Ball Verne Cryocooler System Design, Development, and Initial Qualification

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ABSTRACT

Low-cost proliferated cryogenic space payloads are driving use of tactical cryocoolers to meet SWAP-C requirements. Historically tactical cryocoolers have not been considered for space flight due to short MTTF (0.5-1yr) against typical mission lifetimes on the order of 3-5 years. To mitigate reliability concerns, Ball has worked closely with our partners at Sunpower Inc. to develop a very low-cost, turn-key cryogenic cooling system called Verne that is designed for a 3-year mission life. The Ball Verne Cryocooler System includes a TRL6 Low Exported Vibration Cryocooler Assembly (no launch-locks) mated to a TRL8 Sunpower DS-Mini cryocooler, TRL8 Iris Technology ICE-G2 Cryocooler Control Electronics (CCE) and includes a low-cost thermal strap heat rejection system. The Verne system has successfully passed random vibration and Exported Force and Torque (EFT) qualification and has been baselined for a future spaceflight mission. This paper discusses the design, development, and initial qualification of the Verne Cryocooler System.

INTRODUCTION

Historically aerospace cryocoolers have been designed for class A/B missions focused on high reliability (5-10 yr mission life) and high performance that has historically led to high cryocooler sub-system cost. In the past five years there has been industry emphasis on developing more cost-effective active cooling systems that push the state-of-the-art in Size, Weight and Power and Cost (SWAP-C) at a cost point significantly lower than heritage aerospace cryocooler systems. The driving force for lower cost active cooling systems is Proliferated LEO (PLEO) missions, smaller/compact payloads, and Class C missions with lifetimes of 1-3 years. To tackle this challenging problem, tactical cryocoolers are being adopted and qualified for space applications based on their attractive price point, small form factor and readily available industry base to supply in quantity. [1, 2, 3] Challenges with this approach include reducing the Cryocooler Control Electronics (CCE) cost by a similar amount and demonstrating a terrestrial cooler design can be successfully utilized in space applications.

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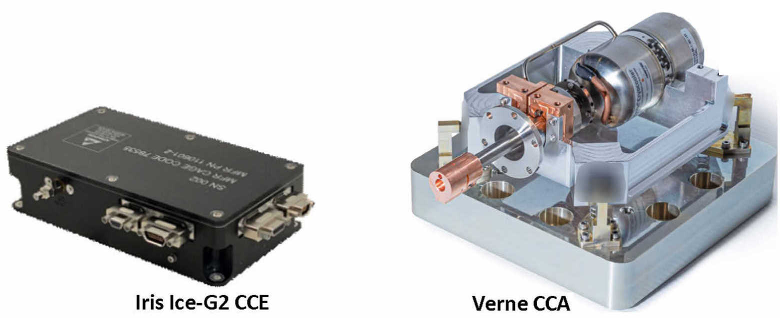

Figure 1. Ball Verne Cryocooler System that consists of (Left) Iris Ice-G2 Cryocooler Control Electronics, and (Right) Low-cost, Low-Vibe non-launch locked CCA with Sunpower DS-Mini TMU. Image blur is intentional to protect proprietary information.

For the past five years Ball has been focused on developing low-cost next generation active cooling solutions in collaboration with our partners at Sunpower Inc., Technology Applications Inc. (TAI) and Iris Technology. The lowest SWAP-C output of this effort was completion of an internal IRAD program that developed the Ball Verne Cryocooler System – a turnkey, very low-cost, cryogenic cooling system illustrated in Figure 1.

VERNE CRYOCOOLER SYSTEM DESIGN AND DEVELOPMENT

The Ball Verne Cryogenic System consists of the following integrated component technologies:

- Low SWAP-C Sunpower DS-Mini cryocooler (TRL8) using a passive balancer for vibration cancelation of the displacer,
- Ball very low-cost, Low Vibe CCA (Cryocooler Assembly) (TRL6)
- High conductance, low stiffness thermal straps for heat rejection from TAI (TRL6)
- Reduced form factor CCE (Cryocooler Control Electronics) from Iris Technology (TRL8)
- Complete set of flight harnesses

The remainder of this section discusses these various components in addition to the system level assembly.

