A Step-Change in CubeSat Architecture: Moving from Stacked to Slotted Design

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ABSTRACT

Exo-Space, Inc. has developed and tested a CubeSat design utilizing a slotted architecture. The new CubeSat design allows for electronic boards to be easily inserted and removed by sliding them along rails and connecting them to a common electrical backplane called the Bus Connector Card (BCC). The BCC consists of multiple edge card connectors and sits on the back-face of the CubeSat acting as the shared electrical bus. Making each electronic board structurally independent of the boards above and below it, allows for a 1U CubeSat to be assembled in 15 minutes rather than ~3+ hours. Furthermore, the chassis steps away from the monoblock design and instead has six plates that are fastened together to form a cube. Two plates have six protruding rails along their faces that help guide the electronic boards into the structure and secure them in place. The structural design was tested and improved by iterating through multiple 3D printed models and electrical connectivity tests were conducted on the BCC. The tests and models helped verify and validate the structure as well as the electrical architecture of this new slotted CubeSat.

NOMENCLATURE

PC-104 . . . . CubeSat Bus Interconnect Interface

U . . . Standard CubeSat Unit (10 cm X 10 cm X 10 cm)

ACRONYMS/ABBREVIATIONS

ABS . . . . Acrylonitrile Butadiene Styrene

BCC . . . . Bus Connector Card

CAD . . . . Computer Aided Design

FEA . . . . Finite Element Analysis

FR. . . . . Flame Retardant

GEVS . . General Environmental Verification Standard

ISS . . . . International Space Station

LEO . . . . Low-Earth Orbit

LED . . . . Light Emitting Diode

NASA National Aeronautics and Space Administration

P-POD . . . . Poly-Pico Satellite Orbital Deployer

INTRODUCTION

University engineering programs around the United States use CubeSats as a way to teach students about the engineering design process. After reaching out to leading universities and CubeSat professionals a common trend began to emerge. Most feedback echoed the idea that there is a need for faster testing methods and more ergonomic designs in the lab. Instead of assembling a CubeSat from the bottom-up by stacking electronic boards on top of each other, a new proposed design utilizes a “server rack” approach wherein individual electronic boards can be inserted and removed without affecting the other boards in the stack. Exo-Space, Inc. has developed and tested a CubeSat design utilizing the slotted architecture.

This paper reflects on the current state of the CubeSat architecture and explores a new design using a slotted architecture attempting to eliminate the inefficiencies with the status quo CubeSat architecture. A proposed step-change and analysis of the slotted CubeSat design will be covered in detail.

DESIGN OVERVIEW

CubeSat manufacturers have attempted to improve assembly time, however, these attempts do not address the core problem of the current CubeSat design. The

core problem is that CubeSats are assembled by stacking circuit boards, one on top of the other. This stacking approach is very time consuming and not conducive to rapid testing and iteration of individual boards. Exo-Space has designed a CubeSat consisting of a slotted design that is also compliant with the CubeSat standard as seen in Figure 1. This CubeSat architecture allows for electronic boards to be easily inserted and removed by sliding them along rails. The advantages of the slotted design is that it eliminates the need for PC-104 headers and standoffs between electronic boards, and allows boards to be removed without having to de-integrate the entire CubeSat. A 1U CubeSat with the BCC architecture can be assembled in 15 minutes rather than the typical ~3+ hours. In addition to reducing assembly time, the slotted architecture also maximizes volume within the structure. Compared to a standard CubeSat, the usable surface area on an electronic board increased by 10% with the Slotted Chassis. The reason for the increase is the replacement of a PC-104 header with a smaller pitched connector and elimination of vertical rails. The CubeSat consists of two main items; the Slotted Chassis, and the Bus Connector Card (BCC).

