Payload Design of RHOK-SAT, a 1U CubeSat to Characterize Perovskites in Low Earth Orbit

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RHOK-SAT's scientific mission is to characterize the performance and degradation of novel perovskite photovoltaic cells in low Earth orbit (LEO). This paper details the current payload development, focusing on the mechanical and electrical components of the satellite. The mission will test 36 perovskite solar cells and one control copper indium gallium selenide (CIGS) solar cell, which will be measured using dedicated measurement microcontrollers. Cell temperature will be measured with resistance temperature devices (RTDs) and the angle of incident sunlight will be measured with a custom sun sensor. The greatest challenge of this project is fitting all necessary components within a payload volume of 211 cm^3. This paper will outline the custom design of the electromechanical assembly, sun sensor, and printed circuit boards (PCBs) housed within RHOK-SAT's payload.

I. Nomenclature

V_{OC} = open circuit voltage
I_{SC} = short circuit current

II. Introduction

RHOK-SAT is a 1U CubeSat collaboration between Rhodes College and the Photovoltaic Materials and Devices Group at the University of Oklahoma. The satellite is part of the 12th round of NASA's CubeSat Launch Initiative (CSLI) and is planned for launch on an International Space Station (ISS) resupply mission in late 2023 or early 2024. The project's primary mission is to provide real-world engineering experience to students at Rhodes College, a liberal arts institution with no engineering program. The team at Rhodes College is responsible for designing the payload and high-level software of the satellite, while the team at the University of Oklahoma (OU) provides the experimental cells and analysis. The RHOK-SAT bus is purchased from Innovative Solutions in Space (ISISpace), based in Delft, Netherlands, and includes the following subsystems:

- On-Board Computer (iOBC)
- Electrical Power System (iEPS)
- Three-axis magnetorquer (iMTQ)
- Transceiver (TRXVU)
- Antennas (AntS)
- Solar Panels (iSPA)

Subsystems are mounted on the CubeSat's internal stack, as shown in Fig. 1

A. Mission Description

RHOK-SAT's secondary mission is scientific and aims to characterize the behavior and degradation of novel perovskite cells in low Earth orbit (LEO). The RHOK-SAT team will be flying six perovskite samples, each with six independent cells called pixels. This research is an area of active investigation by the group at OU headed by Dr. Ian Sellers. RHOK-SAT will also contain one copper indium gallium selenide (CIGS) solar cell as a reference to track perovskite cell degradation. All cells will be mounted on the CubeSat's +Z face, referred to as the payload face. The

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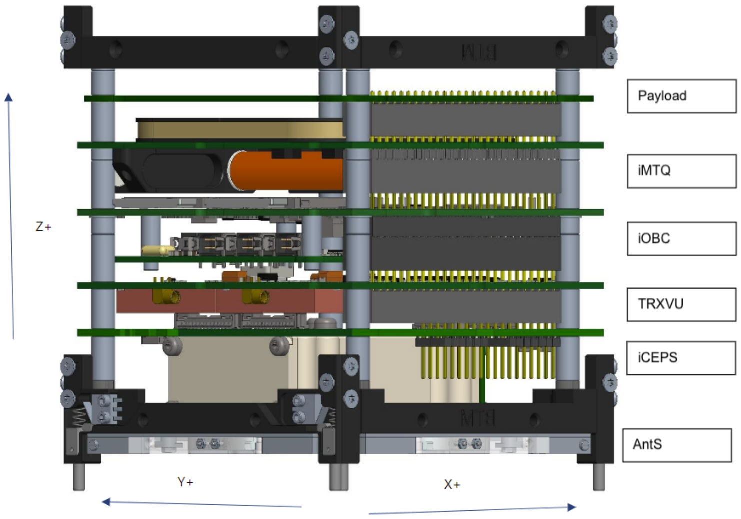

Fig. 1 Labeled internal stack

payload will measure sun angle and cell temperatures as well as current-voltage (IV) pairs over the course of the nine- to eighteen-month mission. The experimental cells will not be used for power generation. RHOK-SAT's power will be generated by ISISpace solar panels on the other five faces of the satellite. Data will be collected using dedicated measurement microcontrollers called Aerospace Measurement Units (AMUs). The data will be downlinked when RHOK-SAT passes over the Rhodes College ground station in Memphis, Tennessee. RHOK-SAT's flight software is custom built and more information about its design and development can be found in [1].

