Solving Thermal Control Challenges for CubeSats: Optimizing Passive Thermal Design

Jennifer Young
Blue Canyon Technologies
5330 Airport Blvd.
Boulder, CO 80301
720-450-8209
jyoung@bluecanyontech.com

Scott Inlow
Blue Canyon Technologies
5330 Airport Blvd.
Boulder, CO 80301
720-450-8428
sinlow@bluecanyontech.com

Brett Bender
Blue Canyon Technologies
5330 Airport Blvd.
Boulder, CO 80301
720-450-8408
bbender@bluecanyontech.com

Abstract—**The advantages of utilizing CubeSat and Microsatellite buses are numerous and in high demand, but thermal control can pose a significant challenge. High power density, limited radiator size, and limited heater power are among the top concerns when designing a small satellite. This paper will discuss the most common thermal challenges and describe how passive thermal design can be optimized while holding traditional thermal margins. Four CubeSats - in low earth orbit with drastically different mission objectives and temperature control requirements - will be discussed. The thermal design, test, and flight results will be presented along with lessons learned and considerations for concurrent mechanical, electrical, and thermal design to allow for mission success.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. COMMON THERMAL CHALLENGES 1
3. THERMAL OVERVIEW 2
4. CUBESAT EXAMPLES 2
5. SOLUTIONS & DESIGN OPTIMIZATION 5
6. SUMMARY 5
ACKNOWLEDGEMENTS 6
REFERENCES 6
BIOGRAPHY 7

1. INTRODUCTION

A common request from customers for CubeSat buses is to maintain a completed full-sized payload design and simply compress it into a small space. The primary difficulty in the thermal analysis of a payload in a 3U or 6U sized spacecraft especially with this requirement is power density. Payload packaging details including mounting type, number of bolts, number of copper layers in boards, interface geometry, and materials used affect the thermal design outcome, which is why concurrent thermal, mechanical, and electrical design for CubeSat payloads at the beginning of the design process is so valuable.

The first section of this paper will discuss the most common thermal challenges that customers are faced with when trying to condense their payload into a CubeSat format. The next section will provide an overview of the thermal design process, thermal margin philosophy, and test description. It will then go into details of four spacecraft that are currently in orbit to explain the payloads, their temperature requirements, challenges, and outcomes. Finally, lessons learned from these examples will lead into considerations for optimization of passive thermal design features that can improve thermal performance for future missions.

2. COMMON THERMAL CHALLENGES

The main drivers for thermal design are component power dissipation, available radiator area with adequate view factors, and the amount of power available for heater control. On a full-sized bus, these are common and achievable tasks. For a small satellite, they can be major design drivers forcing changes to board layouts, addition of heat straps, and flight orientation constraints. Experienced CubeSat bus providers understand these challenges and inherently have bus designs that are optimized to perform at lower power with condensed thermally conductive heat paths.

Power Dissipation

Power density is often the most significant challenge for a CubeSat thermal design. At the electronics component level, boards are smaller with increased component density. Boards may also be divided and stacked to fit into the chassis, creating a longer conductive path from board to radiator. Instrument detectors, mechanisms, antennas, motors, etc. are also packed together tightly, creating a high power to area ratio and competing for the best location for heat rejection.

Radiator Area

Radiator area is in high demand when power density increases. Often one side of the chassis has a more desirable view to a cold sink, with approximately 10 x 8 square inches available in the payload zone. Layout of the payload enclosure benefits from concurrent thermal engineering input.

Heater Control

Passive design for temperature control can be achieved by cold biasing the spacecraft and/or payload area and then applying a heater to maintain cold limit temperature control

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over the duration of the mission. If payload power dissipation is high, there may not be enough remaining in the thermal budget to supply to the heater system. This becomes especially important when the system needs tight temperature stability and significant cold biasing.

3. THERMAL OVERVIEW

Thermal Design

All three 6U CubeSats used the Blue Canyon XB1 bus configuration shown in Figure 1. The bus is an avionics stack up of modules including electronics (1), star trackers (2), reaction wheels and torque rods (3), batteries (4), and radio (5).

