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An Electrical Power System Development for VERTECS: A 6U CubeSat Mission for Observation of the Extragalactic Background Light

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ABSTRACT

This paper focuses on an overview of the electrical power system (EPS) implemented in the Visible extragalactic background radiation exploration by CubeSat (VERTECS), a 6U CubeSat developed by a collaboration of the Kyushu institute of technology (Kyutech), JAXA, universities, and companies. Its mission aims to reveal the star-formation history of the universe through observations of the extragalactic background light (EBL) in visible wavelength. This article presents the three primary functions of the EPS in VERTECS design (i.e., power source, energy storage, and power control) in detail, as well as the verification of the system by the breadboard model (BBM).

Numerous factors are considered in designing and developing the power source for VERTECS. The keys of the design consist of end-of-life (EOL) requirements, the selection of solar cell type, the solar array mass and area, power input, and power consumption. Most designs of the EPS have flight heritage from previous satellites developed at Kyutech. Given the application of high-throughput optics in the payload for efficient handling and processing of large amounts of light, significant updates are required in the EPS design, particularly concerning power consumption. Consequently, the design of solar panels has been enhanced by increasing the two deployable solar panels to serve more power for the mission. The triple junction GaAs solar panels with five solar panels are utilized for VERTECS. There are three panels mounted to the satellite structure and two panels deployed. Secondly, VERTECS adopts the Li-ion battery as the energy storage due to its superior capacity-weight ratio. The battery screening approaches are essential to ensure the operational efficiency of the battery throughout the mission in space. The battery screening consists of physical and cell screenings conducted before and after vacuum and vibration testing. After the screening, the batteries are selected according to the appropriate and standard criteria. Regarding the power control, the peripheral interface controller (PIC), known as the Reset PIC, controls the electrical power supply for VERTECS satellite system. Its primary function is to reset the power supply of other microcontrollers in the event of failure. In the design to mitigate potential issues of the Reset PIC, its programming code is straightforward, and a simple external watchdog is provided to facilitate recovery. Furthermore, functional testing of the BBM is conducted to verify the EPS. It includes verifying voltage ratings, overcurrent protection, and DC/DC converter efficiency.

INTRODUCTION

VERTECS is a 6U CubeSat developed under the JAXA-Small Satellite Rush program. Its astronomical mission is to observe visible extragalactic background light. The satellite inherits most of the designs from the Kyutech BUS (in KITSUNE mission)[1], the BIRDS satellites, the CURTIS satellite, and the LEOPARD satellite. However, significant modifications, especially the EPS, have been implemented to accommodate the complex mission requirements. For instance, the mission demands precise attitude control to achieve high-quality observations of visible EBL, resulting in increased power consumption for the attitude determination and control system (ADCS). Consequently, additional solar cells, including deployable solar array panels (DSAP), are required to meet the satellite's power needs.

The EPS plays a critical role in VERTECS. It stores electrical power in batteries during the sun phase for utilization in eclipse, regulates power going into a load, and distributes electrical power to each subsystem. The sole source of the satellite is electrical power converted from sunlight by solar cells. The power with fluctuating voltage from the variable projection to the sunlight is regulated by a battery charge regulator (BCR) to maintain a constant voltage. The regulated power is applied to charge the battery pack. It is called the raw power. Following this, the raw power from the battery pack is distributed to various power lines before being converted to the required voltage by DC/DC converters in each power line, which is called the bus voltage. However, there exists a power line that bypasses the DC/DC converter and directly supplies the raw power to a subsystem known as the unregulated line. Subsequently, the subsystems utilize this power to operate and support the satellite mission. This paper describes the design and basic verification methods of the EPS for a 6U CubeSat, illustrated through the development of VERTECS.