III. Photovoltaic Devices

Perovskites were selected as the primary photovoltaic devices for this mission because they show promise for power generation in space. They exhibit high tolerance to radiation [2, 3] and extreme temperatures [4]. Perovskite efficiency tends to degrade under continuous illumination. However, performance is recovered when the cells are stored in a dark location. RHOK-SAT seeks to characterize the effects of radiation, thermal cycling, and periods of sunlight and eclipse to learn how viable the perovskites may be in a space environment.

The experiment consists of characterizing 36 distinct perovskite pixels. Each of the six pixels on a given sample slide act as detached electrical negatives and are joined at a common positive terminal as seen in Fig. 2 This configuration allows the pixels to function independently. The pixels are attached to electrodes that sit along the perimeter of the glass substrate. The electrodes are padded with a layer of indium tin oxide (ITO) and a layer of gold. This two-layer design ensures conductivity despite potential scratching which may occur in the high-vibration environment present during launch. One CIGS solar cell, whose performance at different illuminations and temperatures is well characterized, is included as a control for the perovskite measurements.

Characterizing a solar cell consists of assessing its power generation performance under illumination. The RHOK-SAT design uses AMUs to sweep the cells passively, varying a resistive load from open circuit voltage (V_{OC}) to short circuit current (I_{SC}) in order to plot IV curves. The AMUs also measure the temperature of the cell before and after each sweep. A full measurement procedure of the payload takes approximately four seconds.

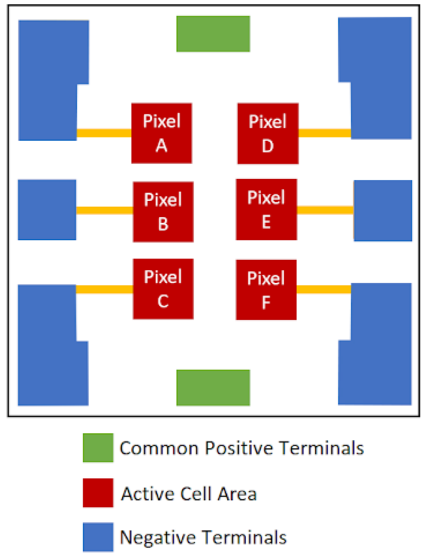

Fig. 2 Layout of a perovskite cell

The team has encountered a variety of challenges working with perovskites on the ground including sensitivity to humidity, ensuring a reliable electrical connection, and degradation at V_{OC}.

- Perovskite material is particularly sensitive to moisture and must be encapsulated to survive even a few days outside of a controlled environment. Encapsulation is an active area of research. The team has changed the specific cells for the payload multiple times due to design improvements. The RHOK-SAT encapsulated perovskites are manufactured by Swift Solar.
- A dry connection is needed to connect to the perovskites, i.e. no solder or epoxy can be applied. The prolonged high heat associated with soldering can damage the crystalline structure of the material, and epoxies obstruct electron transfer.
- Degradation occurs when the perovskites are under illumination and at V_{OC} but not supplying power to any component. This is not a problem when the pixels are being measured. However, there will be periods of time when the cells are illuminated but not measured. In order to mitigate this degradation, resistors were added to hold them as close as possible to their maximum power point (P_{MP}), where degradation is minimized. Switches were added to connect the pixels to the resistors when not being measured.

Perovskite fabrication is still in its infancy. The circuit design has been modified several times as the encapsulations improve and the samples become more robust. The perovskite encapsulation will maximize the time they can be exposed to a non-controlled environment. The satellite will sit stowed for up to six months before launch and then again before deployment from the ISS. Although it is assumed that the satellite will be kept in a temperature-controlled environment between integration and deployment, it will still be exposed to air and humidity.

IV. Measurement Devices and Procedures

A. Lab Setup

Lab measurements of photovoltaic devices are common and are typically made using a Source Measurement Unit (SMU), such as a Keithley device. A benchtop SMU is an active measurement device which applies a voltage to the cell and measures the output current. Rhodes College purchased a Keithley 2401 SMU with funding from the SPS Chapter Research award in 2021 for in-lab measurements to aid in the payload design process [5]. With the help of the OU group, members of the RHOK-SAT team developed a testing protocol to understand the functionality of the solar cells. The testing protocol involved the range of voltages that should be swept over and number of data points that should be recorded per sweep. The team learned how to take IV sweeps and began testing CIGS cells using the Keithley.

