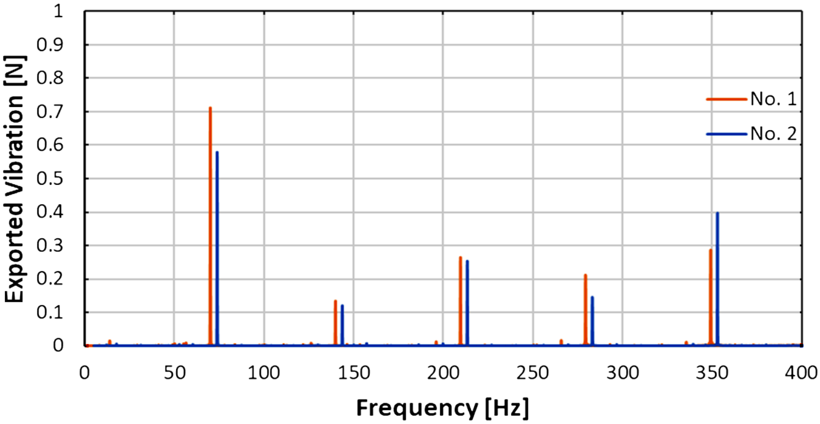


Figure 9. Exported vibration in the compressor drive axis of the two selected HyTI coolers. One flight unit plus one spare delivered by AIM. Coolers #1 and #2 both operated at 65 Hz; Cooler #2 data shifted +4Hz at all frequencies for clarity.

frequency. For clarity in the figure, the frequency for cooler No. 2 is shifted by +4Hz. The measurement was performed with fixed input power of 35WAC at 23°C. The cooler operating frequency is 65Hz. Both coolers achieved the required performance of 300mW@65K at 23℃ reject with < 30WDC input power (to the cryocooler electronics).

Cryocooler Electronics – MCCE and CARF

The MCCE for HyTI is a derivative of Creare's Micro-Cryocooler Control Electronics for Tactical Space (MCCE-TS). Since 1991, Creare has been developing electronics to drive multiple types of cryocoolers, including turbo-Brayton, Stirling, Pulse Tube, and Joule-Thomson varieties. Based on market needs, in 2017 we with our partner, West Coast Solutions (WCS), started development of a linear cryocooler drive that balances cost, size, performance and reliability for cost-sensitive, "tactical space" missions. Most parts were selected to meet EEE-INST-002 Level 3 standards. The result of this effort, the MCCE-TS, was primarily developed on NASA Contract 80NSSC18C0059. The unit is shown in Fig. 10, and the general architecture is shown in Fig. 11. The board mass is 200 grams and the size is 10 cm x 10 cm x 2 cm. These electronics were qualified for space through a combination of performance, thermal and launch vibration testing. Results of performance testing with a Thales LPT9510 cryocooler are shown in a companion paper in this volume (Pilvelait, et. al). The prototype demonstrated 96% conversion efficiency when driving a Thales LPT9510 at 35 W per channel at cold head temperatures as low as 70 K. In addition, we performed EMI characterization tests to guide the optimization of the input ripple filter.

The extremely challenging size target for the HyTI program necessitated an even smaller MCCE. In addition, EMI requirements dictated the inclusion of an input ripple filter on a second board, putting further pressure on the MCCE design to minimize size and mass. To achieve this size and mass reduction objective, we eliminate one of the channels of the electronics and drive both pistons of the AIM SF-070 Cryocooler with a single output channel.

In addition, we developed in collaboration with WCS an active input ripple filter, dubbed the "CARF" (Creare Active Ripple Filter). A prototype of the CARF was built and tested with the MCCE-TS by WCS, first with dummy loads, and ultimately with an SF070 (non-flight unit) provided by AIM; see Fig. 12. All goals were achieved. A 90-92% efficient ripple filter was achieved by implementing a boost circuit with demonstrated operation from 11.7V to 16.0V bus input while outputting a tightly regulated 32Vout. Certified CE101 testing was deemed unnecessary and outside the budget limitations for HyTI, so clamp-on current probes such as shown in Fig. 12 were used to measure AC current ripple across the CARF input to output. An attenuation of 27 dB was measured at ~60W input.

Notably, the complete CARF-MCCE-SF070 chain was operated at full power under MCCE closed loop temperature control at multiple power levels without complication.

Figure 10. MCCE-TS During Integration with CubeSat Frame. The MCCE-TS is a single board assembly designed to fit on a side of a 1U CubeSat.