Sunpower TMU

The Sunpower DS-Mini TMU was selected based on very small form factor, high thermodynamic performance, configurability with respect to performance and physical packaging, gravitational performance independence, and well-established space flight heritage of the fundamental cooler technology via the Sunpower MT/CT product lines. The DS-Mini Stirling cryocooler directly leverages the Sunpower CT/GT/MT product lines but uses an opposed piston compressor in place of the heritage single piston compressor on the CT/GT/MT models. The DS-30 displacer is a free-piston Stirling design that uses a passive balancer to attenuate the displacer free-piston vibration during operation

The Sunpower DS-Mini TMU and thermodynamic performance for heat lift as a function of cold tip temperature and input power is shown in Figure 2. The only changes required for a spaceflight version of the commercial DS-Mini TMU are custom-tailored build processing developed in collaboration with Sunpower.

Two high risk areas in adapting a tactical cryocooler, such as the DS-Mini, to space applications are: surviving launch/shock vibration environments and ensuring the Exported Force and Torque (EFT) is suitable or able to be attenuated to acceptable mission levels. In development of the Ball Klondike Cryocooler System these risks were mitigated through specific component level tests. In the case of the DS-Mini, no testing was performed at the component level. Surviving random vibration was deemed low risk for the DS-Mini due to the innovative isolation system discussed later in this paper. EFT performance was also deemed low risk due to the small size and low input power level of the DS-Mini TMU.

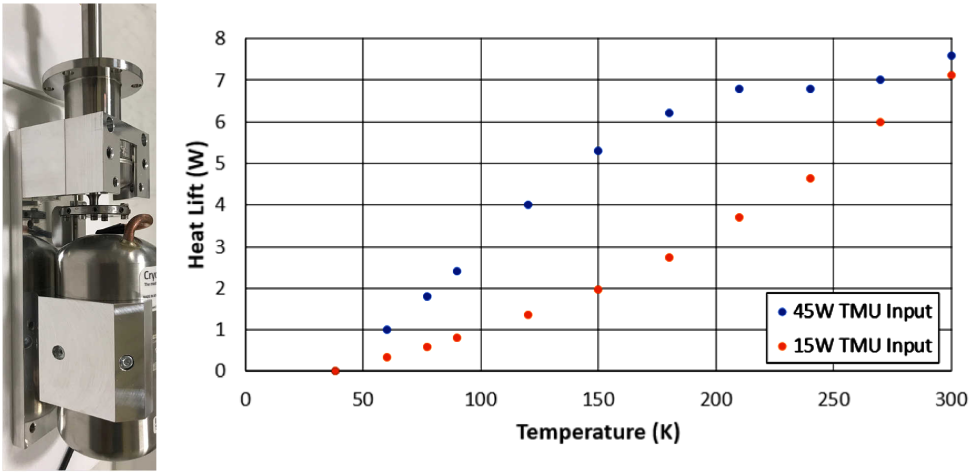

Figure 2. (Left) Sunpower DS-Mini TMU and (Right) DS-Mini Heat lift as a function of cold tip temperature and input power.

IRIS CCE

The CCE used to power the DS-Mini TMU is the next generation Iris Technology Ice-G2 electronics shown in Figure 3. The Ice-G2 electronics are TRL8 and capable of a maximum output power of 60W across two motor drives, active vibration cancellation for the first 5 harmonics, and possesses a very compact form factor and low mass (<800 grams). An additional key discriminator is Ice-G2 leverages GaN FET technology that reduced the size and form factor from their heritage LCCE electronics. These electronics are low-cost and have lead times compatible with 18-24-month concept to launch missions. The Iris Ice-G2 BOM is compatible with NASA Mission Class C requirements.

Verne Low Vibe Isolation Assembly

Ball Aerospace has had multiple jitter sensitive programs and applications that require very low levels of cryocooler generated EFT. Ball heritage Low Vibe CCA's significantly attenuate the already low EFT output a TMUs approximately 50:1 compared to the original EFT from the TMU. Details of Ball Low Vibration CCA heritage and performance can be found in Reference [4].

In many low-cost missions the EFT requirements are relaxed allowing for use of less sophisticated attenuation systems. In collaboration and partnership with Sunpower (cryocooler suppliers), and TAI (flexible link supplier), Ball has leveraged our low vibration CCA expertise to rapidly design, build, and test the Verne CCA - a very low-cost and minimal part count non-launch locked low vibration CCA for space and airborne applications. In the development of the Verne isolation system we were targeting an EFT attenuation of >20:1.

Figure 3. IRIS Ice-G2 low-cost cryocooler control electronics used in the Verne Cryocooler System.