MISSION AND DESIGN REQUIREMENTS

VERTECS's mission is to observe and measure the emission spectrum of cosmic background radiation in visible light to determine whether it originates from an early universe object or a nearby object, such as Intra-Hola Light (IHL).[2] In each orbit, the satellite will observe the EBL brightness four times, with each observation having a 60-second exposure duration. VERTECS is designed as a 6U CubeSat to accomplish the mission based on the Kyutech BUS. It consists of a 3U optical module and a 3U bus system. The bus system includes an attitude control device, transceiver, electronic boards, and batteries. The satellite is designated to orbit in a sun-synchronous orbit (SSO) at an altitude of around 500 km and will be launched in 2025. The specifications of VERTECS compared with those of KITSUNE are shown in Table 1.[3]

Table 1: Comparison of VERTECS and KITSUNE Specifications

Specification	VERTECS	KITSUNE
Size	6U	6U
Weight	≤ 8 kg	6.72 kg
Orbit	Approximately 500 km	380 to 420 km
Mission Payload	Four-band (400-800 nm) telescope	Visible spectrum telescope
Communication	S-band X-band	C-band Tx IHF Tx/Rx
Power Generation	30.3 W	14 W
Power Storage	74.5 Wh	74.5 Wh

(*) Tx: Transmitter
Rx: Receiver

POWER SOURCE

Power Consumption

The power consumption represents the total amount of energy required by the electrical components to ensure system operation. Table 2 outlines the power consumption of VERTECS in each operational mode. The downlink mode consumes a peak power of 25.75 W during operation, excluding the deployment of DSAP.

Table 2: Power Consumption of VERTECS

Operation Mode	Power Consumption (W)
Sun-pointing Mode	6.22
Mission Mode	17.36
Downlink Mode	25.75
Uplink Mode	13.37
Deployable Solar Array Panel Deployment	28.33

Energy Balance

The energy balance determines the amount of energy available per orbit, dividing the satellite's orbit into two distinct periods: the sun stage and the eclipse stage. The satellite is exposed to direct solar radiation during the sun stage, which constitutes approximately 60 minutes per orbit for a sun-synchronous orbit. The sun stage allows the satellite to generate energy using solar cells and store the surplus in its batteries. Conversely, during the eclipse stage, when solar radiation is absent for around 35 minutes, the satellite relies solely on the energy stored in these batteries.

The initial estimation of the minimum solar array size is based on this peak power consumption from the downlink mode, including electronics losses. The calculation by Equation 1 is as follows:

$$\Delta E = E_{in} - E_{out} \quad (1)$$

$$E_{eclipse} = E_{gen} - E_{use}$$

$$(P_{X-downlink})(t_e) = (P_{gen})(t_s) - (P_{sun-point})(t_s)$$

where
$E_{eclipse}$ = energy consumption during eclipse;
E_{gen} = energy generated by solar arrays;
E_{use} = energy consumption during sun stage;
$P_{X-downlink}$ = power consumption in downlink mode;
$P_{sun-point}$ = power consumption in sun-pointing mode;
P_{gen} = power generated by solar array;
t_e = time in eclipse; and
t_s = time in sun stage.

From the calculation, P_{gen} = 21.24W. As a result, the solar arrays must produce a minimum power output greater than 21.24 W.

Solar Cell

The sun serves as a vital energy source for a satellite, with sunlight striking the surfaces of their solar panels and being transformed into electricity by solar cells. These solar cells are crucial for a satellite, enabling power generation and ensuring operational functionality. Without solar cells, a satellite could not produce electricity to achieve the mission. Recently, the triple junction GaAs solar cell has been extensively adopted for satellites because of its high efficiency, approximately 30%. VERTECS utilizes the triple junction GaAs solar cell according to the specifications in Table 3.[4]

Table 3: Solar Cell Specifications

Parameter		BOL	EOL
Average Open Circuit (V_{oc})	[V]	2.62	2.48
Average Short Circuit (I_{sc})	[mA]	457	444
Voltage at Maximum Power (V_{mp})	[V]	2.32	2.18
Current at Maximum Power (I_{mp})	[mA]	436	422
Maximum Power (P_{max})	[W]	1.01	0.92
Average Efficiency (η)	[%]	28	25.5

(*) BOL: Beginning-of-life
EOL: End-of-life

Solar Panel Design

Solar panels and arrays are composed of individual solar cells connected in series to form strings and in parallel to form circuits. These circuits are then mounted on a substrate, such as a printed circuit board (PCB) or a composite fiber reinforced panel (CFRP).[5] PCBs are commonly used in CubeSat designs, while CFRP is more suitable for larger-class satellites. The primary solar panel, which is oriented towards the sun, is equipped with 12 solar cells to generate power. However, due to the higher power demand for achieving accurate attribute control in VERTECS's mission, VERTECS requires the deployable solar array panel to generate adequate electrical power. The DSAP is a key design feature that allows VERTECS to increase its power generation capacity, ensuring that the satellite has enough power to operate and support its mission requirements.