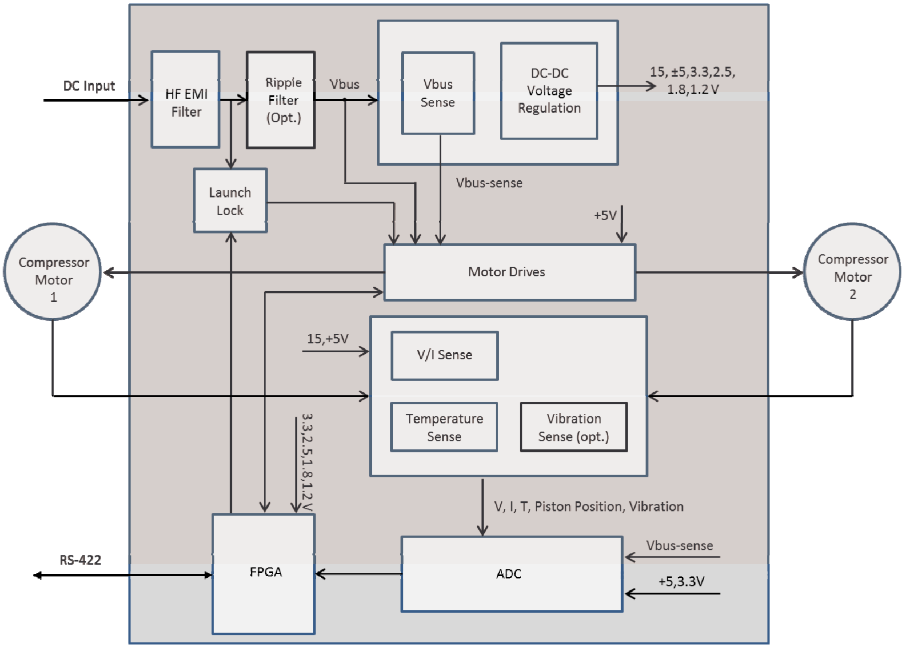
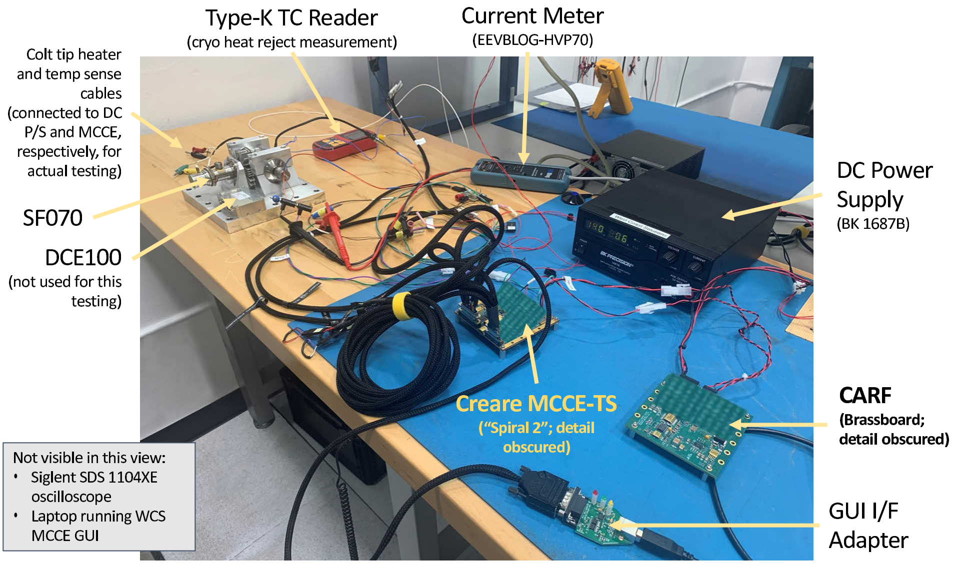


Figure 11. "Standard" MCCE-TS Functional Architecture. The optional Vibration Sense was not required for HyTI, so this functionality was omitted for mass savings. Furthermore, one of the two motor drives was omitted for additional mass reduction.



Not visible in this view:
- Siglent SDS 1104XE oscilloscope
- Laptop running WCS MCCE GUI

Figure 12. Brassboard HyTI Cryocooler System Test at WCS. Laboratory SF070 and brassboard MCCE and CARF modules combined to perform a highly-representative demonstration.

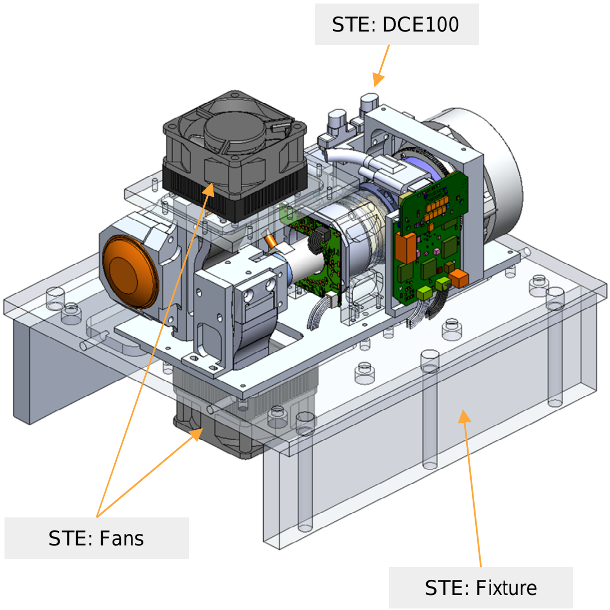


Figure 13. HyTI optical payload in the ground test configuration.