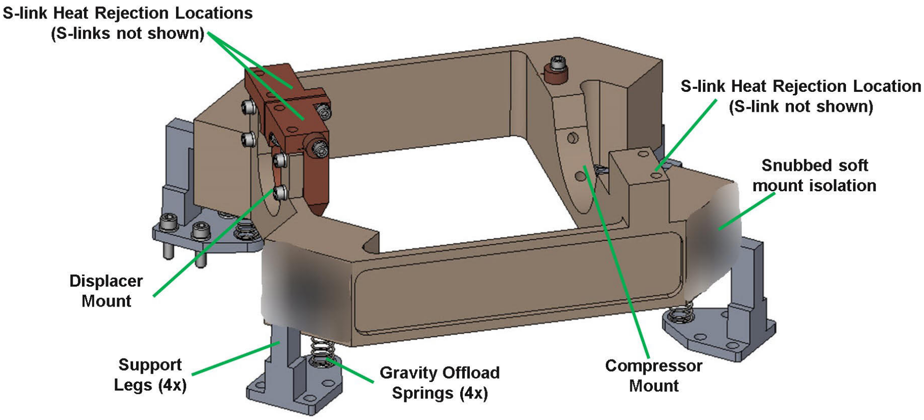

Figure 4. Verne Low Vibe CCA plate for the DS-Mini TMU. Image blur is intentional to protect proprietary information..

The Verne CCA is a new Ball low vibe CCA design that focuses on small volume, low mass and EFT attenuation levels compatible with coolers producing up to 15N of exported force. The Verne CCA plate, shown in Figure 4, is a very simple aluminum structure that has saddle mounts for the DS-Mini displacer and compressor. These mounts also serve as the conductive thermal interfaces from the TMU components to three heat rejection interfaces. Heat rejection from the CCA plate occurs at the three interfaces to high compliance and high conductance thermal straps that would terminate to the payload or space vehicle heat rejection system. Vibe and EFT attenuation occurs at the four corners of the CCA plate through use a new and novel snubbed isolation system that eliminates the needs for a launch lock. The entire CCA plate and isolation system is mounted at the base through four aluminum arms/posts.

Verne CCA

The Verne CCA is the integration of the isolation assembly, DS-Mini TMU, flight harnesses (not shown), and S-link heat rejection system (not shown). The deliverable Verne flight CCA is shown in Figure 5. Mass breakdown of the Verne CCA, CCE and peripheral components is summarized in Table 1.

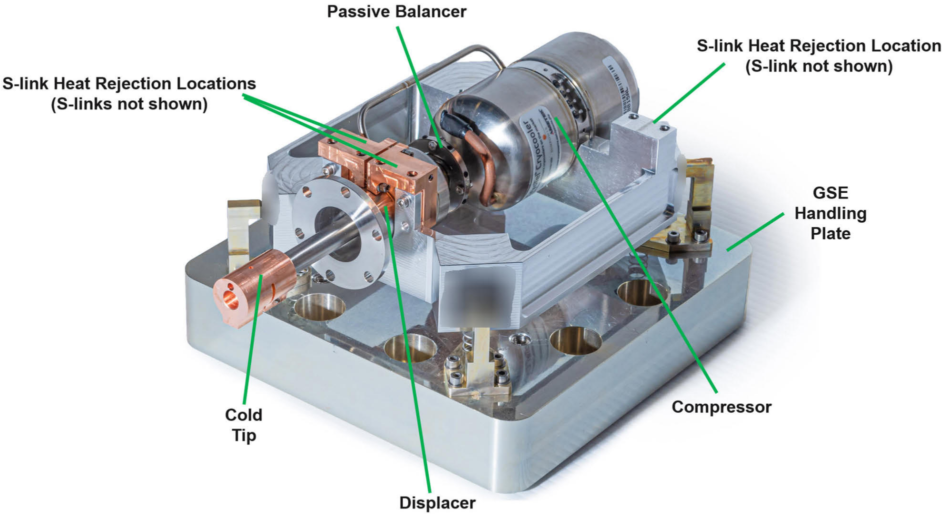

Figure 5. Ball Verne very low-cost, low vibe CCA. Image blur is intentional to protect proprietary information.

Table 1. Ball Verne Cryocooler System mass allocations.

Summary Table

Subassembly	Component	Mass (lbs)	Mass (kg)	Basis
CCA with TMU	TMU (DS-Mini)	3.10	1.40	As measured
	Low Vibe CCA Platform	1.20	0.54	As measured
	Thermal Links	0.50	0.23	Design
	Subtotal	4.80	2.17	As measured
CCA with TMU and CCE	CCE	1.76	0.80	NTE
	Subtotal	6.56	2.97	NTE
CCA with TMU, CCE, Link	Thermal Link	0.22	0.10	Design
	Subtotal	6.78	3.07	NTE

VERNE INITIAL FLIGHT QUALIFICATION

Iris CCE random vibration testing is being performed to acceptance levels based on heritage flight program PSD levels that were deemed bounding for present and future Verne applications.