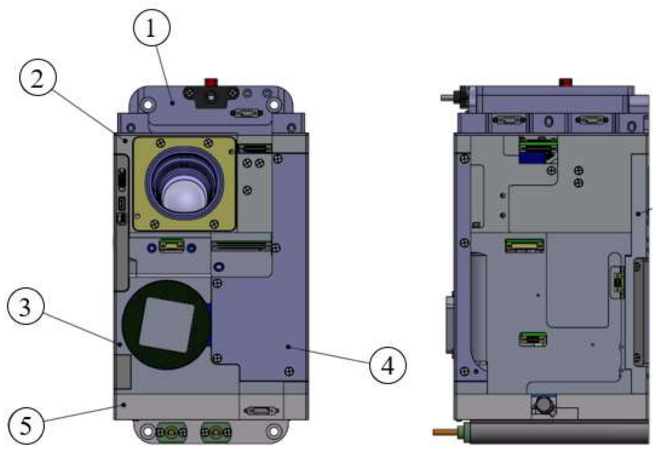

Figure 1. Blue Canyon XB1 Bus

The thermal design for all four CubeSats are primarily passive designs augmented with heaters to maintain minimum temperature when necessary. Bulk spacecraft temperatures are adjusted by modifying the surface properties (thermal optic properties) on the spacecraft. The spacecraft chassis is aluminum with Iridite (protective chromate conversion film that is electrically conductive) as the default surface coating. Aluminized Teflon tape or Silver Teflon tape is used as the default radiator coating.

Thermal Analysis

Thermal analysis is performed in Thermal Desktop with industry standard thermal design methods of bounding the hot and cold worst-case parameters for beta angle, solar flux, Earth IR, Earth albedo, altitude, beginning of life and end of life optical properties, and power dissipation. Margin is held at a minimum of 15°C between thermal model predict and test limit, or 5°C and 25% control authority on heater-controlled components.

Thermal Testing

Thermal cycling and thermal balance testing are completed on all the following CubeSats. For the 6U spacecraft, dedicated thermal balance test GSE was designed and used during testing to provide a flight-like environment focused on correlating the model. Two thermal balance points were performed, one hot operating and one cold operating.

Thermal Model Correlation

After testing, the thermal models were correlated to the test data to within 3°C for all critical nodes. These changes were propagated into the on-orbit thermal model and all cases were rerun to produce final on-orbit predictions prior to launch.

4. CUBESAT EXAMPLES IN ORBIT

The following CubeSats were analyzed to the specifications in section 3. Their thermal requirements, challenges, and final on-orbit flight results are discussed below.

TEMPEST-D, 6U

TEMPEST-D is a demonstration mission by Colorado State University and JPL of a microwave radiometer designed to study precipitation events on a global scale, Figure 2. The payload required tight temperature control of +/- 1.5 K on critical components and a maximum temperature gradient across the payload mounting platform of 5 K.

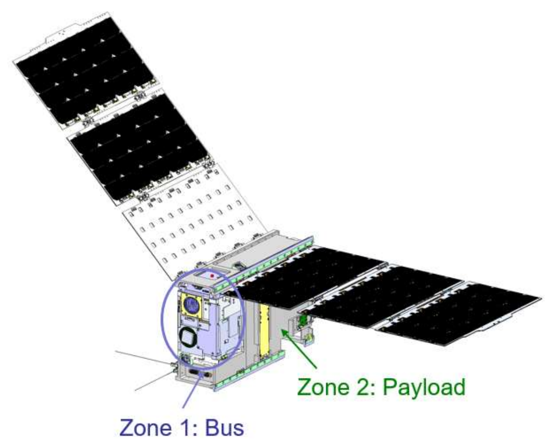

Figure 2. TEMPEST-D Thermal Zones

The payload platform was thermally isolated from the chassis and under heater control, essentially creating two distinct thermal zones. This allowed the payload to be less influenced by the bus power transients and allowed available heater power to the payload to be optimized. Figure 3 shows the separation between the two thermal zones and the conductive and radiative heat paths from each.

The platform/bench thermal isolation was designed with the goal of providing a single temperature set point for the payload to operate over the life of the mission. The chassis was similarly cold biased to a temperature that allowed the platform to remain under positive heater control as well. The power dissipation of the payload components was relatively low, which aided heavily in having enough heater power to thermally stabilize the platform.

