Thermal Design of the Earth Surface Mineral Dust Source Investigation (EMIT)

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ABSTRACT

The Earth Surface Mineral Dust Source Investigation (EMIT) instrument, designed and built for NASA by the Jet Propulsion Laboratory, will map the surface mineralogy of arid source regions in the visible and short-wave infrared (VSWIR) from the International Space Station. EMIT requires a longlife mechanical cooler that provides cooling at 150 K and a heat rejection system (HRS) that can efficiently absorb, transfer, and reject instrument waste heat to space. The Thermal Control System (TCS) consists of a combination of active and passive components to maintain instrument components within the allowable flight temperature (AFT) limits. The active components include a mechanical cryocooler, heaters, and variable conductance heat pipes (VCHP). The passive TCS include multi-layer insulation, constant conductance heat pipes (CCHP) and coatings. The focal plane array (FPA) and spectrometer are cooled to 155 K and 240 K, respectively, by a single-stage split Stirling linear pulse tube cryocooler (LPT9310), powered by HP-LCCE2 electronics. High performance Pyrolytic Graphite Sheet (PGS) thermal links are used to transport operational and parasitic heat loads from the FPA and spectrometer to the cooler cold tip. This paper provides an overview of the EMIT instrument TCS architecture, cryocooler and instrument/ISS requirements, key design drivers, and top-level thermal design and analysis approach, and reports preliminary test results.

INTRODUCTION

The Earth Surface Mineral Dust Source Investigation (EMIT) is a NASA-JPL instrument designed to measure mineral compositions of the Earth's dust source regions from International Space Station (ISS). EMIT is planned to launch in 2022 on a Commercial Resupply Services 2 (CRS-2) SpaceX Falcon 9 Launch Vehicle aboard the Dragon spacecraft and will be deployed at EXPRESS Logistics Carrier 1 (ELC-1) Flight Releasable Attachment Mechanism 8 (FRAM 8) shown in Figure 1. ELC-1 is a multipurpose platform where scientific activities including Earth observation can be conducted. The EMIT mission life is twelve months plus one month for in-orbit checkout.

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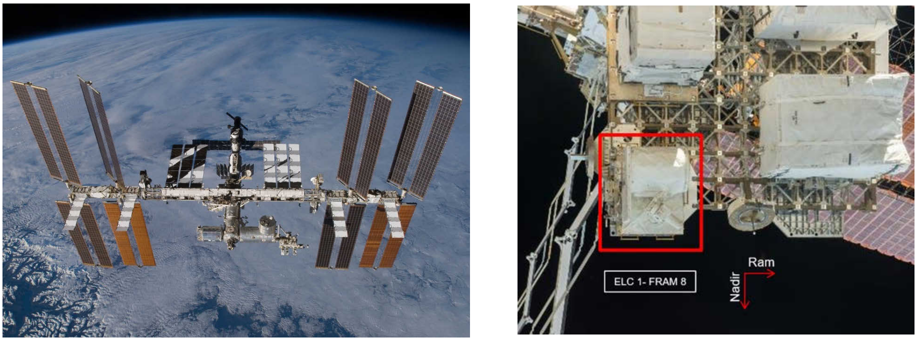

Figure 1. ISS (left) and ELC-1 FRAM 8 external payload attachment locations (right)

The ISS provides latitudinal coverage from 51.6° South to 51.6° North. This unique orbit covers 85% of the Earth's surface and allows EMIT to take observations at different times during each day over the seasons to provide coverage over North and South Americas, Africa, Asia, Australia, and other parts of the world.

EMIT will measure different wavelengths of light emitted by minerals on the surface of deserts and other dust sources to determine their composition. This composition data will advance the understanding of the role of atmospheric dust in Earth's climate and better predict how it can be expected to change in the future [1].

This paper provides an overview of the thermal architecture, requirements and key design drivers, design and analysis approach and reports preliminary test results.

THERMAL ENVIRONEMNTS

The ISS is maintained in a nearly circular orbit with an average altitude of 400 km at an inclination of 51.6° to Earth's equator with an orbit period of ~90 minutes. EMIT will be exposed to extreme hot and cold conditions, the solar cycle and solar events, atomic energy, and high energy radiation [2]. The ISS orbit beta angle will fluctuate from -75° to +75° and at higher beta angles, the instrument will be more exposed to Sunlight per orbit. The Torque Equilibrium Attitude (TEA) on ISS will also vary during mission. EMIT thermal environment parameters are shown in Table 1.