The DS-Mini TMU random vibration setup and PSD protoqual levels are shown in Figure 6. GEVS 14.1 GRMS protoqual levels were utilized as it envelopes most launch vehicle – spacecraft combinations. It was predicted the GEVS environment would be significantly attenuated by the isolation system and not risk the cryocooler. A 1 G sine sweep from 5-100 Hz was considered but tabled pending further information regarding an actual launch environment as this is expected to be a more severe load case than GEVS for this type of assembly. A 0.25 G sine sweep was performed versus a standard 0.1G sine sweep as this elevated level would produce considerable excitement of the isolated system to better predict the sine environment response at higher flight levels. Heat rejection S-links (3x) were installed and attached to a non-flight chiller plate and ground-attached frame that accurately represents the "fixed" end of the S-links in a flight application. The cold tip had a 56-gram heater block installed. This load is enveloping for a cold tip S-link, the flight S-link is expected to have a half-mass of around 35 grams.

Frequency (Hz)	ASD Level (g^2/Hz) Qualification	ASD Level (g^2/Hz) Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

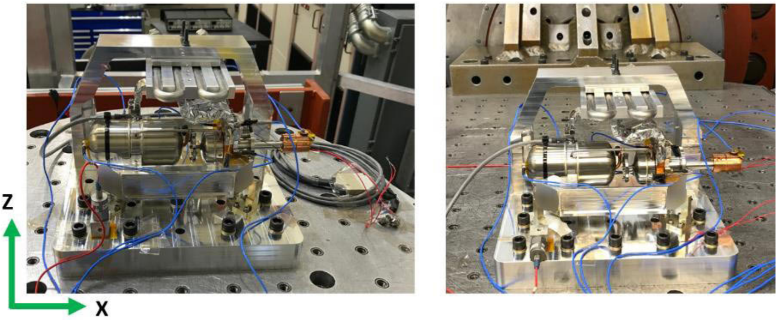

Figure 6. (Top) GEVS Protoqual PSD levels used for random vibration testing, (Bottom) Verne CCA random vibration setup and loading axes. Image blur is intentional to protect proprietary information.

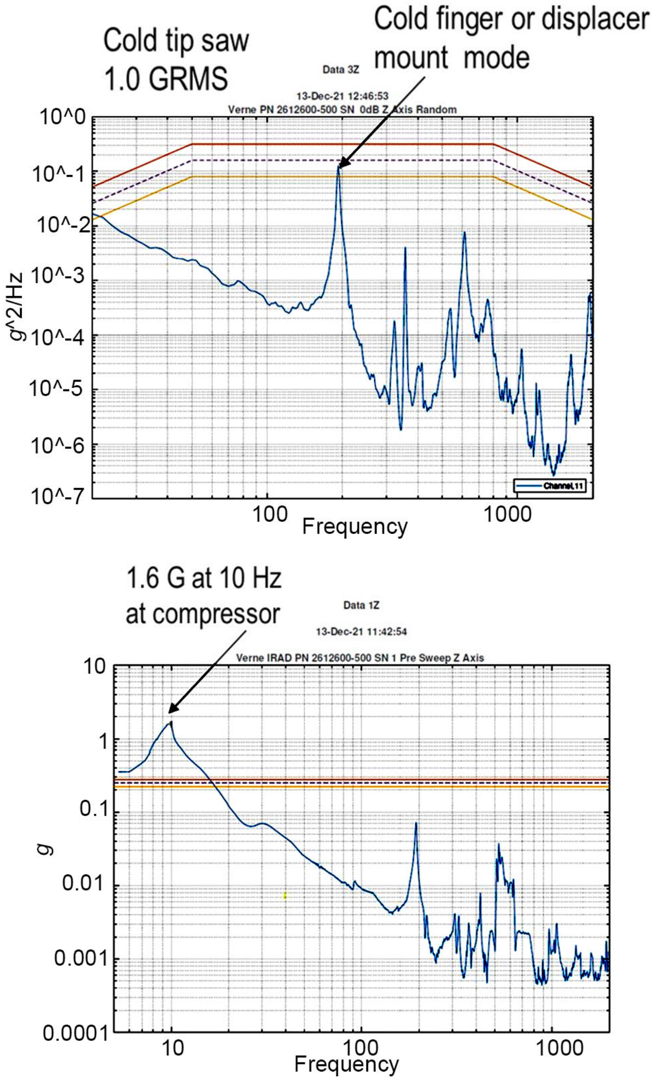

Figure 7. (Top) Random vibration results for the stressing case on the Verne CCA, and (Bottom) 0.25 G sine sweep results for the stressing axis on the Verne CCA.