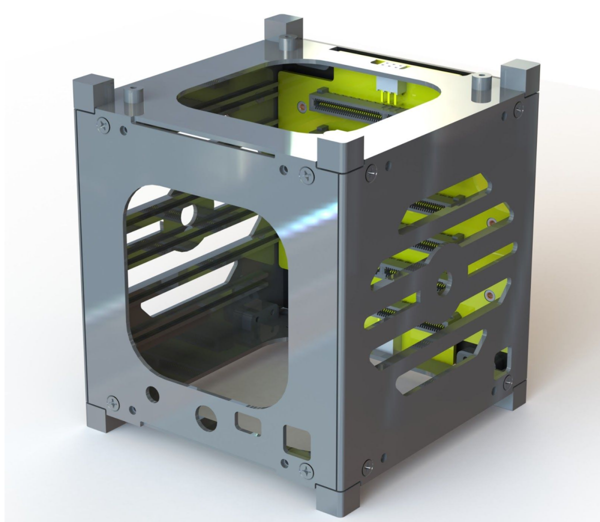

Figure 1: Slotted Architecture CubeSat

Slotted Chassis

The Slotted Chassis comprises six panels: a front panel, bottom panel, top panel, back panel and two side panels. A survey was sent out to universities actively working on CubeSat missions. Feedback was received from three participants which helped inform the slotted design and resulting electrical architecture. The mono-block chassis has been replaced with a modular six piece chassis, which allows access to electronic boards without complete disassembly as the front, top, or bottom panels can be removed without compromising the structure. The unique aspect of the slotted chassis are the rails that hold the electronic boards in place. Each side panel has six protruding rails along it’s horizontal axes. The rails help guide the electronic boards into the structure and secure them into the BCC along the X, Y and Z axis. This is detailed in Figure 2.

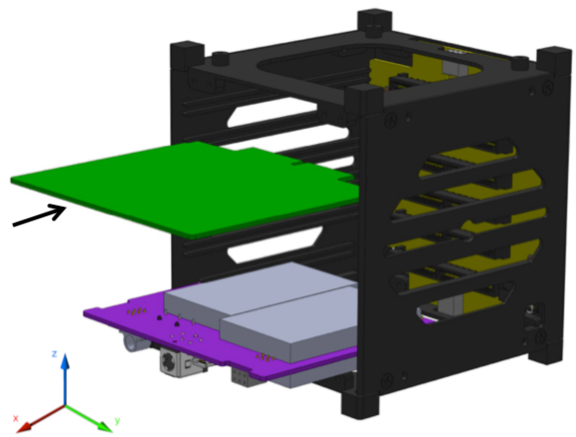

Figure 2: Electronic Boards Sliding into CubeSat

The chassis can accommodate six boards with equal spacing between them. The spacing highlighted in orange in Figure 3 is 12.4 mm. To allow for integration of boards with a taller footprint in the Z axis, the spacing highlighted in blue is larger than the board to board spacing, at 14.7 mm. Even with the increased interior area, the slotted design still meets all requirements stated in the CubeSat Design Specification Rev. 13.[1]

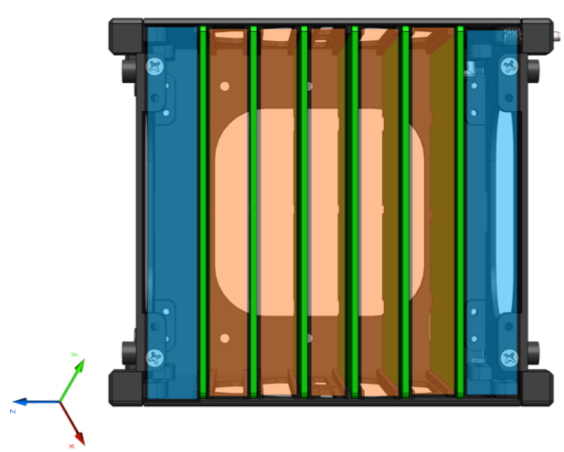

Figure 3: Slotted Chassis Board Spacing

Bus Connector Card

The Bus Connector Card (BCC) is the common electrical backplane that all CubeSat's boards connect to. The BCC acts as the common bus between all the subsystems. Thus, the BCC allows for power and data transfer between all parts of the CubeSat.

In order to facilitate independent and rapid integration/ de-integration of the boards, the conventional PC-104 connection method was dropped in favor of multiple mini edge card connectors, which gives the BCC its server rack like form. There are 6 vertically mounted 120 pin edge card connectors on the BCC. 120 pin connectors were used in order to accommodate PC104 based designs which used 104 pins. These edge card connectors are in line with the rails on the side panels which allows the CubeSat cards/ boards to slide along the rails and connect to the BCC as shown in Figure 2 above. There is a one to one connection between all 120 pins on each of the edge card connectors which forms the common electrical bus for the entire CubeSat, and thus allows for power and data transfer between all its components. As there is a one to one correspondence between all the pins, the bus and in turn the CubeSat boards become position agnostic. Any board can be plugged into or pulled out of any of the 6 connectors, independent of the other boards, and the behavior would remain the same. This provides massive improvement over the PC104 method as all boards of the CubeSat can now be independently tested, integrated and de-integrated without affecting the rest of the CubeSat. It also provides complete flexibility in positioning the boards. Careful positioning of the boards can be very helpful in reducing electromagnetic noise, improving radiation shielding as well as thermal management.