Referring to Table 3, the P_{max} for EOL is 0.92 W per individual solar cell. The minimum solar array output is 21.24 W. Thus, at least 24 solar cells are required. Figure 1 shows the configuration of VERTECS' solar panels. The satellite structure accommodates three body-mounted solar panels, with the -Y panel featuring 3 solar cells and both the +X and -X panels equipped with 15 solar cells each. Additionally, the +X and -X panels incorporate DSAPs, each comprising 15 solar cells. The solar cells on the +X and -X solar panels, both body-mounted and deployable, are configured in 3 cells in series and 5 strings in parallel. In sun-pointing mode following DSAP deployment, a total of 33 solar cells will be oriented towards the sun.

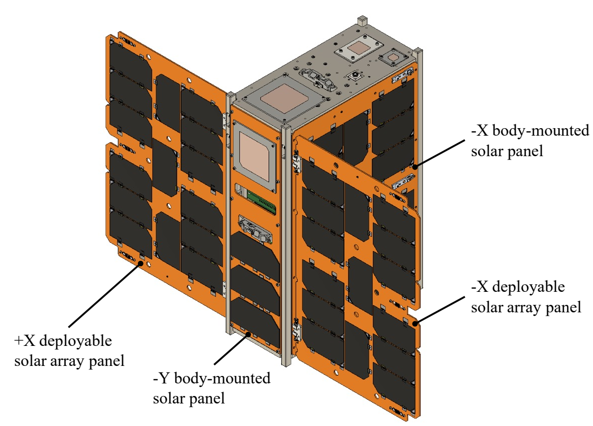

Figure 1: Solar Panel Configuration of VERTECS

ENERGY STORAGE

VERTECS applies the NCR18650GA Li-ion batteries for energy storage connected in a configuration of 2 series and 3 parallel cells. These batteries offer notable volumetric and energy density advantages compared to other types.[6] The battery specifications are detailed in Table 4.[7]

Table 4: NCR18650GA Battery Specification

Battery Classification	Lithium Ion Battery
Rated Capacity	3300 mAh
Capacity	Minimum: 3350 mAh
	Typical: 3450 mAh
Nominal Voltage	3.6 V
Charging	Method: CC-CV
	Voltage: 4.2 V
	Current: 1475 mA (standard)
	Time: 270 min. (standard)
Weight	48 g
Temperature	Charge: +10 to +45°C
	Discharge: -20 to +60°C
	Storage: -20 to +50°C
Energy density (*)	Volumetric: 693 Wh/l
	Gravimetric: 224 Wh/kg

(*) Energy density is calculated using bare cell dimensions (without tube).

Battery Screening

Battery screening is employed to identify the most suitable electrochemical batteries and ensure they possess optimal characteristics for space applications. The screening can verify whether each satellite battery cell meets the requirements. The screening methods include physical measurement, resistance test, and charge/discharge cycle test conducted before and after environmental testing.