During launch, ISS berthing, and unpowered transfer operation (from SpaceX Dragon to ELC-1), EMIT will be subjected to extreme thermal conditions. Depending on the launch vehicle's flight trajectory and its orientation, the Sun angle (the angle between direction normal to the Zenith plane and Sun vector) can vary from -90° to +90°. Once SpaceX Dragon is berthed to the ISS, EMIT will be transferred from the unpressurized Dragon cargo bay to ELC-1 via ISS robotic arms. EMIT is required to survive 6 hours with no survival heater power during this unpowered transfer.

Table 1- Mission Thermal Environment Parameters

	Cold case	Hot case
Solar Flux (W/m^2)	1321	1423
Albedo (--)	0.22	0.35
EARTH IR (W/m^2)	217	273
Beta Angle (degrees]	-75° to +75°	-75° to +75°

Table 2. Allowable Flight Temperature Limits

	Allowable Flight Temperature (°C)	
Instrument	**Operating**	**Non-Operating**
FPA	150 K to 160 K	145 K to 303 K
Spectrometer	238 K to 242 K	200 K to 303 K
Electronics/Cryo compressor	-15 to 40	-40 to 40
Cryo Expander	-25 to 40	-65 to 40
FPIE-D	-15 to 35	-40 to 40
Telescope	-28 to 27	-60 to 40
Heat Rejection System (HRS)		
Radiator CCHPs	-55 to 40	-72 to 60
EMP	-20 to 40	-55 to 60
VCHPs	-15 to 30	-72 to 50
Enclosure	-70 to 60	-75 to 60
Government Furnished Equipment (GFE)		
FRAM (ExPA)	-92.8 to 126.7	-92.8 to 126.7

Table 3. Key and Driving Thermal Requirements

Description	**Requirement**
Spectrometer spatial gradient	< 6.5 K
Telescope spatial gradient	< 2.5 K
Unpowered transfer survivability	6 hours in any orientation across all possible beta angles
FPA stability	100 mK RMS over any 260s interval (sun-lit)
Spectrometer	240±2 K
Telescope	245-300 K
Cryocooler electrical power	≤70 W
Survival power	66 W in SpX Dragon 80 W at ELC1
Temperature maintenance	Maintain op and non-op AFTs for 13 months
Op heat rejection capability	Up to 225 W at ELC1

THERMAL REQUIREMENTS AND KEY DESIGN DRIVERS

The EMIT thermal design is driven by six key requirements: (1) the FPA temperature must be maintained at 155 K±5 K with a 100 mK RMS stability during any 260 s segment in the sunlit portion of the orbit, (2) the spectrometer temperature must be maintained at 240 K±2 K, (3) the telescope spatial gradient must be less than 2.5 K across the bench, structure, and optics, (4) the instrument must survive 6 hours unpowered during robotic arm transfer between the SpaceX Dragon and the ELC-1, (5) compliance with EMIT environmental requirements document, and (6) the instrument must maintain operational allowable flight temperatures for a 13 month period after initial power on at ELC. The key thermal requirements are listed in Table 2 and Table 3.

THERMAL ARCHITECTURE

The block diagram of EMIT instrument TCS is shown in Figure 2. The TCS is comprised of a combination of active and passive components. The active thermal control systems (ATCS) include mechanical cryocooler, HP-LCCE2, heaters, and a pair of variable conductance heat pipes. The FPA detector and spectrometer are cooled to 155 K and 240 K, respectively, by a single mechanical cryocooler (Thales LPT9310). The passive TCS includes honeycomb panels with constant conductance heat pipes, radiators, blankets, flexible thermal links, aluminum clamp, and coatings. The electronics mounting plate (EMP), VCHPs, reservoir CCHP, and two radiator assemblies constitute the EMIT heat rejection system (HRS). The passive shutoff capability of VCHP is used in the design to decouple the radiator from EMP during 6-hr unpowered transfer.

The parasitic heat load and waste heat from FPA and spectrometer are transferred to cooler cold tip via flexible pyrolytic graphite sheets (PGS) and aluminum foils, respectively. (Both are provided by the Utah State University Space Dynamics Laboratory.) Additional PGS links connect the expander aluminum clamping block to the wake radiator panel for heat rejection. The waste heat from electronics and cryocooler compressor are absorbed by CCHPs on the EMP and transferred to wake side and ram facing radiators by two VCHPs. The telescope is covered in MLI blankets and thermally isolated from surroundings via low conductance bipods.

