Integrated Cryocooler Assemblies for Miniature Satellite Applications

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ABSTRACT

The Microsat Cryocooler System (MCS) and Cubesat Cryocooler System (CCS) are radiation-hard, space-qualified integrated cryocooler assemblies (ICA) for miniature satellite platforms. The MCS and CCS have been developed on AFRL and NASA SBIRs, respectively, and are comprised of a high-reliability miniature cryocooler, a set of miniature Low Cost Control Electronics (mLCCE), and supporting thermal management components.

The mLCCE supports any of a wide range of linear cryocoolers in its design output power range, nominally 25W, and with minor adaptation, can accommodate rotary coolers as well. This paper highlights the evolution of the mLCCE supported by test results from the flight module phase of the more mature MCS program. For the MCS, a space-grade mLCCE rated for 55 krad has been built and integration tested with the AIM SX030. The test results for the system are discussed herein, and the overall cubesat-compatible mechanical subsystem design is also presented, including a description of the thermal management approach.

More broadly, the Iris Technology mLCCE represents a software-based general purpose, radiation hardened platform for the control of a variety of device types such as motors, actuators, solar power / battery charging systems, and optical bench thermal stabilization.

INTRODUCTION

The dramatic increase in small satellite use for commercial and government applications can be linked to their growing technological capabilities. As requirements for remote sensing and science data gathering missions grow more demanding, the need to mature small cryocooler systems that enable high performance mid-wave infrared (MWIR) and shortwave infrared (SWIR) sensors becomes more evident. To satisfy these needs, the MCS and CCS have been developed and designed with the purpose of simplifying integration in various microsat and cubesat applications, without the need for costly customized drive electronics and systems.

To demonstrate the versatility of the mLCCE, several different cryocoolers have been driven and controlled successfully: a Thales LPT 9510 pulse-tube cooler, an AIM SX030 single piston linear cooler, and a Lockheed Martin Microcryocooler. To further explore compatibility with different temperature sensors needed for precise temperature control, the MCS utilizes a 1 mA diode sensor compatible with the AIM SX030 while the CCS utilizes a 100 μA Cernox sensor compatible

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with the Lockheed Martin Microcryocooler. Both systems can be adjusted to accommodate either sensor with a simple change to the component assembly of the board.

MINIATURE LCCE EVOLUTION

Iris Technology initially leveraged its higher power LCCE designs under IRAD funding to produce a miniature COTS version of a proof-of-concept board that demonstrated full drive capability and temperature control of the AIM SX030 cryocooler. The effort evolved through the support of an AFRL SBIR which allowed the initial design to be expanded to generate an appropriate path for flight electronics. The new MCS met this criterion and has become a mature flight system while CCS, developed through a NASA SBIR, for now remains a COTS system with mLCCE efficiency improvements and flexible temperature sensor implementation for diode and cernox sensors. These improvements have also been included in the flight version of the MCS mLCCE.

Gen I for MCS

The MCS, comprised of a space-grade mLCCE and the SX030 cryocooler, has reached flight maturity through AFRL's Phase II SBIR award and is currently being evaluated for NASA's Lunar IceCube mission to the moon. The mLCCE specifications and test results will be discussed in the following sections. Further funding is expected to qualify the complete system to TRL-6, including TVAC, vibration, and EMI testing as well as triple mode redundancy (TMR) functionality.

Gen II for CCS

The CCS developed under NASA's Phase I SBIR uses a COTS mLCCE fully compatible with Lockheed Martin's mature TRL-6 Microcryocooler. The cooler was successfully tested with the mLCCE using a Cernox temperature sensor at Lockheed Martin's facility in Palo Alto, CA. The CCS has served as another platform to show how quickly a new ICA prototype can be built up and tested using the mLCCE and a cryocooler other than the SX030.

MINIATURE LCCE SPECIFICATIONS

Table 1 provides a summary of critical performance criteria and design performance specifications of the mLCCE.