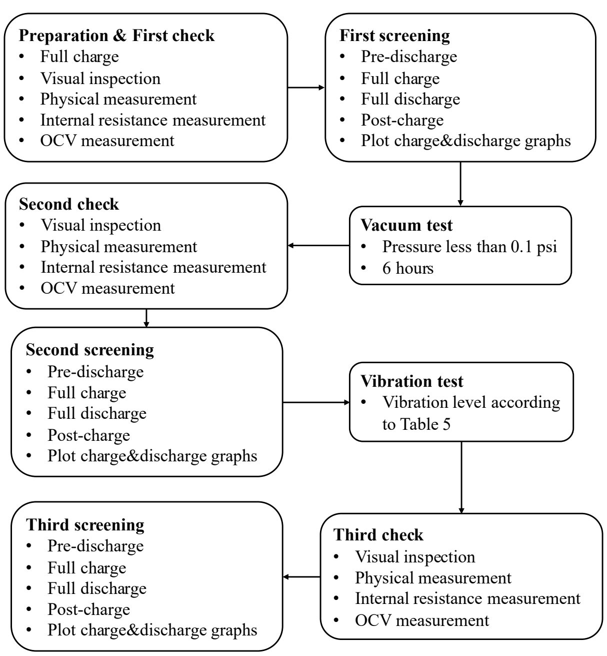

Figure 2: Battery Screening Processes

Figure 2 presents the battery screening processes. The battery verification process includes two crucial tests: vacuum and vibration. These tests, following the battery verification test from JEM small satellite orbital deployer (J-SSOD) of Japan aerospace exploration agency (JAXA) and crewed space vehicle battery safety requirements, are instrumental in confirming the battery's functionality and safety in space conditions. The vacuum test, conducted under low pressure of less than 0.1 psi for 6 hours, ensures the battery assembly can maintain function and be safe after exposure to a vacuum environment. The accelerated vibration test, on the other hand, checks the battery's tolerance to internal shorts, aiming to detect material and workmanship defects before flight by exposing the battery to a dynamic vibration environment. The vibration level test details are provided in Table 5.[8,9]

Table 5: Vibration Level for Battery Pack

Frequency [Hz]	PSD [G^2/Hz]
20	0.01
80	0.04
350	0.04
2000	0.007
Overall	6.06 Grms

(*) Test duration ≥ 1 minute

(**) A maximum allowable tolerance of ±1.5 dB

Battery Selection and Matching

Prior to battery selection, lot sampling tests must be performed. Cells from the flight lot should undergo acceptance screening to exclude outliers beyond the ±3 standard deviation range for the following key performance metrics: open-circuit voltage (OCV), mass, dimensions, direct current internal resistance, leak integrity, charge and discharge capacity, and charge or voltage retention. If more than 15 percent of the cells in the lot fail to meet the acceptance screening criteria, the entire lot will be rejected.[9]

Parameter	Criteria
Open Circuit Voltage Change	≤ 0.1 %
Mass Change	≤ 0.1 %
Capacity change	≤ 5 %
Internal Resistance Change	≤ 10 %
Temperature during screening	≤ 45°C

Table 6: Success Criteria of Cell Screening

Moreover, before and after the environment tests, the OCV, internal resistance, capacity, and mass of the individual battery shall be measured and compared, as well as visually inspected. The change of those shall conform to the success criteria as illustrated in Table 6.

Imbalanced internal resistance within batteries can cause temperature variations in the battery pack. Hence, compatible batteries with similar internal resistance are matched and assembled into a battery pack to prevent thermal gradients. VERTECS selects 2 sets of battery packs for the engineering model (EM). Table 7 presents the performance parameters of the batteries before and after the vibration test.