The enclosure structure is covered in MLI with beta cloth as outer layer. The survival heaters with thermal switches maintain the electronics and cryocooler to their non–operating AFT limits.

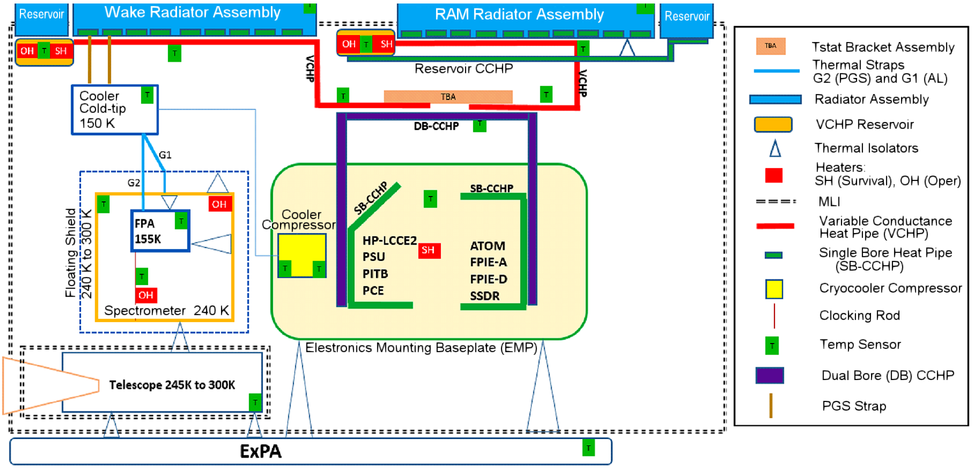

Figure 2. EMIT Thermal Architecture. EMIT instrument electronics include the HP-LCCE2, PSU, PITB, PCE, ATOM, FPIE-A, FPIE-D and the SSDR.

CRYOCOOLER AND ELECTRONICS

The Thales LPT9310 pulse tube cooler (Figure 3) was chosen for the EMIT instrument; the 70 W power limit by EMIT is a small fraction compared to the capability of the cooler. The LPT9310 cooler is cost-effective and space demonstrated. In 2013, the LPT9310 cooler underwent a comprehensive flight qualification test program at JPL [3]. It will provide 155 K cooling to the focal plane while simultaneously cooling the spectrometer to 240 K (three LPT9310 coolers have been used successfully on the JPL ECOSTRESS instrument on the ISS since 2018[4, 5]). The total estimated thermal load on the cooler cold tip is 3.65 watts at 150 K (4.93 W with 35% margin). This requires 56.7 W compressor input power at 40C; the cooler plus electronics consumes 69.2 W. The EMIT power allocation for the cryocooler system is 70 watts.

The compressor is mounted to the instrument EMP, with the expander mounted above the compressor on top of a tripod stand at the level of the spectrometer and focal plane. The focal plane and spectrometer are cooled by the cooler via a bifurcated flexible thermal strap containing Pyrolytic Graphite sheets (PGS) (Figure 4), each appropriately sized to carry the heat from the spectrometer and the focal plane.

The compressor heat is removed via conductive heat sink clamp around the compressor (Figure 5). A mu-metal Magnetic Shield surrounds the cooler compressor to satisfy ISS requirements. Results of the magnetic field attenuation will not be available until early 2021.

Waste heat from the expander is rejected directly to the wake radiator via flexible PGS thermal straps. The thermal strap is designed to remove approximately one half of the 60 W of the cooler input power plus the 4.93 W heat picked up from the pulse tube cold tip.

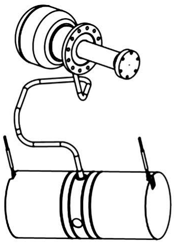

Figure 3. EMIT Cooler

Figure 4. EM PGS flexible link

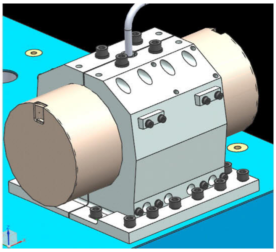

Figure 5. Compressor Clamp

Table 4. HP-LCCE2 Random Vibration Environment

GEVs		HP-LCCE axial		HP-LCCE Lateral	
Freq	**PF/Qual**	**Freq**	**PF/Qual**	**Freq**	**PF/Qual**
Hz	**G^2/Hz**	**Hz**	**G^2/Hz**	**Hz**	**G^2/Hz**
20	0.026	20	0.08	20	0.02
50	0.16	100	0.08	50	0.02
800	0.16	200	0.3	80	0.5
2000	0.026	300	0.3	150	0.5
		2000	0.02	250	0.08
				500	0.08
				2000	0.02
Grms	**14.14**	**Grms**	**13.09**	**Grms**	**11.79**

