Linear Cryocooler Electronics for Tactical Space Missions

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ABSTRACT

Many future space science and military missions will utilize small spacecraft, and many of these missions will require cryocoolers for cooling electro-optical payloads. For Class C and D missions, the cryocooler technical requirements for performance, size, and mass, coupled with the programmatic requirements for minimal cost and development time, are extremely challenging. Flight-ready cryocoolers and associated control electronics developed for traditional satellites do not meet these technical, cost, or schedule requirements for future small space platforms. Creare, with our partners from West Coast Solutions (WCS), have recently developed and qualified low cost cryocooler control electronics for linear cryocoolers. These electronics leverage technologies and capabilities that were demonstrated on prior programs. This paper provides an overview of the design, qualification results and initial performance testing with a commercially available tactical cryocooler.

INTRODUCTION

Since 1991, Creare has been developing Micro-Cryocooler Control Electronics (MCCE) to drive multiple types of cryocoolers, including turbo Brayton, Stirling, Pulse Tube, and Joule Thomson varieties. Our MCCE products which support linear cryocoolers include three primary variants, tailored for commercial, tactical space, and radiation hardened space applications with correspondingly increasing levels of quality assurance, reliability, radiation hardness, and cost.

This paper describes development and testing of the tactical space version (MCCE TS) on NASA Contract 80NSSC18C0059. The MCCE-TS variant shown in Figure 1 is a derivative of our MCCE COM (commercial) and MCCE RH (radiation hardened) variants. Falling between MCCE COM and MCCE RH in terms of reliability, radiation hardness, and cost, the MCCE TS is intended for radiation tolerant, low cost space missions where commercial electronics are not suitable. These electronics are being developed with our partner, West Coast Solutions, for NASA's Class C/D missions.

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Figure 1. MCCE TS during integration with CubeSat frame. The MCCE TS is a single board assembly compatible with CubeSat and other space vehicle configurations.

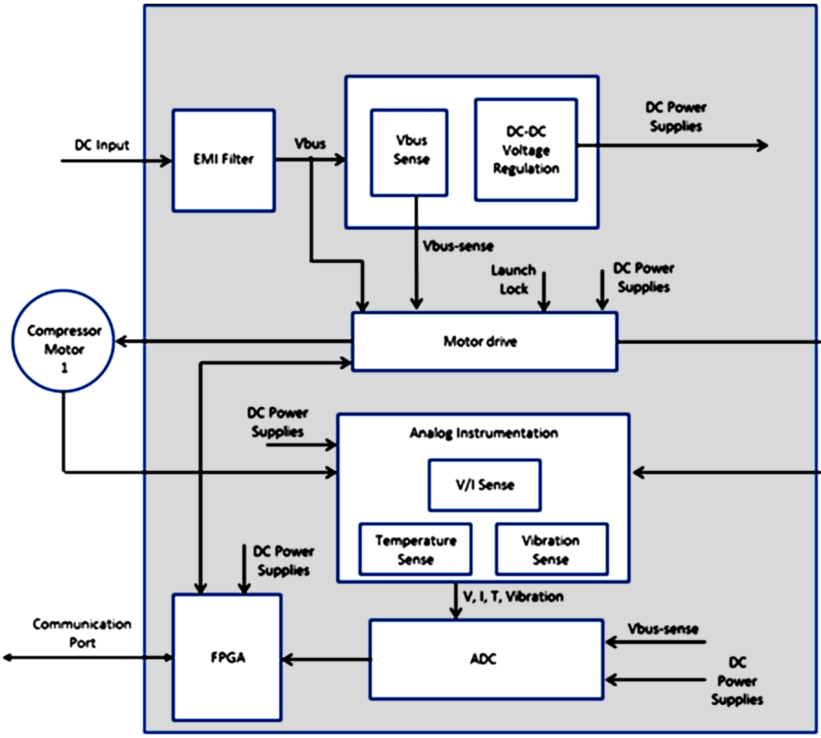

Figure 2. MCCE TS functional architecture.

The architecture is shown in Figure 2 and important characteristics are shown in Table 1. The electronic components have been selected through consultation with subject matter experts at WCS and the Institute for Space and Defense Electronics (ISDE) at Vanderbilt University. Most components meet EEE INST 002 Level 3 standards where non Level 3 parts comprise magnetics we expect to be accepted for NASA Class C missions through a parts review board. The unit is designed for current levels up to 4 ARMS per channel and can drive linear cryocoolers with total maximum AC input power of up to 200 W.

Table 1. Summary of MCCE-TS Specifications.