A variety of factors introduced complications and errors to these measurements. The first improvement the team made was moving from two-wire to four-wire measurements, reducing the internal resistance in the measurement circuit. Four-wire measurements make use of two wires to probe current and two to sense voltage. The wires are connected such that their internal resistance is bypassed. This technique increases the accuracy when compared with a two-wire measurement for low resistance measurements.

Initial tests showed noisy data instead of the expected smooth IV curve. The tests were conducted in a windowless lab where ambient natural light could not affect the measurements. The noise was likely due to interference from fluorescent lights in the lab. A simple box was used as a shield to mitigate the impact of the lab's lighting, covering the cell and its light source. This solution posed a new problem; heat collected in the box and raised the cell temperature, impacting the measurements. A solid copper block was placed under the cell to dissipate the heat. The shield was also quickly removed between measurements to allow heat to escape before affecting the cell's temperature.

Another issue was determining an appropriate light source for the measurements without needing to buy an expensive solar simulator. Simple flashlights were initially used to understand how the cells respond to light and how good data should look. To refine the lab procedure, the team gathered different light sources to determine what would make better measurements. A large 1000-watt light bulb was used to test whether the increased intensity would improve the data. This light was extremely bright and heated up very quickly, leading to significant changes in cell temperature, particularly when under the shield. This bulb did not mimic the Sun's spectrum and was too intense for the team's needs. The test was repeated using a 100-watt incandescent bulb and a standard desk lamp fixture. This fixed the distance between the light source and the top of the cell, reducing variation between trials. The 100-watt bulb was also much smaller than the 1000-watt bulb and heated up slowly, leading to lower temperature fluctuations. A potential source of error came from the AC power outlet leading to very fast fluctuations in the lamp's light. However, the impact on the data was negligible, as the 100-watt bulb did not flicker as an LED bulb would. This became the final measurement setup for functional hardware testing at Rhodes.

B. Sun Sensor

The sun sensor construction is inspired by the sun sensor flown on Pico-Satellite Solar Cell Testbed-2 [6]. RHOK-SAT will have a fine sun sensor mounted on its payload face to measure the angle of incident light on the experimental cells. Sweeps are conducted when an angle threshold is met. The sun sensor is constructed in-house from a TO-5 quad-photodiode and an aperture plate bonded to the top glass. The aperture plate is made from a blackened photo-etched metal foil with a square hole in the center to create a square light spot on the active areas of the diode[7], as shown in Figs. 3 and 4.

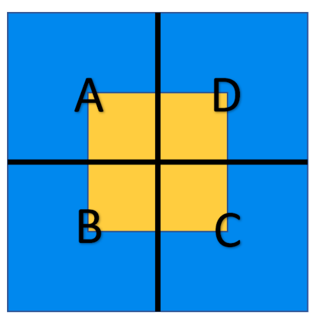

Fig. 3 Quadrants on sun sensor (top view)

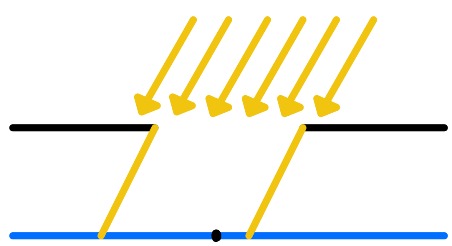

Fig. 4 Changing light spot with position of light source (cross-sectional view)

As the position of the Sun moves across the face of the sensor, the light spot will move in the opposite direction across the diode's four active areas (see Fig. 4). When illuminated, the diode material produces a voltage proportional to the percentage of the quadrant illuminated and the intensity of light shining on the diode. By comparing the voltage outputs from each of the four active areas (V_a, V_b, V_c, V_d) of the diode, the angle of the light illuminating the face of the satellite can be determined while on orbit [8].

Each sun sensor is handmade by the RHOK-SAT payload team and individually calibrated to ensure precise measurements. A sun sensor calibration consists of a light source and rotation stage to shine light at various angles about the pitch and roll axes of the sensor. Using Eqs. (1) and (2), the pitch and roll ratios, P and R, are plotted against the known angle of light. The line of best fit can be calculated and solved for the angle of the incoming light.

$$P = \frac{(V_b + V_c) - (V_a + V_d)}{V_a + V_b + V_c + V_d} \tag{1}$$

$$R = \frac{(V_a + V_b) - (V_c + V_d)}{V_a + V_b + V_c + V_d} \tag{2}$$

Equation (1) is used for calibration of the sun sensor as the Sun angle rotates about the x-axis of the payload face of the satellite. The value generated for P is plotted against the angle of light to generate a linear relation.