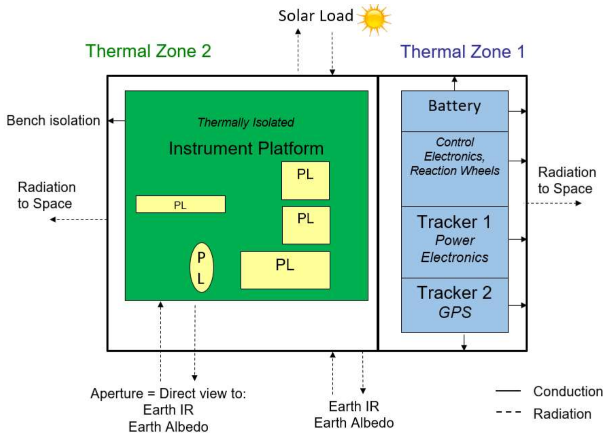

Figure 3. TEMPEST-D Thermal Zones Heat Map

The flight data for the TEMPEST-D payload in Figure 4 showed excellent thermal stability during the cold case of +/- 0.5°C while under positive heater control with the spacecraft at a 5° beta angle and a 36-minute eclipse.

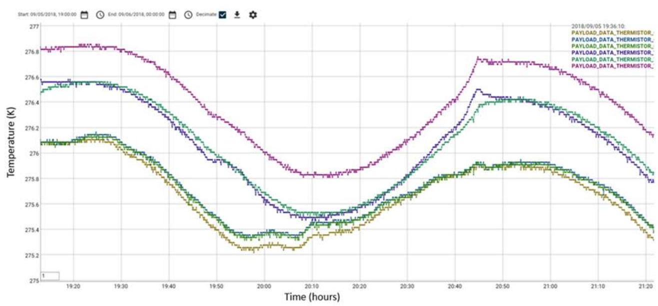

Figure 4. On-orbit thermistor data

As the beta angle increased to 50° and eclipse duration ceased, the payload temperature rose as expected and stayed within limits but was no longer under heater control. The stability drifted but stayed within limits, Figure 5.

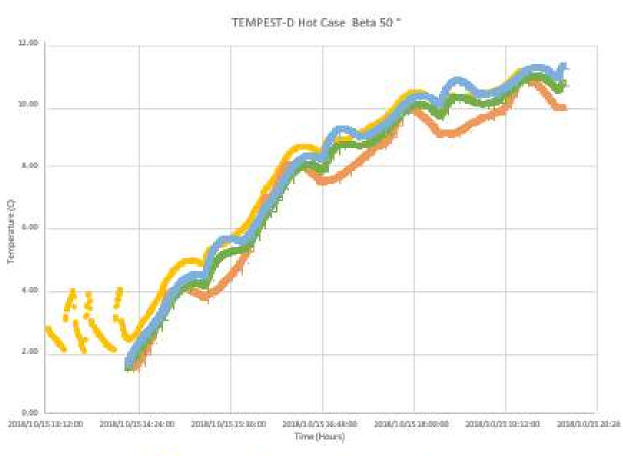

Figure 5. On orbit thermistor data

HaloSat, 6U

The HaloSat mission from the University of Iowa and NASA Goddard Space Flight Center and is designed to help resolve the missing baryon problem by mapping the hot gas in the Milky Way to determine if the halo is extended or compact. The instrument operational science mode temperature range is -20 to +25°C. Payload power dissipation is low, and the unit was designed in a stand-alone package with a continuous interface mounting surface containing many bolted attachment points, Figure 6.

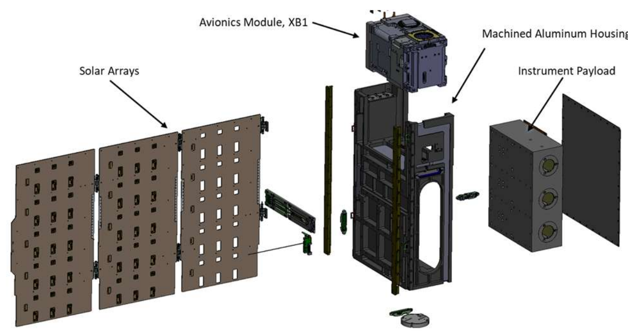

Figure 6. HaloSat Expanded View

The thermal design is primarily passive with heaters to maintain -20°C. The spacecraft can handle more solar loading due to the low power of the payload, therefore radiator area was not a limited commodity. The thermal model is shown below in Figure 7.