Selected results from the random vibration and elevated sine sweep is shown in Figure 7. The isolation modes of the platform performed as expected and make random vibration extremely benign at the cryocooler as shown in Figure 7. Attenuation of the GEVS 14.1 GRMS base input was approximately 14X.

As expected, sine input is the worst environment for the Verne low vibe isolation system. Accelerations on the platform exhibited a gain of 3-6X. We expect this gain factor to decrease slightly as sine input levels increase based on prior similar tests. The heat rejection S-links (3x) survived the sine deflections without any indications of MLI or thermal link layer failure. The DS-Mini passive balancer saw minimal excitation during sine sweep and random vibe. The cold tip loads, the often-stressing case, were very benign. This coupled with the test simulated thermal strap mass is not a concern for the cold finger in random vibration. However, the sine environment will define the limit for the maximum strap mass, but we expect the as-tested 52-gram mass covers the expected mass of S-links that would be considered for this application

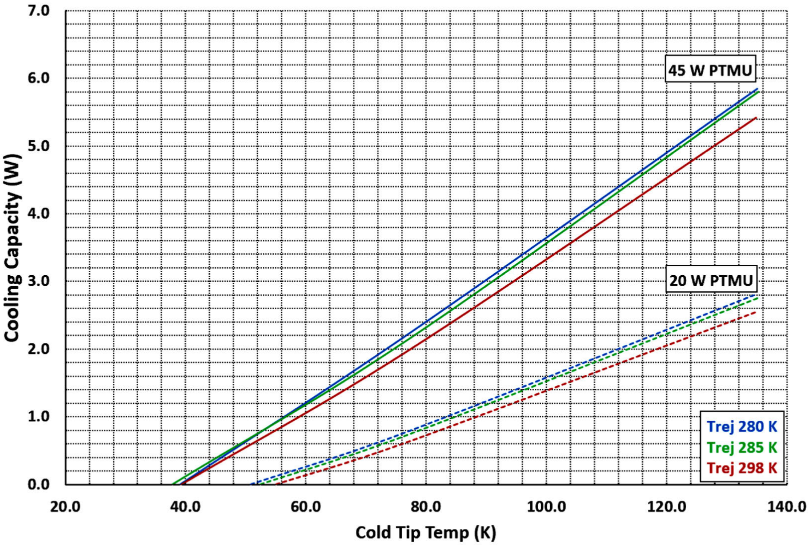

Figure 8. Verne DS-Mini thermodynamic performance for heat lift as a function of cold tip temperature, TMU input power and heat rejection temperature.

VERNE SYSTEM LEVEL PERFORMANCE

The Verne Cryocooler system thermodynamic performance has been characterized at the cooler level during the flight build process. Cooling performance, shown in Figure 8, was characterized as a function of rejection temperature, TMU input power, and cold tip temperature. Overall measured performance is excellent and exceeds published performance specification above 80 K.

EFT testing of the Verne system was performed at Ball using high-fidelity EFT test facilities. EFT data was extracted for the mechanical interfaces of the Verne System: thermal strap heat rejection interface and base interface. Isolation of the heat rejection EFT path was performed by connecting the mechanical interface to the dynamometer or off-loading the path from the dynamometer. The EFT test setup for the Verne Cryocooler System is shown in Figure 9.

EFT results are shown in Figure 10 for: 1) Hard mounted configuration where the isolation system is shunted to ground, 2) base and heat rejection paths tied to the dynamometer, 3) off-loading the heat rejection path, and 4) EFT transmission through the heat rejection path.