Equation (2) is used for calibration of the sun sensor as the Sun angle rotates about the y-axis. The value for R is plotted against the angle of light, generating a second linear relation.

An equation for the line of best fit is computed from each set of measured values (P and R). The inverse of the two equations is taken [9] to get the respective light angle values, θ_{pitch} and θ_{roll},

$$\theta_{pitch} = \frac{P - b_p}{m_p} \tag{3}$$

$$\theta_{roll} = \frac{R - b_r}{m_r} \tag{4}$$

P and R are the measured pitch and roll ratios from Eqs. (1) and (2) and b_p, b_r, m_p, and m_r are the unique y-intercept and slope constants taken from the lines of best fit of the pitch and roll calibrations respectively. While on orbit, RHOK-SAT will take voltage measurements from the sensor, compute Eqs. (1) and (2), and use the stored values for b_p, b_r, m_p, and m_r to solve for the position of the Sun using Eqs. (3) and (4). If the Sun is measured to be within a pre-determined field of view, discussed below, it will trigger a measurement of the cells.

C. Aerospace Measurement Units

An AMU is a passive measurement device that uses a variable resistive load to conduct IV sweeps on solar cells. The AMU's resistance starts at a maximum to measure V_{OC} and is decreased at predetermined intervals toward I_{SC}. The IV pairs that the AMU measures can be graphed to calculate the efficiency, fill factor, and P_{MP} of the cells at the time of measurement, as seen in Figure 5.

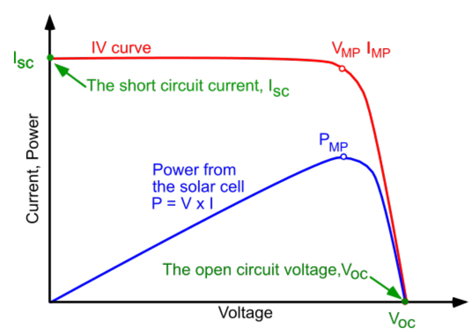

Fig. 5 IV curve of a solar cell. ***Taken from [10]***

Since the AMU takes passive measurements, it does not have the same capabilities as a Keithley SMU. For instance, the AMU relies on the voltage generated by the cell, meaning that sweeps can only occur when the cell is illuminated.

On the other hand, the Keithley SMU applies a voltage and measures current to sweep the cell regardless of light conditions. Further, the Keithley is capable of producing negative voltages. Since the AMU does not apply a voltage to the cell, it cannot use that technique to determine I_{SC}. These fundamental differences led to variations in data that the RHOK-SAT team was not prepared for until the function of the AMU was fully understood.

D. Temperature Sensors

RHOK-SAT will contain seven 1000-ohm platinum resistance temperature devices (RTDs) that will function as temperature sensors. An RTD's resistance varies with temperature in a predetermined profile. The AMU will apply a small current to each sensor, generating a voltage from which resistance is calculated. Temperature can then be determined from this resistance. Seven temperature sensors will be placed close to the cells, as discussed in the electromechanical assembly section.

E. On-orbit procedure

The payload volume can only accommodate eight AMUs. Six are used to measure the perovskites, one to measure the CIGS, and one for the sun sensor. Each AMU connected to a solar cell also measures the cell's temperature. The protocol for gathering data is as follows:

1) Sun angle measurement determines the threshold is met
2) Temperature measurements of all cells
3) IV sweeps of all pixels and the CIGS
4) Temperature measurements of all cells
5) Sun angle measurement

V. Electromechanical Assembly

A. Mechanical Design

The primary constraints guiding the mechanical design of RHOK-SAT's payload are the experimental perovskite samples, available payload volume, and mass limit. Perovskite cells are still in the early stages of development, making them more delicate than commercially available solar cells. The cells must be connected using a "dry" connection to avoid any chemical or thermal interference with the photovoltaic material. To meet this requirement, a custom electromechanical assembly was designed and fabricated by the RHOK-SAT team. The assembly uses a spring pin design (pogo pins) to create the electrical connection to the perovskite cells and an aluminum face plate to compress the cells to the pins. Fig. 6 shows an exploded view of these components.