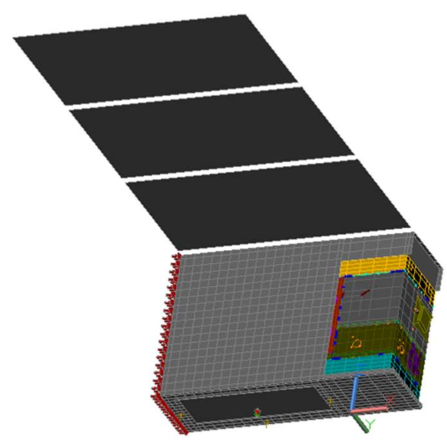

Figure 7. HaloSat Thermal Model

HaloSat was within temperature limits on orbit and the thermal model matched exceptionally well to the flight data as shown in a sample, Figures 8 and 9. Flight data is depicted by solid lines and model predicts are dotted. Telemetry of the spacecraft positions in vector format was imported into Thermal Desktop and run to provide accurate predicts for a detailed comparison.

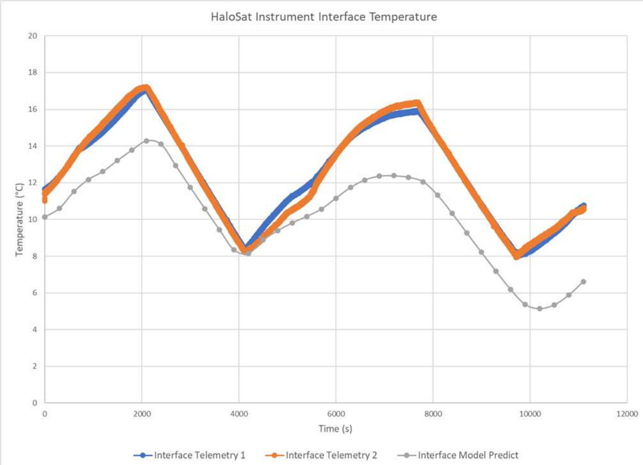

Figure 8. HaloSat Flight Interface Temperatures

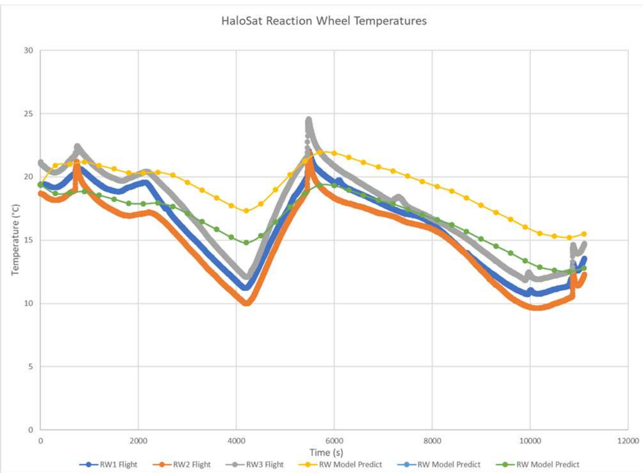

Figure 9. HaloSat Flight Reaction Wheel Temperatures

CubeRRT, 6U

The CubeSat Radiometer Radio Frequency Interference Technology Validation Mission from Ohio State University, in conjunction with NASA GSFC and NASA JPL, can detect and discard man-made radio frequency interference (RFI) from the Earth's naturally fluctuating microwave signals, Figure 10.

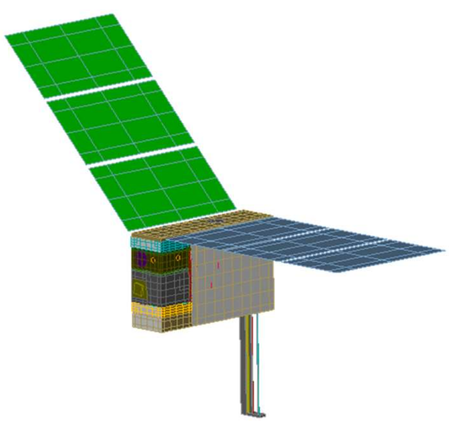

Figure 10. CubeRRT Thermal Model

The thermal challenge on CubeRRT was to cool a high-power component within the RDB electronics box with a long heat path. The surrounding electronics boxes (MWA and LOIF) mounted near the RDB, Figure 11, had significantly lower power dissipations, making cold biasing difficult without over cooling the rest of the spacecraft. Heater power was limited, and heaters were placed between boxes to maintain minimum temperatures on the chassis interface.