Input Voltage	28 VDC nominal, 22 VDC – 36 VDC unregulated
EMI	MIL-STD-461, optional input ripple filter for low CE-101
Max AC Output Current	8 ARMS (2 channels @ 4 ARMS per channel)
Max AC Output Power	150-200 W (2 channels @ 75-100 W per channel at 28 VDC input voltage) depending on cryocooler impedance
CCE Thermal Management	Conductive cooling
Size (including chassis)	670 cc w/o ripple filter
Mass (including chassis)	630 grams w/o ripple filter
Operating Temperature Range	-40ºC to 71ºC (depends on heat rejection surface temperature)
Parts Quality	EEE-INST-002 Level 3 or best commercial practice
Radiation Hardness (TID)	Suitable for two-year LEO mission
Radiation Hardness (SEL)	Suitable for two-year LEO mission
Reliability (MIL-HDBK-217)	>96% for two-year mission
Active Vibration Control	Optional for closed loop
Command and Control	RS-422
Programming	Hardware Description Language (HDL) firmware
Temperature Sensors	PRT or other nominal 100 Ω sensor
Control Temperature Range	50 K to 200 K
Temperature Control	+/- 0.1 K
Temperature Accuracy	+/- 1 K from 70 K to 150 K

CRYOCOOLER SYSTEM TESTING

This section summarizes characterization testing using a combination of a Thales LPT9510 cryocooler driven with Creare's MCCE-TS. Critical metrics include minimizing average input power consumption while providing adequate output power to the Thermo-Mechanical Unit (TMU) to achieve greater than 2.5 W of cooling at a cold tip temperature of less than 130 K and expander rejection temperature of greater than 35°C.

The MCCE-TS was configured to drive the LPT9510 under representative thermal conditions (35°C heat rejection, 2.5 W of lift). After allowing the cryocooler to cool to cryogenic temperature in a zero lift configuration with up to maximum available power, 2.5 W of lift was applied to the cryocooler thermal interface in a sequence of 0.25 W steps. During this test, the interface temperature, input voltage and current, output voltage and current, and the applied thermal interface power were measured. From these data, estimates of the converter efficiency and the cooldown performance were compared to cryocooler performance estimates.

Testing was conducted with the MCCE-TS electronics installed on a cooling plate via the thermomechanical mounting rails, as shown in Figure 3. The cooling plate supplies both mechanical support for the electronics as well as conductive thermal management. The LPT9510 is installed in a cryostat providing interface temperature (via PRT), a thermal mass, and an external heater for applying heat to the cold interface of the LPT9510. The cryostat also provides a vacuum enclosure for the cryogenic components, mechanical supports for thermal interfaces, and a thermal mass simulating the system interface. An external circulating chiller maintained the electronics baseplate, compressor housing, and the expander throat at a temperature of approximately 35°C. To reduce parasitic heating of the thermal interface in the cryostat, it is

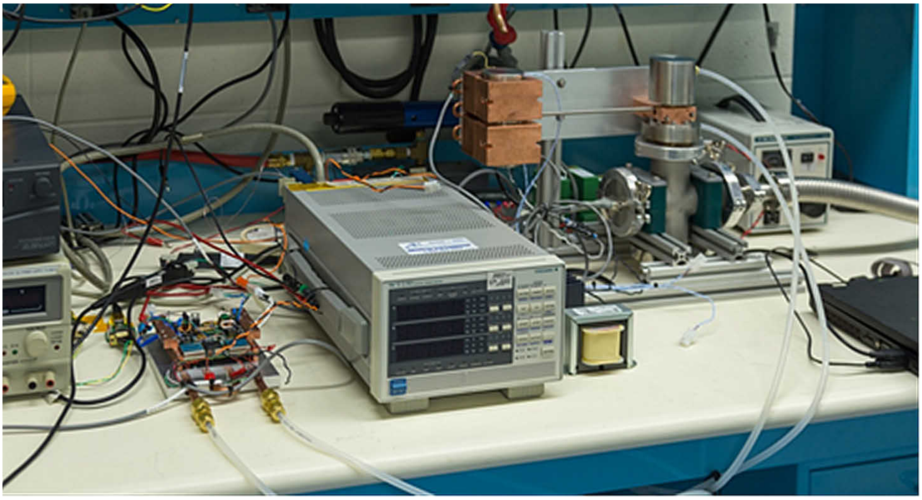

Figure 3. MCCE TS electronics and LPT9510 in test fixture with Cryostat.