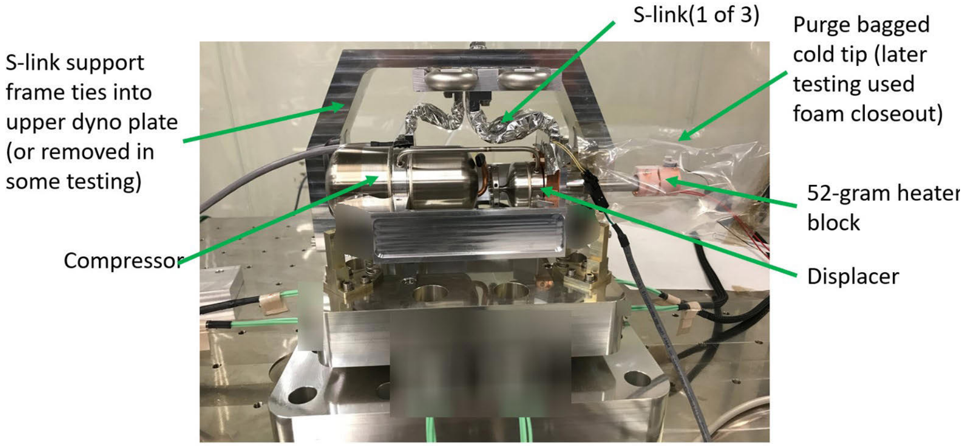

Figure 9. Verne EFT testing setup.

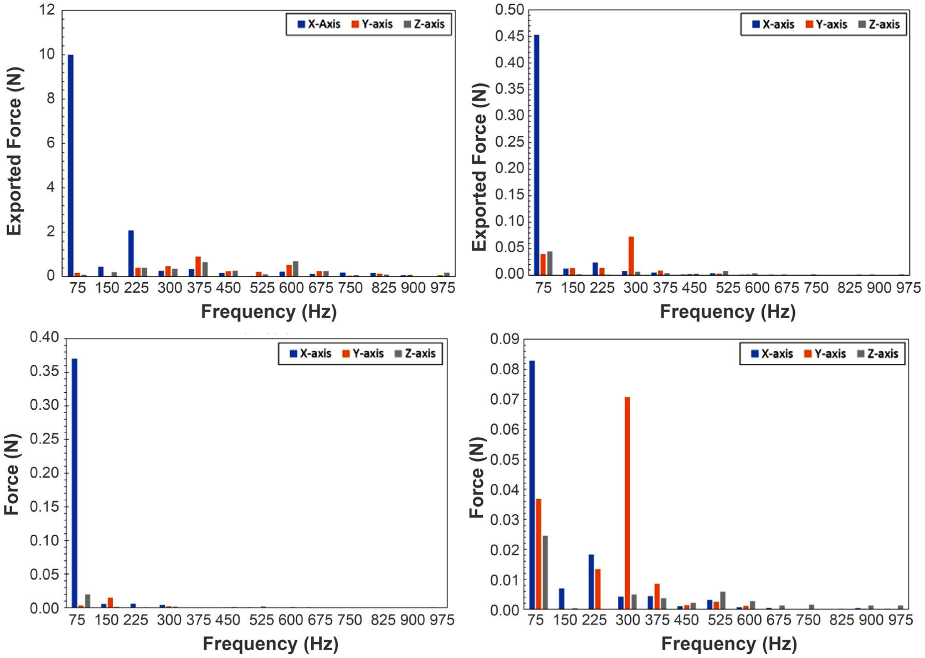

Figure 10. Verne EFT performance at the mechanical interfaces to the system for 130 K cold tip temperature and 35 W TMU input power for: (Upper Left) Hard mounted configuration where the isolation system is shunted to ground, (Upper Right) base and heat rejection paths tied to the dynamometer, and (Lower Left) off-loading the heat rejection path, and (Lower Right) EFT transmission through the heat rejection path.

The EFT test results show the Verne CCA attenuation is 27:1; roughly 50% lower than heritage Ball Low Vibe CCA**.** It should be noted the EFT performance is not optimized due to passive balancer non-axial motion that was noticed using high speed video during test**.** We expect the EFT performance to improve when a better tuned balancer is available with the flight TMU. EFT testing also showed successful demonstration of attenuation of the TMU exported force through the heat rejection path**.** The heat rejection path exported force is ¼ the overall exported force (82 mN)**.** Full EFT characterization to include active cancellation and a better tuned passive balancer is planned once the Flight TMU and CCE are available at Ball in late 2022.

CONCLUSIONS

The Ball Verne product represents a leap forward in SWAP-C optimized active cryogenic cooling technology available to the space community. Verne is designed for and enables very low-cost missions while preserving or exceeding the thermodynamic performance of larger and more costly heritage aerospace cooling systems. The Ball Verne Cryocooler system has successfully passed initial random vibration qualification and the initial flight unit will be subjected to full flight qualification after delivery to Ball in late 2022.

ACKNOWLEDGMENT

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