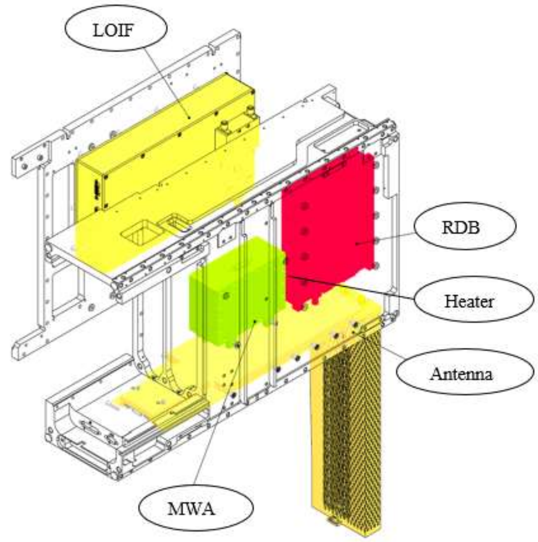

Figure 11. CubeRRT Payload Component Locations

The initial thermal model results showed that the RDB power board was exceeding temperatures due to its placement within the electronics stack up. The power board was dissipating its heat conductively through standoffs to the board below it, and then out to the chassis radiator which did not have an adequate heat sink. A heat strap was designed to shorten the heat path significantly to the adjacent chassis wall, and also with a radiator surface coating and improved view to space. All bus and payload components are within limits on orbit, Figure 12.

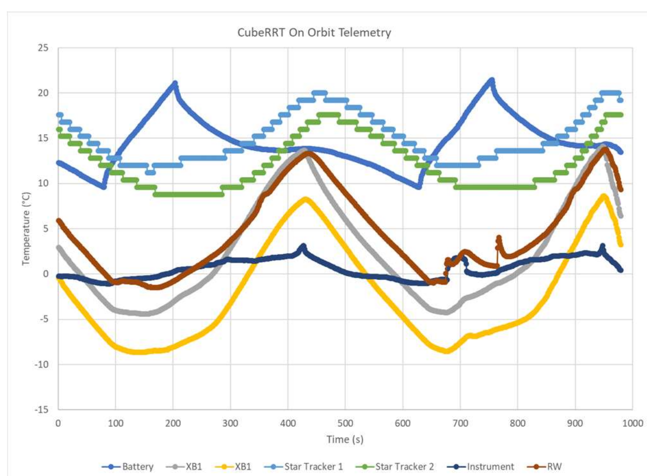

Figure 12. CubeRRT Flight Temperatures

RAVAN, 3U

RAVAN: Radiometer Assessment using Vertically Aligned Nanotubes is an Applied Physics Laboratory mission to provide high accuracy absolute Earth outgoing radiation measurements, Figure 13. As a 3U CubeSat, radiator area is small, however the RAVAN power dissipation is low as well. The thermal design is a slightly cold-biased design with only a small amount of heater power applied to the payload during eclipse.

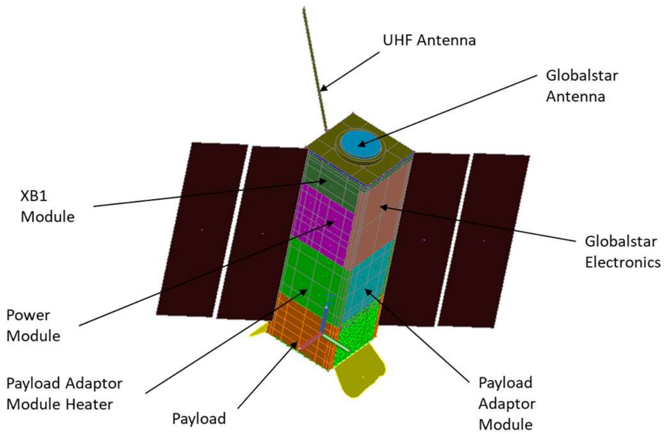

Figure 13. RAVAN Spacecraft

The RAVAN payload has a temperature range of -20 to +30 °C at the mounting interface, which is successfully running within temperature limits on orbit.