Table 1. mLCCE Performance Specifications

Parameter	Characteristic
Operating Input Voltage	9 to 35 VDC
Number of Motor Drives	1
Total Output Power	Continuous operation @ 25 WAC maximum at 22 VDC
Max Output Voltage @ 27°C	> 39 Vpp @ 22 VDC; > 16 Vpp @ 9 VDC
Efficiency	> 85%
Tare Power	< 1.5W
Output Voltage Sinusoidal Symmetry	Sine wave output, with less than 0.3V DC offset and < 3% THD including harmonics up to 5 kHz
Operating Frequency Control	Output drive frequency shall be adjustable from 40 to 200Hz with 0.1 Hz resolution
Number of Temp Sensors	1 (configurable for RTD (e.g. Cernox, PRT) or diode)
Temperature Sensor Bias	- 1 mA ±0.05 mA bias current to the temperature sensor (Diode configuration) - 100 µA ±5 µA bias current to the temperature sensor (Cernox configuration)
Temperature Sensor Set-point	- Adjustable in range 0 V to 3.2 V with 0.8 mV resolution (Diode configuration) - Adjustable in range 0 V to 3.2 V with 49.0 µV resolution (Cernox configuration)
Temperature Sensor Sensitivity	- Detectable in range 0.73 V to 1.13 V with 99 µV resolution (Diode configuration) - Detectable in range 0 V to 2.00 V with 3.06 µV resolution (Cernox configuration)
Temperature Response Time	Response to a detected temperature change shall be asserted in drive voltage within 36 ms

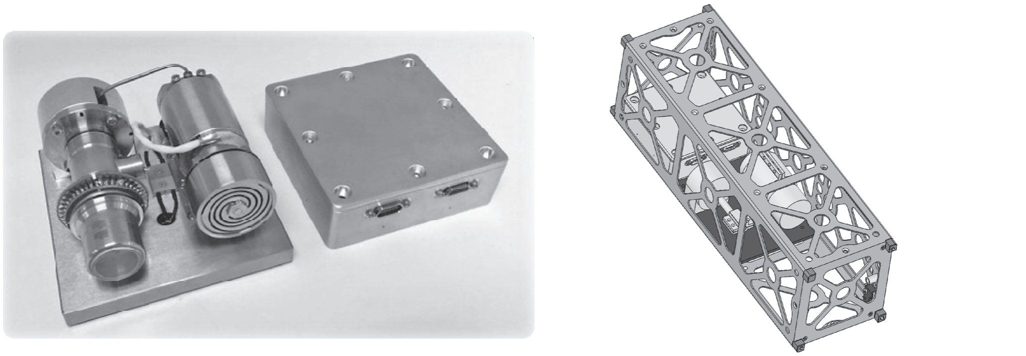

Figure 1. MCS SX030 Cryocooler with mLCCE (left) with implementation in a 3U skeleton (right)

SYSTEM SOLUTIONS

Since the MCS is a flight mature system, it will be the primary point of discussion in the following sections which will provide test data collected in a clean room environment, appropriate for radiation-hardened, high-reliability electronics and hardware.

MCS with AIM SX030

The MCS and its mock-up implementation within a 3U size cubesat skeleton are both shown in Figure 1. The AIM SX030 cryocooler, shown with a test dewar, as well as the flight mLCCE each fit inside of a 1U frame, streamlining full system integration for cubesats. The maximum input power to the cooler is 12 W at 65 Hz and its cooling capacity is shown in Figure 2. At this power level, the efficiency of the mLCCE is approximately 88% at 28 V but depending on the input voltage, can reach as high as 90%.

CCS with Microcryocooler

The CCS Microcryocooler and a mock-up implementation of the whole system within a 3U cubesat skeleton are shown in Figure 3. The maximum input power to the cooler is 20 W at 90-105 Hz, allowing a higher cooling capacity up to 2 W. The mLCCE is compatible with the Microcryocooler as well and was able to drive it at full power with 28 V applied to its input.