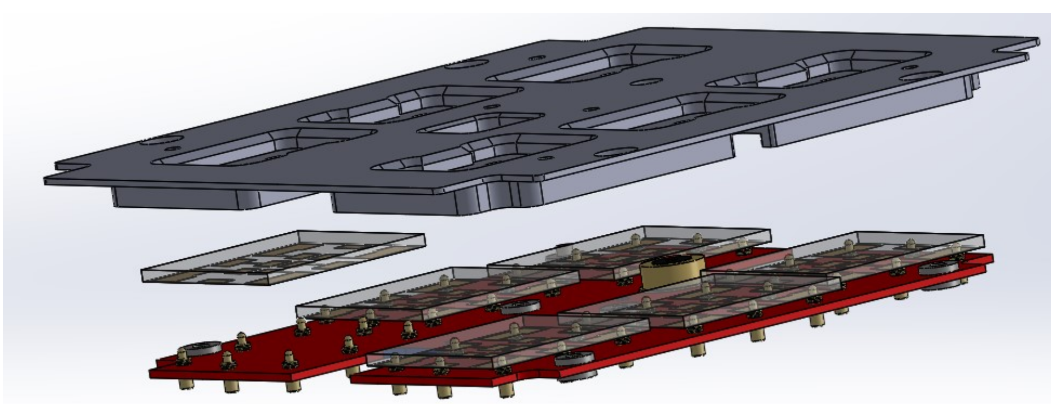

Fig. 6   Exploded view of the payload assembly

The aluminum face plate was developed to maximize the number of perovskite samples that could be mounted on the payload face of the satellite while still maintaining a low profile and minimizing volume. The face plate has a total of six square pockets, one securing each perovskite sample. Each pocket has six aperture holes above the six pixels on each sample (see Fig. 7). The aperture holes restrict sunlight to ensure that each pixel has the same area of illuminated

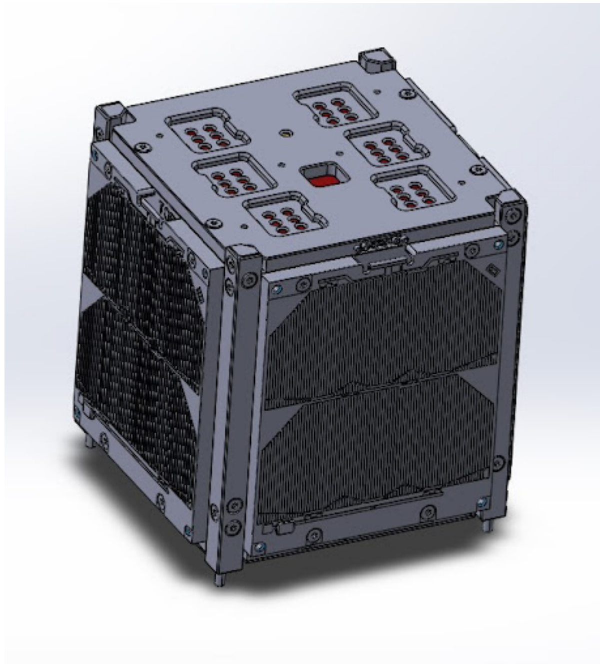

Fig. 7 Payload assembly integrated into the RHOK-SAT model

photovoltaic material. The manufacturing process of the perovskites can occasionally lead to slight differences in active areas. Controlling the illuminated areas of the pixels is needed for accurate data comparison. Each pocket also has a smaller pocket cut out to make room for the temperature sensors that will be mounted on the top side of the perovskite glass substrate.

A small aperture hole in the face plate sits above the sun sensor to restrict its field of view and limit stray light interfering with the sensor readings. The solar cells receive the most sunlight and produce the most power when the Sun is perpendicular to the cells. The Sun will only occasionally be perpendicular to the payload face, and a maximum angle of 35 degrees from perpendicular was deemed adequate. The sun sensor will thus have a 70 degree field of view. The top of the face plate has pockets cut out to minimize the distance between the top of the perovskite samples and the top of the aperture holes. There is no restriction of sunlight and all pixels receive the same sunlight within view of the sun sensor.