Table 7: VERTECS's EM Battery Parameters before and after Vibration Test

Set	Internal Resistance			Capacity			OCV			Mass		
	Before [mΩ]	After [mΩ]	Change [%]	Before [mAh]	After [mAh]	Change [%]	Before [V]	After [V]	Change [%]	Before [g]	After [g]	Change [%]
A	74.2	80.3	+8.22%	3386	3389	+0.09%	3.775	3.773	-0.05%	47.356	47.365	+0.02%
	86.9	80.7	-7.13%	3397	3378	-0.56%	3.719	3.720	+0.03%	47.241	47.243	0.00%
	86.1	80.7	-6.27%	3415	3404	-0.32%	3.719	3.719	0.00%	47.348	47.351	+0.01%
	80.0	80.7	+0.88%	3408	3377	-0.91%	3.728	3.730	+0.05%	47.371	47.371	0.00%
	84.6	80.7	-4.61%	3407	3395	-0.35%	3.783	3.783	0.00%	47.335	47.335	0.00%
	84.2	80.3	-4.63%	3423	3407	-0.47%	3.777	3.777	0.00%	47.361	47.351	-0.02%
B	75.7	83.0	+9.64%	3405	3418	+0.38%	3.768	3.766	-0.05%	47.396	47.399	+0.01%
	85.0	81.9	-3.65%	3388	3348	-1.18%	3.721	3.721	0.00%	47.335	47.336	0.00%
	85.7	81.5	-4.90%	3416	3402	-0.41%	3.713	3.713	0.00%	47.404	47.408	+0.01%
	84.2	81.9	-2.73%	3418	3391	-0.79%	3.722	3.723	+0.03%	47.231	47.229	0.00%
	89.2	81.5	-8.63%	3398	3384	-0.41%	3.784	3.784	0.00%	47.265	47.265	0.00%
	85.0	81.1	-4.59%	3436	3407	-0.84%	3.781	3.781	0.00%	47.385	47.384	0.00%

POWER CONTROL

Power System Architecture

The power generated from solar cells is transmitted through bus power and stored in the batteries. Due to electronic devices within a satellite commonly requiring a voltage level different from the voltage source (i.e., solar cells), DC/DC converters are applied to adjust the input voltage to a specified range.[6] In VERTECS, the maximum power point tracking is selected as the power system architecture because it can maintain power efficiency and extract the maximum available power from solar cells. Nevertheless, the efficiency depends on a DC/DC converter performance.

Power Distribution and Control

A power regulator, such as the BCR, is an electrical device that adjusts unregulated power to meet the specific requirements of various loads within the system.[6] The BCR, in particular, plays a significant role as one of the power regulators in VERTECS. As per the block diagram for VERTECS, as shown in Figure 3, the VERTECS's input voltage of 6.7V to 7.2V from solar arrays is converted to the battery charging voltage by a BCR, called the raw voltage of 8.4V. Then, the raw power is distributed to each power line. Before being supplied to devices, the raw power is regulated to the specific load voltages by a DC/DC converter, called bus voltage. There are several lines of the bus voltage, which are 3.3V, 5V, 12V, and unregulated (8.4V) lines. Behind the DC/DC converter, the overcurrent protection (OCP) is implemented to prevent excessive currents from flowing through the electrical circuit or device. Figure 4 shows the power system diagram of VERTECS. The colors in the diagram indicate which microcontroller controls which switch.

The Reset PIC and the EPS PIC are responsible for the EPS. The EPS PIC collects the electrical power information as a monitoring device. It monitors the voltage and current from the solar cells, including the solar panels' temperature. The Reset PIC controls many power switches to distribute the power. It controls the power management for the COM PIC (the communication microcontroller) and the Main PIC (the command and data-handling microcontroller). Functioning as a watchdog for these microcontrollers, the Reset PIC can force a power reset if they fail to send acknowledgments. Regardless, the satellite's electronic parts have the possibility of failure in orbit because of the single-event effect caused by radiation, and the Reset PIC is no exception. A simple external watchdog is connected to the Reset PIC for recovery purposes to address potential failures.[10]