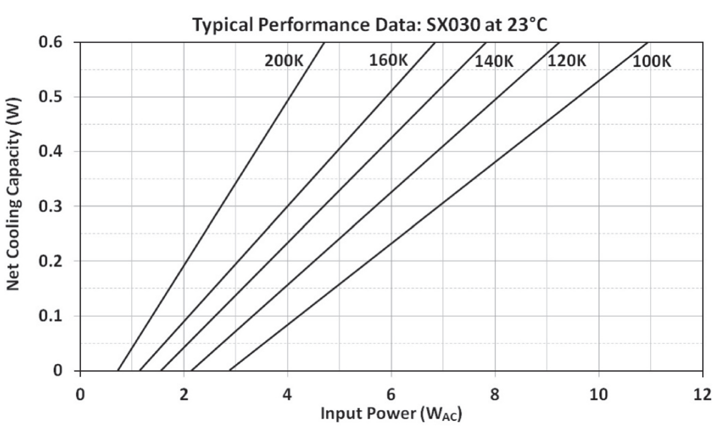

Figure 2. AIM SX0303 Cooling Capacity vs. Input Power

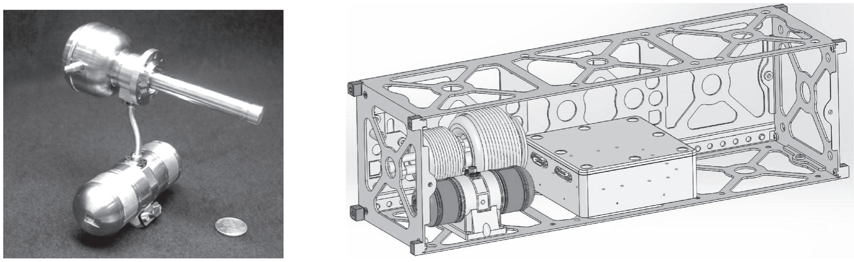

Figure 3. CCS Microcryocooler (left) with mLCCE implementation in a 3U skeleton (right)

MINIATURE LCCE AND MCS TEST RESULTS

The following subsections present the test results obtained for the flight version of the mLCCE as well as the whole system using the AIM SX030 cryocooler.

Tare Power

The mLCCE tare power testing was performed by applying four different input voltages: 9V, 12 V, 28 V and 35 V. During the test, the AC output of the mLCCE was disabled and only the power consumption of the board was measured. The results are summarized in Table 2. Note that a higher input voltage translates to a higher tare power due to increased switching losses in the onboard power supplies.

Output Power and Efficiency

The mLCCE efficiency was first measured with a resistive load to demonstrate its output power capability at power levels beyond what the SX030 can handle. Using a 2.65 Ω resistive load, the mLCCE is able to produce 20 W of output power at efficiencies between 87-89% with either 12 V, 28 V or 35 V applied to its input. Furthermore, it was driven up to 25 W and as high as 35 W at 28 V, reaching efficiencies of 92%.

Next, the efficiency was measured by applying 12 V, 28 V and 35 V and driving the SX030. Since the mLCCE is not capable of boosting its input voltage, it cannot output a peak voltage higher than the input voltage. For example, if 12 V is applied to the mLCCE, its maximum sinusoidal peak output voltage is approximately 11 V, or 22 V peak-to-peak due to some losses in the board and limitations of the duty cycle of the sine wave converter. With an input of 28 V, the maximum output peak voltage is 27 V, or 54 V peak-to-peak. Considerations should be taken when choosing the right input voltage based on the impedance of the cooler that needs to be driven and its maximum allowed voltage rating.

An efficiency of 90% was achieved with a 12 V input to the mLCCE, however, the impedance of the SX030 and the output voltage limitation of the mLCCE only allowed the cooler to be driven up to 8 W. A minimum input voltage of 15 V is recommended for MCS in order to drive the cooler to its full rated power of 12 W Alternative coolers with lower impedances can be driven at higher power since the mLCCE can handle input currents up to 3 A. Similarly, applying a 28 V input to the mLCCE allowed the SX030 to be driven at 12 W with 88% efficiency while 35 V produced an efficiency of 85%. The efficiency plots summarizing the results discussed are shown in Figure 4.