Samtec's HSEC8-160-01-L-DV-A is used for the 120 pin connectors on the BCC. The data rate and power flowing through the connections is limited only by the capability of these connectors. These High Speed Edge Card (HSEC) Connectors are rated for up to 240 VAC and 2.8A current on each pin.[6] Based on a 3dB insertion loss, these connectors are rated to transfer data at speeds of up to 34 Gbps.[6]

To mate with the connectors on the BCC, the CubeSat boards are modeled as cards with goldfingers on their edges. When these cards slide into the connectors on the BCC, the gold fingers come in contact with the pins on the edge connector, and thus allows the card to access the common electrical bus as shown in Figure 4.

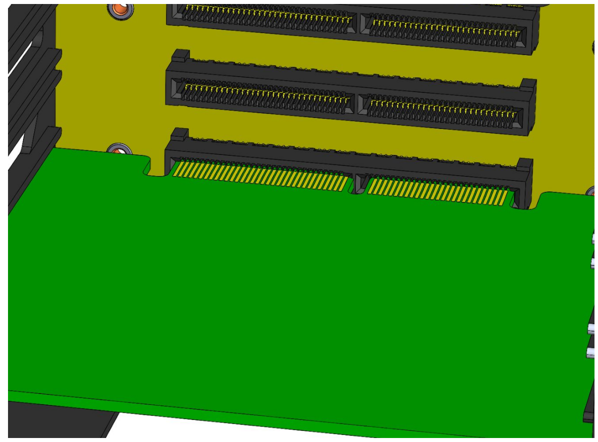

Figure 4: BCC Edge Card Mating

Apart from the bus connectors, the BCC also houses the separation switch that when depressed (as it will be in the dispenser) physically separates the power system circuitry from the rest of the CubeSat circuitry. This is achieved by routing the preallocated power lines to and from the separation switch. When the CubeSat is ejected from the dispenser into orbit, the switch will no longer be depressed and will allow the CubeSat circuitry to connect to the power system. The separation switch is shown in Figure 5.

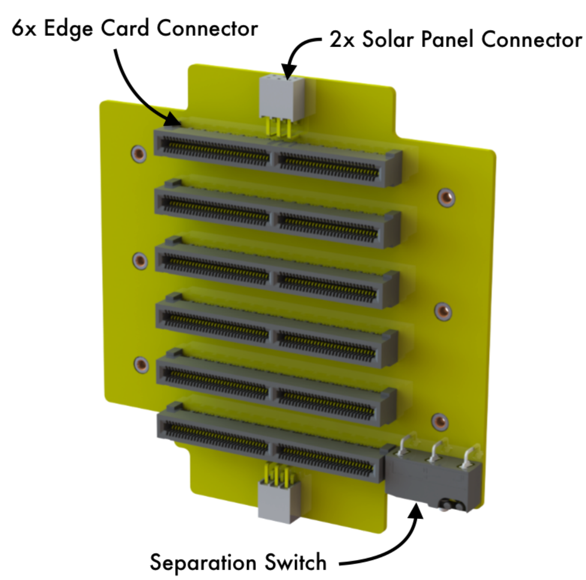

Figure 5: Bus Connector Card

The BCC also contains 2 connectors for the top and bottom solar panels. The power from these connectors

is routed to the common bus which becomes available to the power circuitry.

The overall schematic of the BCC is shown in Figure 6.

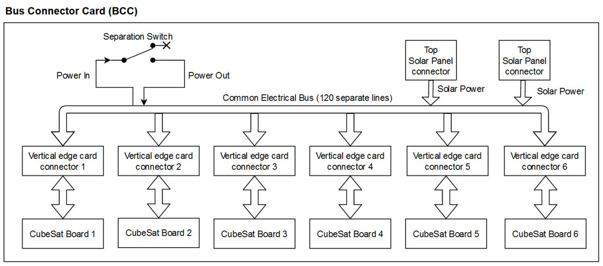

Figure 6: BCC Overall Schematic

SIMULATIONS AND ANALYSIS

Design validation was done using SolidWorks FEA to perform thermal and vibration analysis.