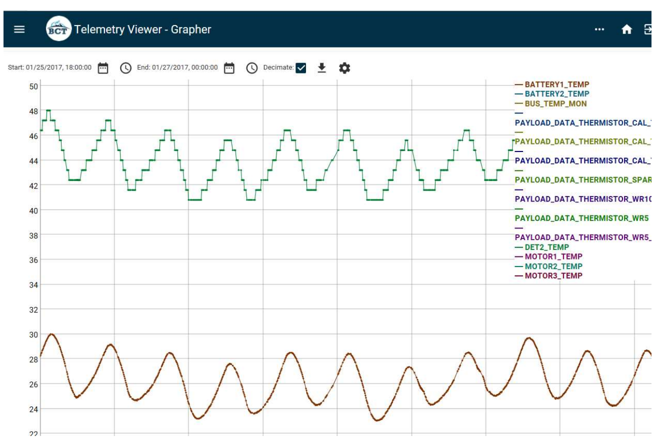

Figure 13. RAVAN Flight Temperatures

5. SOLUTIONS & DESIGN OPTIMIZATION

Power Dissipation

The most significant difference between payload thermal designs, that allow the most flexibility for temperature control, is power dissipation. While it is not always possible to reduce the payload power output, any optimization is directly helpful to the thermal design. On TEMPEST-D, the low powered components on the platform made it possible to isolate it into a separate thermal zone and provide the temperature stability required for accurate science.

Electronics Board Layout

Concurrent electrical and thermal design on electronics boards are advantageous for CubeSats. When power cannot be directly reduced, the ability to conduct heat from within the component out to the radiator is key. The following are straightforward guidelines that directly improve thermal performance:

(1) Mount higher-powered electronics boards closer to the chassis interface

(2) Use thermally conductive standoffs between stacked boards if heat needs to be dissipated

(3) Add additional copper layers within the board

(4) Place high-powered components toward the mounting edge of the board

(5) Spread out high-power components to keep the watt density low

(6) Provide ample fastener locations from the board to the board enclosure or chassis mounting surface

(7) If using Card-Loks, use 5 segmented options with maximum length

Radiator Area

Concurrent mechanical and thermal design for CubeSat mechanical layout is necessary to ensure that warm components can be adequately cooled. Flush mounting surfaces provide the most contact area for conducting heat to the chassis radiator, and thermal interface materials may be used between mounting surfaces to improve the conductance. Mounting locations within the chassis for components with specific temperature ranges, or with high power dissipations, are critical when optimizing heat paths.

Heater Power

Directly related to the total power dissipation, any power available for the heater system can provide cold temperature limit protection, or in the case of TEMPEST-D, allowing for tight thermal stability. For the case of HaloSat, providing a safe minimum temperature was essential.

6. SUMMARY

The four CubeSats described in this paper are good examples of the thermal range of payloads that are proposed to integrate with the XB1 bus for science-based missions, including TEMPEST-D with tight thermal stability, HaloSat with low power consumption and a small temperature control range, CubeRRT with high power dissipating electronics, and finally RAVAN with a wide temperature range and a nearly entirely passive design. CubeSat thermal control is challenging, but with concurrent thermal, mechanical, and electrical input throughout the design process, thermal control was successful for missions described above. Future work on CubeSat payload integration for thermal design can become simplified if steps are taken to optimize, as described in this paper, at the very beginning of the project design phase.

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Biography

Jennifer Young *received a B.S. in Mechanical Engineering at the University of Colorado Boulder in 2002. She has diverse knowledge and experience gained by leading many thermal designs from start to finish during her 10 years at the Laboratory for Atmospheric and Space Physics: 7 instruments on NASA-Goddard missions including MAVEN-Mars, New Horizons-Pluto, and GOES-R. She has worked on thermal designs for more than a dozen CubeSats and is currently at Blue Canyon Technologies in Boulder, CO working to optimize the field of small satellite thermal control.*

Scott Inlow *received his B.S and M.S. in Engineering at the University of Iowa. He worked for 15 years at Ball Aerospace and is currently a Systems Engineer and the lead Thermal Engineer at Blue Canyon Technologies.*

Brett Bender *graduated in 2017 from the University of Colorado Boulder with a B.S. in Aerospace Engineering. While an intern at JPL, he analyzed the Mars Science Laboratory rover operations related to the Dust Removal Tool and supported development of operations concepts for the 2020 rover mission. He currently works at Blue Canyon Technologies as both a Thermal and Mechanical Engineer.*