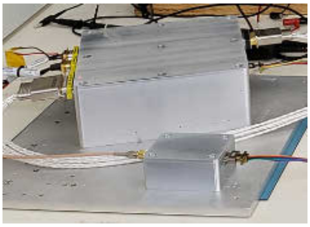

Figure 6. Cooler Electronics HP-LCCE2

During the 6-hour unpowered transfer, the expander gets very cold due to the PGS thermal straps connecting the expander to the cold radiator; thus the expander has been tested to -80°C to demonstrate successful survivability.

The cooler is powered by the Iris Technology 200-watt capable HP-LCCE2 (shown in Figure 6) cooler drive electronics. For the anticipated 58 watts of power delivered to the cooler, the 82 % efficient electronics will dissipate roughly 12 watts internally. The electronics are qualified to TRL 6 on another JPL program [3, 5]. The electronics will be tested to slightly greater thermal and dynamic levels (Table 4 compares the EMIT dynamic levels against the GEVS) for EMIT. The cooler electronics (HP-LCCE2) were also analyzed to RV levels higher than PF GEVS and results showed sufficient technical margins. Flight HP-LCCE2 environmental testing is planned for 1/2021. The small box is the pre-amplifier for an accelerometer for vibration control, which is not expected to be utilized/included in flight.

The EMIT flight cryocooler (Compressor and Expander) was tested to vibration levels shown in Table 5, and the levels are compared to the GEVS. During launch EMIT cooler will be subjected to peak level ~4.4x (for compressor) to ~31x (for expander) higher than PF GEVs at low frequencies. JPL conducted RV testing on the COTS LPT9310 unit as part of risk mitigation activity, first testing the overall cooler to the compressor levels, and then testing the expander only at the coldhead levels. Thales also conducted random vibration testing on the flight compressor and expander components separately due to the very different dynamic conditions on the compressor and the expander. Both COTS and flight cooler components successfully survived the challenging EMIT RV levels.

Table 5. EMIT Cryocooler Random Vibe Environment

GEVS		EMIT Comp Axial		EMIT Comp Lateral		EMIT Cooler Coldhead	
Freq	**PF/Qual**	**Freq**	**PF/Qual**	**Freq**	**PF/Qual**	**Freq**	**PF/Qual**
Hz	**G^2/Hz**	**Hz**	**G^2/Hz**	**Hz**	**G^2/Hz**	**Hz**	**G^2/Hz**
20	0.026	20	0.08	20	0.02	20	0.08
50	0.16	130	0.2	45	0.03	50	0.08
800	0.16	160	0.7	70	0.5	70	5
2000	0.026	250	0.7	150	0.5	110	5
		300	0.04	250	0.04	150	0.25
		500	0.04	500	0.04	375	0.25
		2000	0.01	2000	0.01	2000	0.02
Grms	14.14	Grms	11.77	Grms	10.02	Grms	21.2

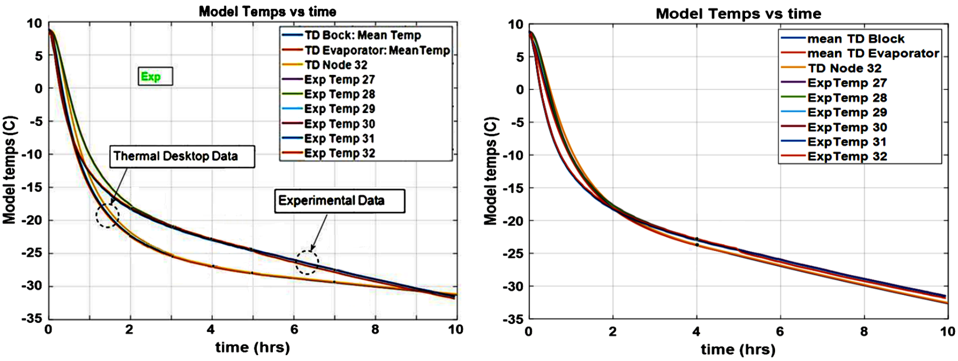

Figure 7. Model simulation vs experiment data comparison of VCHP passive shutoff test. Figure 7(A) shows a comparison of uncorrelated VCHP model predicts vs. experimental data. Figure 7(B) shows correlated VCHP model predicts vs. experimental data comparison.