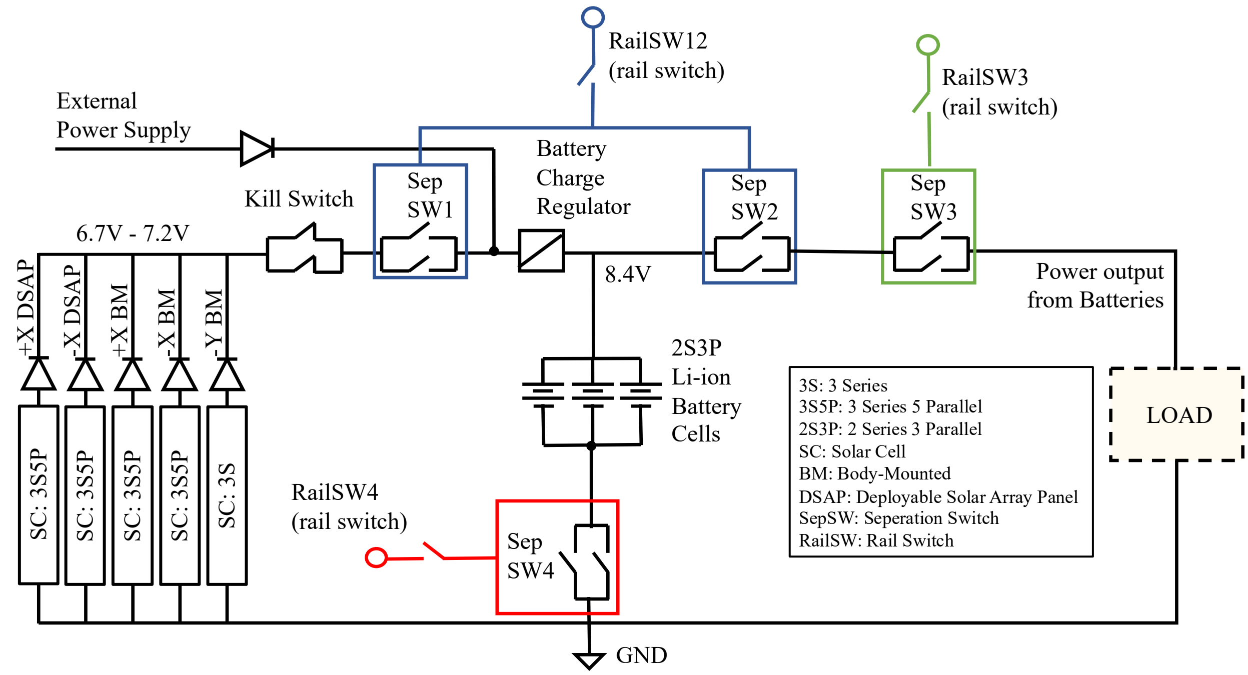

Figure 3: VERTECS's Block Diagram

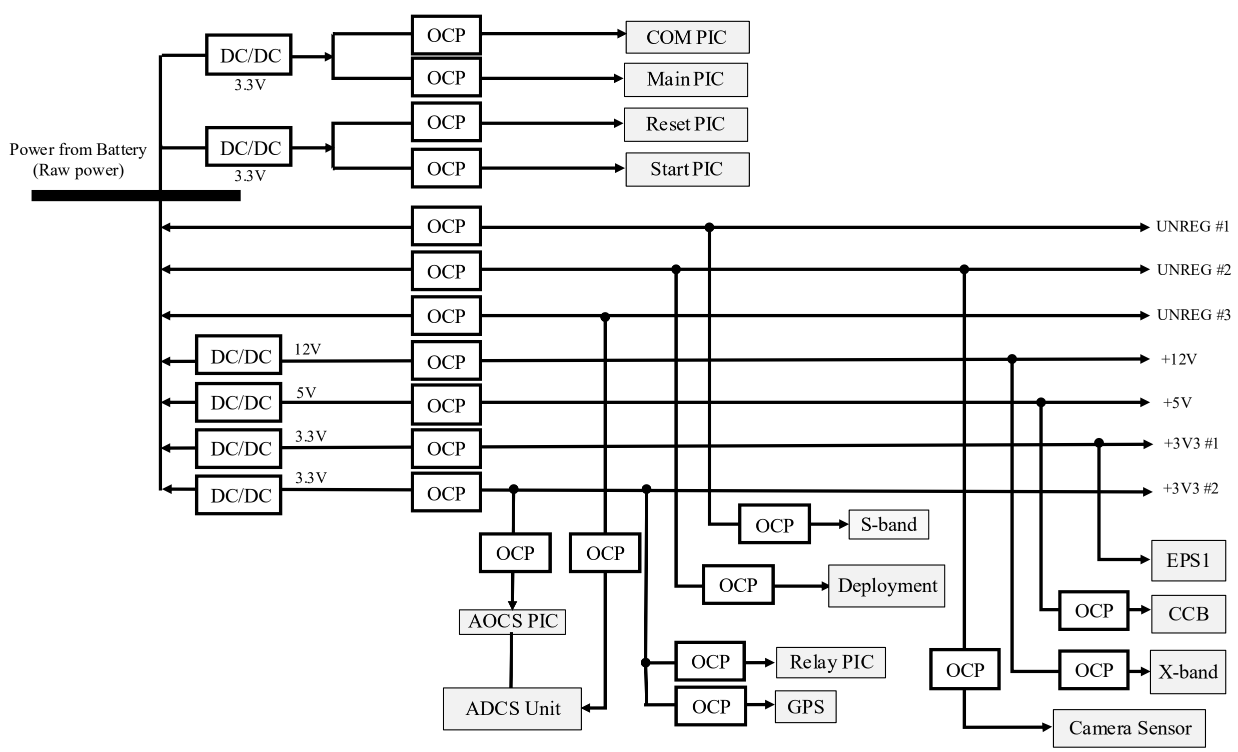

Figure 4: Power System Block Diagram

BREADBOARD MODEL FUNCTIONAL TEST

This section describes the preliminary functional tests of VERTECS's EPS, which include voltage rating, overcurrent protection, and DC/DC converter efficiency tests. These tests are pivotal in verifying the satellite's electrical power system before integrating it into the engineering model. Figure 5 illustrates the connection and location of the VERTECS boards. The functions of VERTECS's boards related to the EPS functional test are as follows:

- Backplane board (BPB): Provide an electrical and mechanical interface between components and satellite components.
- Access and deployment board (ADB): Provide an external power line that supplies power to the batteries (charging) and the loads.
- OBC/EPS board: Distribute the raw power to each power line.
- EPS1 board: Measure voltage and current from solar cells, including solar panels' temperature, and regulate the source voltage to the raw voltage.

Overcurrent Protection

All overcurrent protection circuits on the OBC/EPS board are verified by connecting the board to the BPB along with the EPS1 board. A power supply provides power through the battery connector on the EPS1 board, while an electronic load connected to an output line on the BPB draws the current. The current drawn by the electronic load must exceed the predefined overcurrent limit. When the overcurrent flows to the OCP circuit, the circuit will cut off the power to protect the devices.