Thermal Analysis

In the space environment, the two primary modes of heat transfer are radiation and conduction. Convection is negligible due to the lack of atmosphere, while thermal loads on a satellite are highly dependent on orbit.

The majority of CubeSat missions are launched to low Earth orbit (LEO). The altitude of a satellite in LEO is between 150 km and 1000 km.[3] For the purpose of this analysis, the CubeSat was placed in a 400 km orbit, similar to the International Space Station (ISS), as it's one of the most popular LEO orbits. The external heat sources that were modelled for this analysis were: direct solar radiation, Earth albedo radiation, and Earth infrared radiation. Direct solar radiation is energy from the Sun and is the most significant heat source in LEO. Solar radiation is nearly constant, and is equal along all directions. Earth albedo radiation is the solar energy reflected off the Earth, and Earth infrared radiation is solar radiation incident on the Earth that is not reflected as albedo but absorbed by the Earth and reemitted as long-wave infrared radiation.[4] Heat generated from the CubeSat components was not included in the thermal analysis.

A secondary input for thermal analysis is the beta angle, which could vary greatly from mission to mission. The beta angle is the minimum angle between the orbit plane and the solar vector and can vary from -90 to +90 degrees. The thermal analysis will input the conditions at the two extremes, beta angle of zero and 90 degrees. An orbit with a beta angle of zero will appear edgewise when viewed from the Sun. In this orbit, Earth's infrared radiation will be the highest but the eclipse time will be the longest, which in most cases will create the coldest condition for the CubeSat. As the beta angle increases, the eclipse time drops until it reaches zero at a beta angle of 90 degrees.[4] In this condition, the CubeSat has constant solar radiation which creates a hot environment. If the CubeSat can withstand conditions at a beta angle of zero and 90 degrees, it's implied it can survive any beta angle between those two extremes.

To define the upper and lower bonds on temperature predictions, hot and cold cases were used in the analysis. The input parameters used for these cases are chosen to reflect the realistic extreme temperature loads the satellite could experience. The parameters include external heat sources, beta angle, altitude, and surface properties. Table 1 below describes the calculated external heat fluxes. Table 2 shows input parameters.

Table 1: LEO (400 km) External Heat Flux Inputs [4]

Source	Beta Angle = 0°		Beta Angle = 90°	
	Hot Case (W/m^2)	Cold Case (W/m^2)	Hot Case (W/m^2)	Cold Case (W/m^2)
Solar	1419	0	1419	1317
Albedo	834	0	119.2	35.6
Earth IR	209	209	209	209

Table 2: Thermal Input Parameters

Parameter	Value
Initial Temperature	20 °C
Ambient Temperature	-270.15 °C
Slotted Chassis Material	6061-T6 Aluminum Black Anodized
BCC Material	FR4

Thermal analysis was completed using SolidWorks FEA. Figure 7, shows results for a zero beta angle during the cold case.

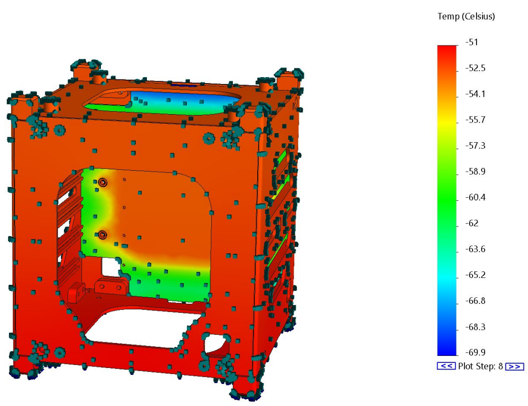

Figure 7: Solidworks Thermal Analysis

The overall maximum and minimum temperatures from all analyses are represented in Table 3.

Table 3: Thermal Analysis Results

Component	Max Temp [°C] Hot Case	Min Temp [°C] Cold Case
Slotted Chassis	15.4	-54.4
Bus Connector Card	8.5	-69.9

The recommended temperature margin during the design phase was 17 °C.[4] With margins added, the temperature values are within the allowable limits of each component.