HEAT REJECTION SYSTEM

The EMIT heat rejection system is comprised of CCHPs, VCHPs, and cross-strapped radiators; it is designed to collect all 225 W of payload dissipation and environmental heating. It is the TCS backbone and interfaces with all dissipating components. The waste heat from all electronics and compressor are absorbed by dual-bore (DB) and single bore (SB) CCHPs on the EMP. The two VCHPs absorb this heat from DB-CCHP and transfers to RAM and Wake facing radiators. The VCHP was chosen to decouple the radiator from EMP during 6-hr unpowered transfer and meets the challenging survival heater power allocation requirements of 66 W (in Dragon spacecraft) and 80 W (at ELC-1). The CCHPs, VCHPs, EMP, and radiator panels, and enclosure panels are all manufactured by Northrop Grumman Space (NGS). A risk mitigation test was performed using a prototype VCHP from the Orbiting Carbon Observatory (OCO) Flight Instrument to confirm the VCHP passive shutoff capability. Test results (shown in Figure 7) indicated VCHP can effectively shut down the radiator with no heater power at the reservoir to minimize heat transfer from the EMP to the radiator panels.

THERMAL MODEL

The EMIT thermal models (Detailed and Reduced) were built in Thermal Desktop (TD) 6.1. The EMP was modelled using tri elements to represent the top and bottom face sheets, quad elements to represent the honeycomb outer side walls, and wedge elements to represent the honeycomb structure. The node density of the honeycomb thickness is simply two nodes coming from each of the two face sheets to minimize node count while capturing the temperature difference across the honeycomb. The node density in-plane of the face sheets is sufficient to

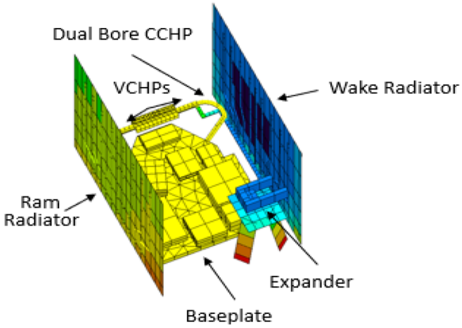

Figure 8. EMP Temperatures: hot operational case at ELC-1 FRAM 8

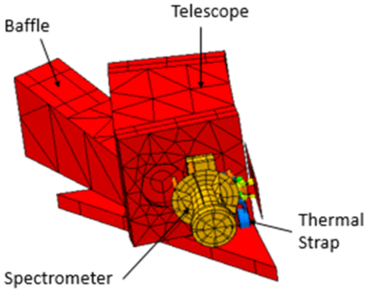

Figure 9. Telescope temperatures: hot operational case at ELC2 FRAM 8

capture gradients and hot spots caused by the ExPA flexures, avionics boxes, and heat pipes. The telescope assembly was modelled using planar surfaces to represent the aluminum outer housing of the telescope, the baffle, and the optical mirrors (see Figures 8 and 9). Finite difference surface primitives were used, where possible, to minimize node count. Irregular surfaces were modelled using finite element techniques. Node sizes were sufficiently small to capture the temperature gradients in the telescope, which would be used later for Structural-Thermal-OPtical (STOP) analysis of Telescope performance. The Telescope support platform was modelled in a similar fashion.

The thermal model was used to predict absolute temperatures, temperature gradients, temperature stability, and heater power use for a range of orbit beta angles in both operating and non-operating states with either maximum or minimum expected environmental fluxes from the sun and Earth. From this data set, the bounding hottest and coldest results were documented, as were the worst temperature gradients and worst orbital temperature stability. The heat loads imposed on the cryocooler cold tip through the thermal strap were also predicted.

Predictions show that all avionics, cryocooler components, telescope and spectrometer, and heat pipes will remain within their AFT ranges for all respective operational and non-operational/survival cases.

All EMIT environments were thermally analyzed, from launch to berthing at the ISS to robotic arm transfer to operation at ELC-1 FRAM 8. In addition to the standard hot and cold operational conditions, the EMIT instrument was analyzed for pitch-yaw-roll (PYR) of the ISS for anticipated TEA variation.