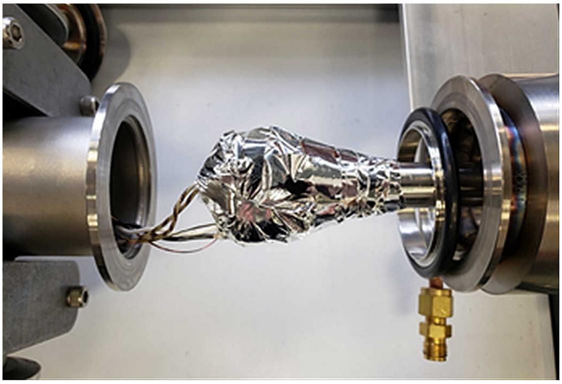

Figure 4. LPT9510 with MLI applied prior to final assembly of the Cryostat.

necessary to provide insulation of the cold tip. The resulting Multi-layer Insulation (MLI) jacketed cold stem is shown in Figure 4.

For this test, a circulating flow was maintained with a setpoint on the chiller to establish a rejection temperature of approximately 35°C. The LPT9510 cryocooler is designed to operate at 45 Hz with input voltages up to 12 V_{rms}. The MCCE communication interface defines the MCCE-TS output frequency and voltage as a peak magnitude, offset, and frequency, and can be adjusted independently for each of the two drive channels for exported vibration suppression.

Maximum cooling was initiated by allowing both drive channels to increase consumed power to the point where the minimum achieved temperature was 68.3 K and the maximum input power was 66 W. At approximately 30-minute intervals, an additional 0.25 W of heat load was applied until a maximum of 2.5 W was achieved. The MCCE-TS operated at maximum available electrical power to cool the cold tip to the minimum achievable temperature at each heat load setting.

The test results are shown in Figure 5, and the performance data points are summarized in Table 2. Throughout the test, the MCCE-TS efficiency was 94–95%. The results demonstrate the MCCE TS and LPT9510 are capable of meeting the required performance metrics with margin, where the metrics are minimizing average power consumption while providing adequate output power to the Thermo-Mechanical Unit (TMU) to achieve greater than 2.5 W of cooling at less than 130 K (actual cold tip temperature was 117 K) and expander rejection temperature of 35°C.

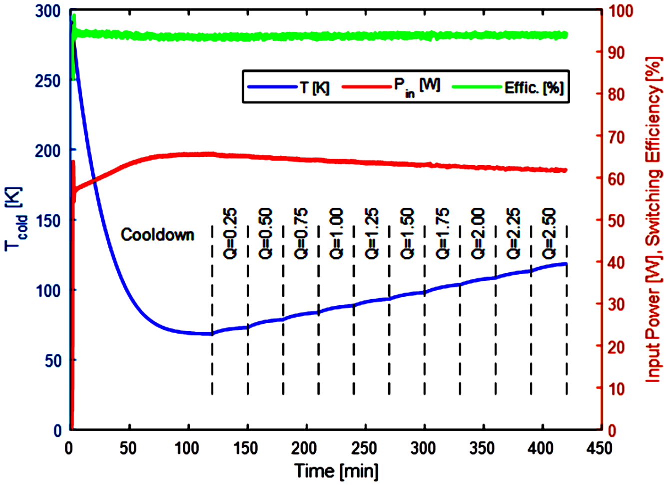

Figure 5. Test results using MCCE-TS and LPT9510.

Table 2. Summary of Actual Performance Test Data.

Parameter	Value
Minimum Temperature (no heat load)	68.3 K
Maximum Required Input Power	66 W
Input Power at 2.5 W Heat Lift	62 W
Efficiency at 2.5 W Heat Lift	94%
Heat Rejection Temperature	35°C

VIBRATION TESTING

This section describes the structural characterization and qualification test results for the MCCE-TS. The overall goal of these tests was to demonstrate capability of correct operation after exposure to defined typical random vibration spectrum associated with space launch. The MCCE-TS vibration test fixture is shown in Figure 6. The test configuration for the Z axis excitation is shown, and the other excitation axes were similar in configuration.

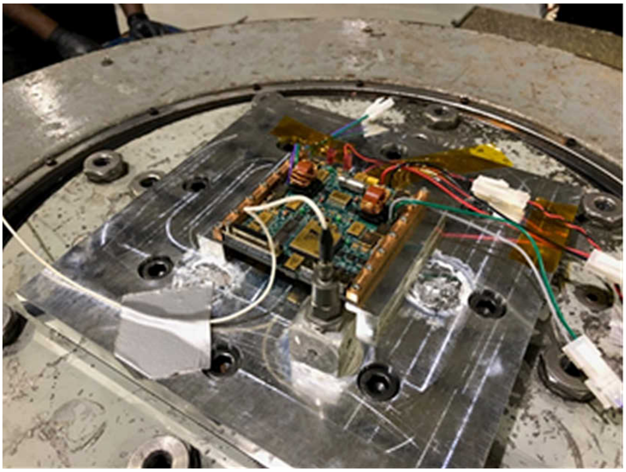

Figure 6. MCCE-TS Assembly mounted on T 1000b Shaker Table, Z axis excitation.