Vibration Analysis

Vibration analysis was performed in order to determine if the slotted CubeSat design could survive the vibrational loads experienced during launch. The CubeSat could be launched on a multitude of different launch vehicles, all with varied loads. The primary launch loads that CubeSats are subjected to are random vibrations due to the engine, mixing of the exhaust with the atmosphere, aerodynamic sources, such as wind, turbulence and air friction, etc.[6]

To ensure that the CubeSat will survive any launch vehicle, the NASA General Environmental Verification Standard (GEVS) levels were used as a benchmark for the analysis. The structure is simultaneously vibrated in x, y, and z axis using the values in Table 4 with a constant damping factor ζ of 5% as per NASA standard.[5]

Table 4: NASA Random Vibration Qualification Levels for Payload under 22.7 kg [5]

Frequency (Hz)	ASD Level (g^2/Hz)
20	0.026
20-50	+6 dB/oct
50-800	0.16
800-2000	-6 dB/oct
2000	0.026
Overall	14.1 Grms

The majority of CubeSats are launched as secondary payloads and are placed inside a Poly-Pico Satellite Orbital Deployer (P-POD). The P-POD therefore sets the boundary conditions of the CubeSat for the vibration analysis. Figure 8 depicts the results for the random vibration analysis.

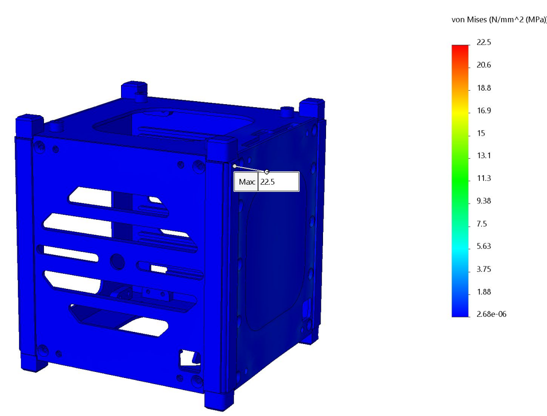

Figure 8: Solidworks Vibration Analysis

The maximum stress values from the analysis for the Slotted Chassis and Bus Connector Card are shown in Table 5.

Table 5: Maximum Stress Values for Random Vibration Analysis

Material	Max Stress Value (MPA)	Material Yield Strength (MPA)	Factor of Safety
Al 6061-T6	22.5	237	2
FR4	0.61	70	2

The vibration analysis test results showed that a slotted CubeSat architecture with a BCC backplane was within the required safety factors for surviving launch.

PROTOTYPE

Prototypes were made for the Slotted Chassis, Bus Connector Card, and demo boards. Prototyping allowed for design iterations of the Slotted Chassis and BCC. Multiple design changes were made through this process such as number of rails, rail spacing, electronic connector location on BCC, fastening locations and many more. The prototype chassis was made from ABS plastic and manufactured using a 3D printer. The BCC and demo boards were designed in house and manufactured by a third party printed circuit board vendor. The electronic components of the BCC were attached using an in-house reflow oven. Figure 9 depicts the CubeSat prototype with the Slotted Chassis, BCC, and two demo boards.

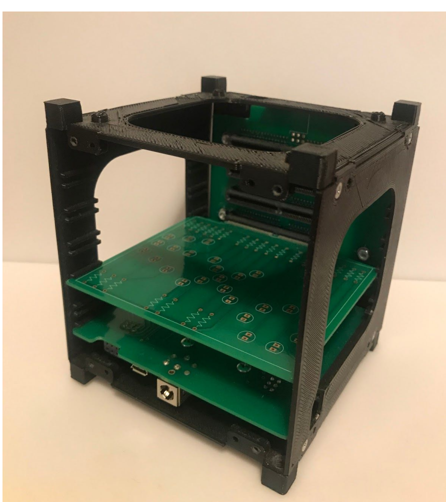

Figure 9: Exo-Space CubeSat Prototype

INTEGRATION AND TESTING

Exo-Space used the prototype components to perform integration and testing. The success criteria for integration were the following:

1) Fastener hole locations align correctly.
2) No interference between components.
3) Rails of the Slotted Chassis align with the connectors on the BCC.
4) Demo boards fit properly between the rails.
5) Demo boards slide in and out of the chassis with relative ease.
6) Demo boards slide directly into the connectors on the BCC.
7) Demo boards are secured in place when connected into the BCC.

The slotted CubeSat design passed the success criterias listed above.

The next step was to validate that the BCC provided an electrical connection to all the boards inside the CubeSat. An electrical test was performed by utilizing two demo boards and an external power supply. One of the demo boards acted as a power board and routed power from the external power supply to the Bus Connector Card. A second demo board acted as a payload board and was equipped with Light Emitting Diodes (LED) that would light up when power was supplied to them. Both boards were connected into separate slots on the BCC as seen in Figure 10.