THERMAL INSTRUMENTATION, INSULATION, HEATERS, AND THERMOSTATS

The EMIT instrument is instrumented with three different types of temperature sensors: Rosemount 0118MM series PRTs, Honeywell HRTS-5760 series PRTs, and Heraeus L420 series PRTs. The components within the cryogenic zone (cold tip, telescope, and spectrometer) make use of 0118MM PRTs due to their high accuracy and wide temperature range. The warm zone makes use of the HRTS PRTs. A limited number of L420 sensors are used for survival mode temperature monitoring; they bypass EMIT avionics and go straight through to ISS avionics. The 0118MM PRTs are lot qualified and calibrated directly by Rosemount Aerospace, while the HRTS PRTs are lot qualified and calibrated by JPL; The L420 sensors are GFE.

There are two sets of heater circuits on the instrument: operational and survival. The operational heaters consist of VCHP heaters, spectrometer trim heaters, and Moore-rod heaters. The PID-controlled VCHP heaters exist to turn down the VCHPs during colder operational conditions. Spectrometer trim heaters are similarly PID-controlled and serve to maintain the spectrometer temperatures and spatial gradients during science modes. Both VCHP heaters and spectrometer heaters are Kapton film heaters. The Moore-rod heaters use a Honeywell HRTS temperature sensor as a heater, using this heat to cause a Moore-rod to thermally expand and provide an extra measure of optical tuning while on orbit.

The survival heaters are used to maintain the instrument above non-op AFTs. This is accomplished by both applying heat directly to the EMP, as well as applying heat to VCHPs to force the shutdown of VCHPs and thus greatly restrict heat flow from the EMP to the radiators. Two types of multilayer insulation are used on EMIT: 20-layer with a beta cloth outer layer, and 20-layer with an aluminized Kapton outer layer. The beta cloth outer layer MLI is used to cover the nadir, zenith, and top faces of the enclosure. The aluminized Kapton outer layer MLI is used on various internal components.

SUMMARY/CONCLUSIONS

A thermal control system has been designed to meet the challenging EMIT thermal requirements. A combination of active and passive thermal control systems was employed to maintain the instrument components within the AFT limits. The COTS and flight LPT9310 coolers were tested to random vibration level higher than PF GEVS at JPL and Thales and demonstrated that they can successfully survive EMIT's challenging random vibration environment. Post vibe cooler performance data showed no performance degradation on both coolers. The LPT9310 cooler appears to be very robust and is ideal for missions with high random vibration environment. The IRIS HP-LCCE2 was analyzed to random vibration environment higher than PF GEVS and also showed sufficient technical margins. The implementation of cross-strapped radiator design led to high reliability and robust thermal design. The passive shutoff feature of the VCHPs allowed EMIT to meet the challenging 6-hr unpowered transfer requirement. The system level thermal control system design will be verified in instrument TVAC testing which is planned for late 2021.

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REFERENCES

1. R.O Green et al., "The Earth Surface Mineral Dust Source Investigation: An Earth Science Imaging Spectroscopy Mission," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp 1-15, doi:10.1109/AERO47225.2020.9172731.
2. Finckenor, M. M. and de Groh, K. K., "A Research's Guide to International Space Station," NASA ISS Program Science Publication, NP-2015-03-015-JSC. March 2015.
3. Johnson, D. L., McKinley, I. M., Rodriguez, J. I., Tseng, H., & Carroll, B. A. (2014). "Characterization testing of the Thales LPT9310 pulse tube cooler," *Cryocoolers 18*, ICC Press, Boulder, CO (2015), pp. 125-133.
4. Cha, J., Carroll, B., Rodriguez, J., Maynard, K., & Romero, M. (2020, March). Thermal design and on-orbit performance of the ECOSTRESS instrument. In *IOP Conference Series: Materials Science and Engineering* (Vol. 755, No. 1, p. 012005). IOP Publishing.
5. Arts, R., Mullié, J., Johnson, D., McKinley, I., Rodriguez, J., & Benschop, T., "LPT9310 COTS Cooler for ECOSTRESS," *Cryocoolers 19*, ICC Press, Boulder, CO (2017), pp. 95-103.
6. Frohling, K. (2016). "Characterization Testing of Iris Cryocooler Electronics," *Cryocoolers 19*, ICC Press, Boulder, CO (2017), pp. 361-368.