The face plate was designed and fabricated from aluminum 6061-T6 in house by the RHOK-SAT payload team, as seen in Fig. 8. Aluminum 6061-T6 was selected for its excellent corrosion resistance, machinability, and thermal properties. The aluminum is anodized before payload integration to further aid in space durability and corrosion resistance. The sun sensor and spring "pogo" pins are mounted onto a printed circuit board (PCB) which screws into the face plate to complete the mechanical and electrical connection to the perovskite cells. This board, called the pogo board, contains the circuitry to connect the 36 perovskite pixels, one CIGS cell and sun sensor to another circuit board with the eight AMU devices.

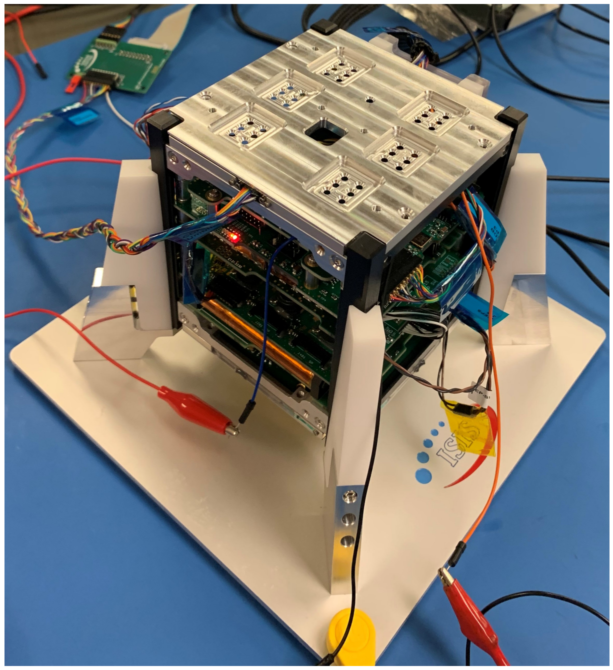

Fig. 8 Payload Face plate Integrated into the Engineering Model

B. Electrical Design

RHOK-SAT's payload includes two main circuits per perovskite sample: one to keep the perovskites under a resistive load and one to take measurements. The perovskites experience faster degradation if they are left in an open-circuit state than degradation caused by radiation alone. The resistor circuit was implemented so that they do not remain at V_{OC} for an extended time. Fig. 9 shows both circuit configurations, labeled "resistor circuit" and "measurement circuit". They are controlled by an analog switch. The same AMU is shown both at the top left and far right of the figure but split to add clarity to the circuit. When the switch is open, IV measurements will be taken with the AMU. When the switch is closed, the pixels will be held under a resistive load close to P_{MP}, and the measurement circuit will be inactive. The switch is closed by default. This ensures that the pixels will be under a resistive load in case the satellite loses power. The AMU contains an N-channel metal-oxide-semiconductor field-effect transistor (MOSFET) that is used as a logic input to control the switch.

The measurement circuit is comprised of perovskites, AMUs, and multiplexers, as shown in Fig. 10. Since the payload volume is limited and each AMU can only take one measurement at a time, multiplexers are used to independently measure all 36 pixels in groups of six. Each group contains one pixel from every perovskite sample, such that all pixels with the same label are measured simultaneously.

All components are spread across two PCBs: the pogo board and the AMU board, each designed in Autodesk EAGLE. The pogo board contains the perovskites, multiplexers, analog switches, resistors, and one side of a 60-conductor connector. It is fixed to the payload face of the satellite under the aluminum face plate. The AMU board contains the other side of the connector along with all eight AMUs. It plugs directly into the CubeSat Kit Bus (CSKB), which connects all major subsystems of the satellite together. The CSKB allows the payload to access the necessary power and data lines. These two PCBs, along with the top plate, allow RHOK-SAT to take effective measurements with the AMUs.