Table 2. mLCCE Tare Power

Input Voltage (V)	Input Current (mA)	Tare Power (W)
9.006	60.75	0.547
12.011	46.40	0.557
28.041	32.00	0.897
35.047	31.40	1.100

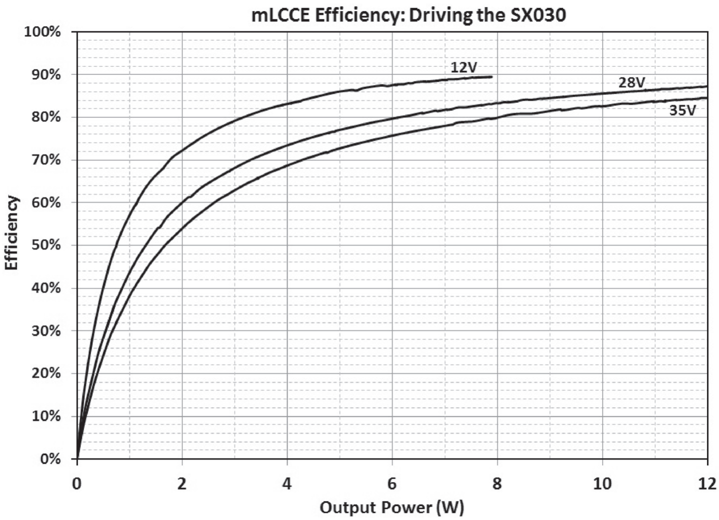

Figure 4. mLCCE Efficiency vs. Output Power

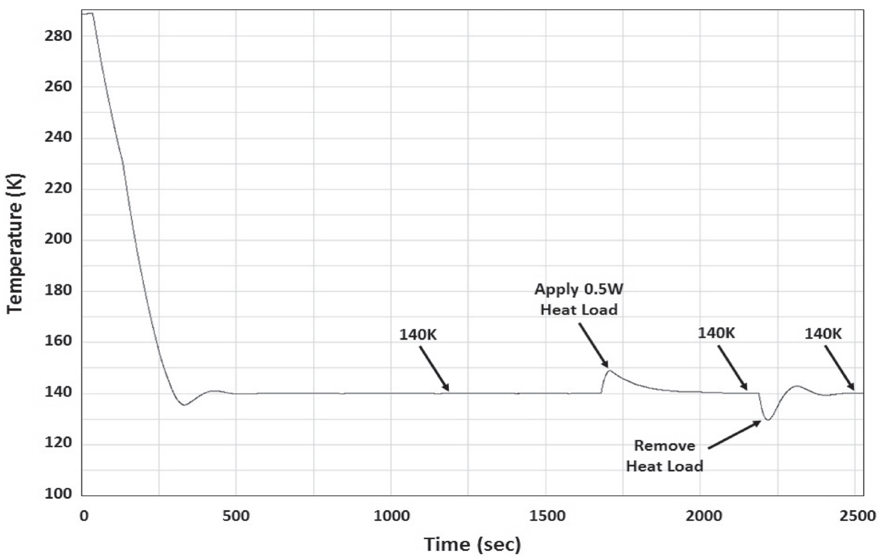

Figure 5. SX030 Cold Tip Temperature with Applied Heat Load

Temperature and Voltage Control

The temperature vs. time plot shown in Figure 5 illustrates the mLCCE operation with the SX030 in temperature mode. Using the Iris communications protocol GUI via RS422, the user can manually control the mLCCE output voltage and set limits for the drive voltage and cooler temperature, at the same time collecting telemetry while plotting various data curves.