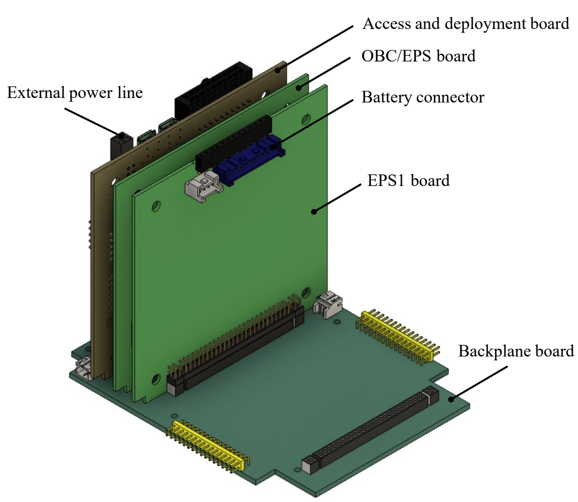

Figure 5: VERTECS's Boards Connection and Location

DC/DC Converter Efficiency

The efficiency of each DC/DC converter is a critical parameter in power budget calculations. Various factors influence the efficiency of DC/DC converters, including the input/output voltage ratio, load current, and switching frequency. In this test, the OBC/EPS board is connected to the BPB, with a power supply providing power to the raw power line and an electronic load drawing current on the BPB. The input and output power of each DC/DC converter are measured and calculated to determine their efficiency by Equation 2.

$$\eta \times P_{in} = P_{out} \tag{2}$$

where η = efficiency; P_{in} = input power; and P_{out} = output power.

CONCLUSION

VERTECS inherits most of the designs from the Kyutech BUS. The satellite is designed to observe visible extragalactic background light. Due to the higher mission requirements of VERTECS, the electrical power system shall be improved to meet such requirements. This article explains the design theory of solar arrays, energy storage, and power distribution and control units of VERTECS. Moreover, it discusses the initial functional tests conducted.

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