Table 3. Defined Vibration Spectrum APSD.

Frequency (Hz)	Amplitude (G^2/Hz)
20	0.026
50	0.16
800	0.16
2000	0.026

Table 4. Generalized Random Vibration Test Levels for Components (ELV) 22.7 kg (50 lb) or less

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	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}

The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800\ Hz)}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800\ Hz)}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).

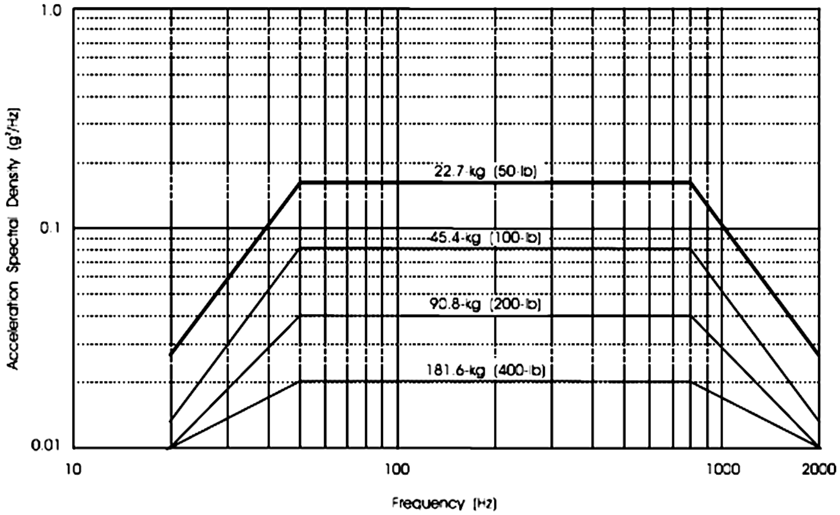

Figure 7. Spectral Density plots of GEVS generalized random vibration test levels.[1]

Prior to testing, overall function of the MCCE-TS was verified to establish a baseline for comparison. The test spectrum was applied at the desired GEVS level for three minutes for the Z, Y, and X axes. Tables 3 and 4 and Figure 7 provide pertinent test condition data.[1]

Accelerometer instrumentation included the usual feedback transducers installed on the shaker table, plus an additional PCB 339A31 tri axial accelerometer mounted at the location of the central mounting hole to characterize the response spectrum of the PCB. To monitor correct function of the MCCE-TS, a combination of a Tektronix TCPA300 current probe and a Tektronix TDS2004C oscilloscope was used to verify the current waveform delivered by the board.

During each test, the unit under test was observed for large deflections or mechanical ringing. None were observed. After each test, the unit under test was inspected for evidence of damage. Each of the large components such as the chokes was mechanically wiggled to verify that their component mounting was secure. No cracking, loosening, or other indication of mechanical failure or fatigue was observed. By connecting an impedance meter to each choke's output terminal and measuring choke resistance and inductance the inductance was verified to be unchanged from the default values after the test. For the final data point the Operational Verification was completed while the system was under test (a functional vibration test). Overall, no failures, changes in electrical properties, or generated waveforms were observed.

EMI/EMC TESTING

The MCCE-TS was characterized in accordance with MIL-STD-461G EMI/EMC requirements to establish baseline performance for specific missions. Current performance is adequate for many missions including some Class C and Class D missions, although optional enhancements such as electrical filter or mechanical vibration control modules may be advantageous for other missions. Quantifying baseline performance informs the design enhancements needed for specific mission needs. Importantly, there were no susceptibility performance issues observed within the tested parameter range for CS101 and RS103.

CONCLUSIONS AND FUTURE WORK

Creare has developed a family of microcryocooler control electronics product offerings to satisfy a range of performance and cost needs for commercial, military, aerospace and space customers. In this paper the characteristics of the mid-range, tactical space product offering (MCCE-TS) were described, along with characterization and qualification testing results. Functional performance demonstrated 2.5 W of cooling from an LPT9510 cryocooler with 39.6 W delivered to the cryocooler and 46.3 W of input electrical power from the DC power source with 21–23°C heat rejection surface. Vibration and EMI qualification tests were conducted to quantify performance for typical Class C and Class D space missions. The results show that this mid-range product meets typical performance metrics and can be used to provide cryocooler control electronics at reasonable cost.

ACKNOWLEDGEMENT

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