Starting at room temperature, as shown at the beginning of the plot in Figure 5, the Iris GUI was set to Temperature Control Mode and a control temperature of 140 K. During the cool down period, safe voltage limits need to be set to protect the cooler pistons from being overdriven at higher temperatures. More power can be applied once the cooler reaches 200 K or below. Once the cold tip of the SX030 reached 140 K, a 0.5 W heat load mounted to the cold finger was applied. The cold tip temperature again reached its 140 K setpoint and stabilized with the mLCCE running continuously at a higher nominal output power. For the final step, the 0.5 W heat load was removed and the mLCCE readjusted its drive level to the cooler to re-stabilize at 140 K. The Iris GUI allows the user to set the PI values for the PI loop of the mLCCE which can be optimized for a desired operating speed and reaction time during cool downs, application of heat loads, and other transitions in the operation of the system.

The Iris GUI also allows the user to run the mLCCE in continuous Voltage Control Mode. The output peak voltage can be set manually for constant voltage outputs needed to test with resistive loads and other control applications independent of temperature sensing.

Total Harmonic Distortion (THD)

For the THD measurement of the mLCCE, an input of 28 V was used to drive a 2.65Ω resistive load at 65 Hz and 12.8 Vpk, providing the maximum rated power output of 25 W as specified in the requirements. At this worstcase condition, the highest THD level measured by the Yokogawa power meter was 0.768%, well below the 3% requirement. Additional testing with the SX030 operating at its maximum rated power of 12 W, revealed maximum THD measurements no higher than 0.72%.

Frequency Control

The mLCCE is designed to support a variety of cryocoolers and is capable of providing drive output frequencies between 40-200 Hz. The frequency of its AC output waveform can be finely adjusted in 100 mHz increments and has been verified and tested for the entire specified range. Scaling the drive frequency by such small increments allows complete drive optimization between the mLCCE and the SX030, as well as any other cryocooler able to operate within this range.

MCS THERMAL MANAGEMENT

The mLCCE chassis draws heat from the PCB via two internal and thermally conductive chassis planes fabricated in the middle of its layer stackup. The copper on the bottom side of the PCB, containing the majority of the power components, is exposed around the perimeter of the board and thermally connected to the internal chassis layers with arrays of vias. The heat generated in the components dissipates through the board to the outer ENIG edges. The chassis is connected to these exposed copper edges of the board with gold foil thermal gaskets to decrease interface resistance. Screws make up the final connection to bring the heat away from the components and the PCB to the exterior of the chassis and a base plate connected to the skeleton of the aircraft.

Figure 6 shows a complete MCS implementation using a common radiator plate connected to both the mLCCE and the SX030. A thermal strap connecting the compressor of the cooler to the radiator plate is also shown. The arrows indicated the thermal flow from the compressor to the thermal strap and finally to the radiator plate. The reason for using the thermal strap rather than securing the compressor rigidly to a plate is to allow for movement. Isolation through flexures from the compressor to the radiator plate further expands flexibility for movement, allowing the mitigation of vibrations escaping from the passive balancer of the cooler.

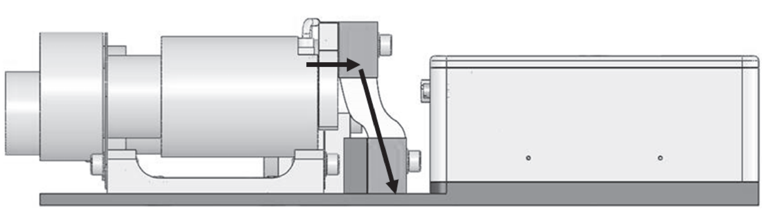

Figure 6. Thermal Heat Strap for SX030 Compressor

CONCLUSIONS

The flight-ready MCS has met all of its requirements and the mLCCE is able to support various different cryocoolers with its wide input voltage range, flexible drive frequency, and support for different temperature sensors. The CCS SBIR serves as an example of how quickly a new ICA can be developed together with the mLCCE for missions requiring a different cryocooler. A novel MCS thermal approach completes the system package and allows for immediate integration into a larger system.

We expect the radiation hardened, software-based mLCCE to soon find many applications in general purpose control systems used aboard the smallest satellite platforms.

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