Upcoming Bench Testing of Flight Payload

Bench testing of the payload with the SF070 in its flight configuration is planned for early 2021. Because an IDCA configuration was selected wherein the cold finger and FPA are in a self-contained vacuum dewar, the HyTI optical payload (including the cryocooler) can be fully characterized outside of a vacuum chamber, i.e., on the benchtop. Waste heat from the cryocooler (compressor and expander), as well as that from the payload electronics, is removed with fans at the locations where the spacecraft radiators will reside in flight, as shown in Fig. 13. Apart from the fans and the operation in lab atmosphere, the thermal configuration is fully representative. Flight-design thermal interfaces, thermal interface materials/gaskets, and thermal straps are all implemented.

In addition to the fans and the test fixture that takes the place of the spacecraft bus to support the payload, the other non-flight feature of the test set is the DCE100 cryocooler electronics, which is the AIM COTS module used for non-space applications. Use of the DCE100 allows the early performance of the payload test while the MCCE and CARF remain in fabrication (expected completion date ~March 2021).

Temperature at several points on the instrument will be monitored using thermocouples. Compressor, expander, dewar cap, cryocooler controller, baseplate, lens, lens motor, electronics, and room temperature, etc. will be recorded as function of time. Cryocooler controller power delivered to the compressor and FPA temperature will be monitored and recorded as a function of time using the AIM DCE100 GUI. Full performance testing including FPA temperature control, drift and stability testing will be performed. At the FPA operating temperature, frames are captured at a selectable interval of nominally 10 seconds for one hour, at the minimum. Time series data will be constructed from the captured data and Fourier transforms of the temporal data will be used to quantify the low frequency drift/noise characteristic. In addition, the FPA temperature date can be Fourier transformed to investigate drift and noise characteristic [7].

CONCLUSION AND NEXT STEPS

A complete space cryocooler system consisting of a long-life tactical cryocooler, radiation tolerance control electronics, and an active ripple filter has been designed and is being implemented on a 6U CubeSat hyperspectral spacecraft. Ground testing of the cryocooler system prototype was successfully performed. Flight integration is planned for early 2021 with a target launch date in late 2021.

ACKNOWLEDGMENT

HyTI is funded by NASA's Earth Science Technology Office InVEST (In-Space Validation of Earth Science Technologies) program element (grant number 80NSSC18K1601). The research was partly carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. https://asterweb.jpl.nasa.gov/
2. Wright R, Lucey P, Crites S, Garbeil H, Wood M, Pilger E, Gabrieli A, Honniball C, "TIRCIS: thermal infrared compact imaging spectrometer for small satellite applications," *Multispectral, Hyperspectral, and Ultraspectral Remote Sensing Technology, Techniques and Applications VI* 2016 Aug 19 (Vol. 9880), International Society for Optics and Photonics, p. 98801K.
3.. Crites ST, Wright R, Lucey PG, Chan J, Gabrieli A, Garbeil H, Horton KA, Imai-Hong AK, Pilger EJ, Wood M, Yoneshige L., "The thermal infrared compact imaging spectrometer (TIRCIS): A follow-on to the space ultra compact hyperspectral imager (SUCHI)," *Sensors and Systems for Space Applications VIII* 2015 May 22 (Vol. 9469), International Society for Optics and Photonics, p. 94690R.
4. Wright R, Lucey PG, Crites S, Garbeil H, Wood M., "TIRCIS: Hyperspectral Thermal Infrared Imaging Using a Small-Satellite Compliant Fourier-Transform Imaging Spectrometer for Natural Hazard Applications," AGUFM, Dec 2015:NH53A-03.
5. Rühlich, I., Mai, M., Wiedmann, Th., Rosenhagen, C., "Flexure Bearing Compressor in the One Watt Linear (OWL) Envelope," *Proc. SPIE,* Vol. 6542 (2007), pp. 654221-1 to -7.

6. M. Mai, I. Ruehlich, C. Rosenhagen, Th. Wiedmann, "Development of the Miniature Flexure Bearing Cryocooler SF070," *Cryocoolers 15*, Kluwer Academic/Plenum Publishers, New York (2009), pp. 133-138.
7. S.B. Rafol, S.D. Gunapala, D.Z. Ting, A. Soibel, C.J. Hill, A. Khoshakhlagh, S.A. Keo, A. Fisher, J.K. Liu, J.M. Mumolo, B. Pepper, "Low frequency 1/f noise on QWIPS, nBn, and superlattice focal plane array," *Infrared Physics & Technology* (84) (2017), pp. 50-57.