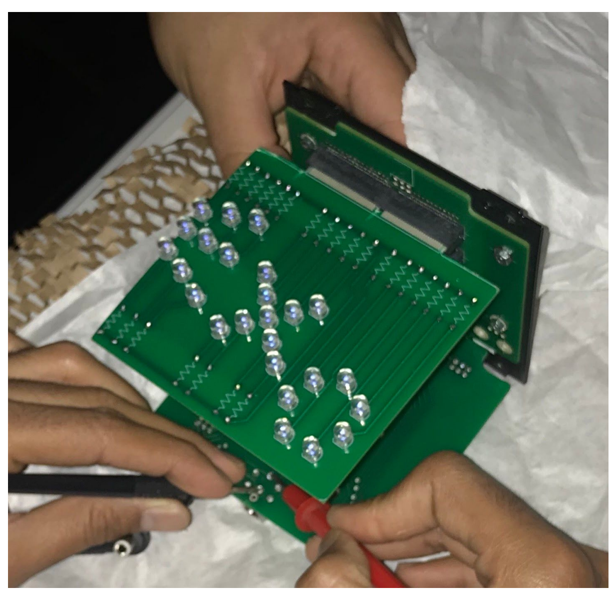

Figure 10: Electrical Test Set-up

The test would be deemed successful if the LED's on the payload board light up when power is supplied regardless of which slot it was connected to on the BCC. As seen from Figure 11, the test was successfully completed.

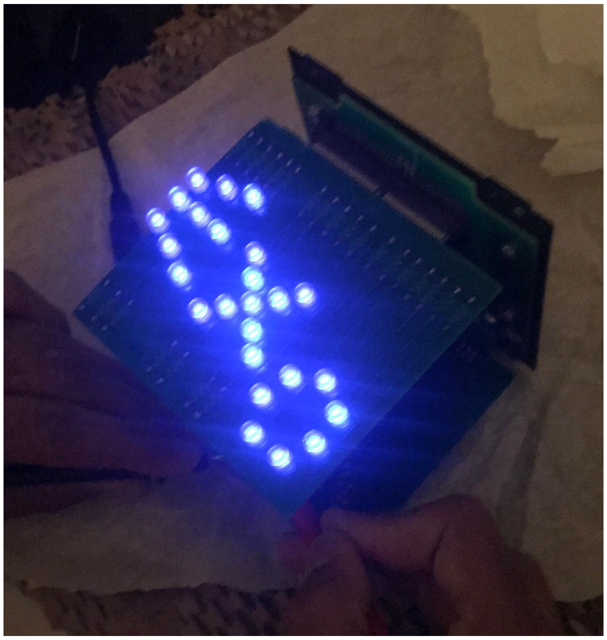

Figure 10: Electrical Test Result

CONCLUSION

Exo-Space has designed and tested a CubeSat that utilizes a slotted chassis and Bus Connector Card to allow electronic boards to horizontally slide in and out of the structure independently. The slotted CubeSat reduces assembly time from ~3+ hours to around 15 minutes, and reduces complexity during the testing phase of a CubeSat mission. Thermal and vibration analysis showed that the assembly of the slotted chassis and BCC can withstand launch vehicle loads, as well as thermal loads from the space environment. A prototype of the slotted CubeSat design was created to demonstrate the technology. The prototype showed that the CubeSat could be assembled by one person as relatively easy as compared to current designs. The electronic architecture allows for quick integration and de-integration in a plug and play fashion.

REFERENCES

1. The CubeSat Program, "Cubesat Design Specification Rev. 13," California Polytechnic State University, February 2014.
2. E.B. Katelyn, "Thermal analysis and control of small satellites in low Earth orbit," Missouri University of Science and Technology, MO, 2018.
3. H. D. Curtis, "Orbital Mechanics for Engineering Students," Butterworth-Heineman, Burlington, MA, 2009.
4. D. G. Gilmore, Ed., "Spacecraft Thermal Control Handbook Volume I: Fundamental Technologies," The Aerospace Press, El Segundo, CA, American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2002.
5. GSFC Flight Programs and Projects, "General Environmental Verification Standard (GEVS)," NASA Goddard Space Flight Center, Greenbelt, MD, March 2019.
6. Samtech, "Product Specification HSEC8," Samtech, Inc, January 2019.