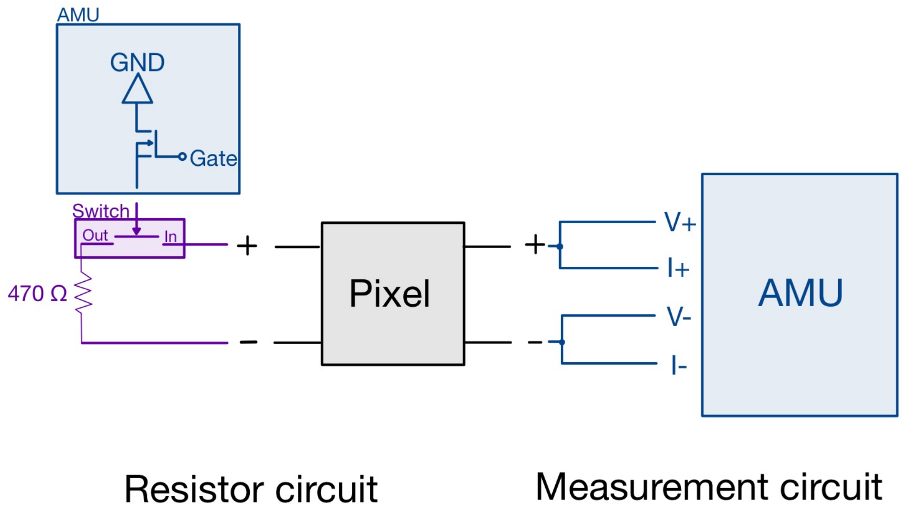

Fig. 9 Payload resistor and measurement circuits

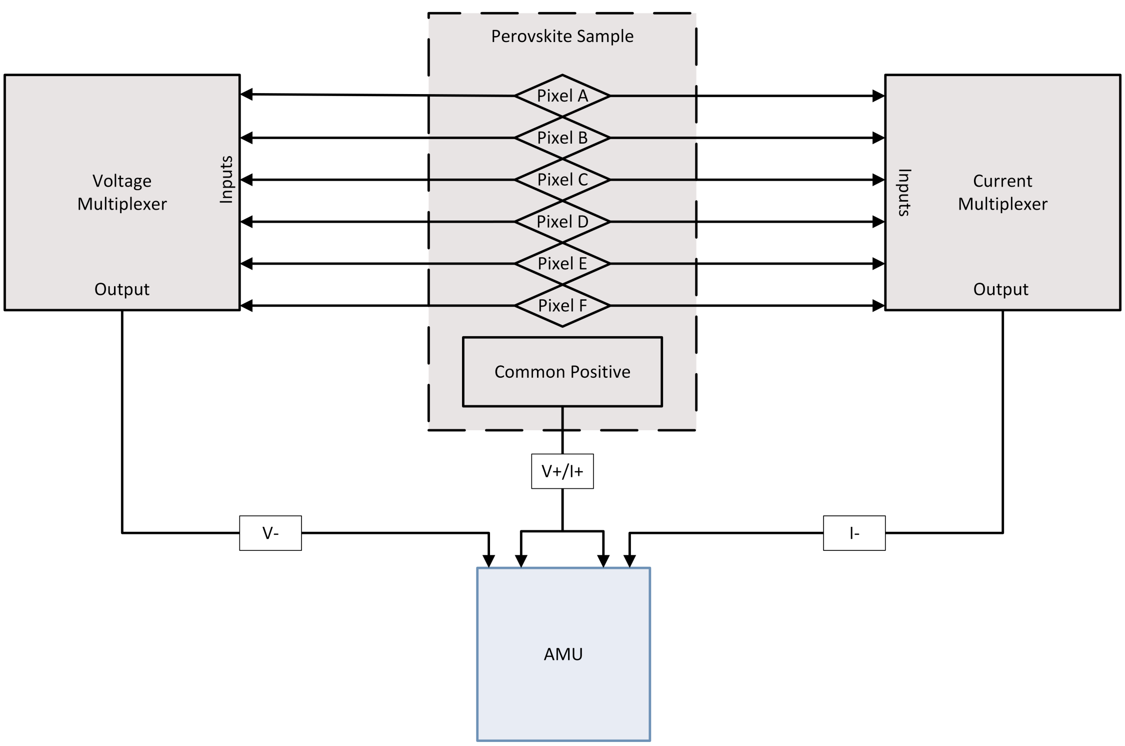

Fig. 10 Measurement circuit

VI. Next Steps

At the time of writing, the RHOK-SAT team is waiting on delivery of the flight model bus and components from ISISpace and other collaborators. All payload designs are complete, but PCB designs must be sent out for fabrication. Next steps for the team include fabricating the payload face plate and integrating all components into the engineering model. All machining will be completed in the Rhodes College machine shop on a HAAS Mini-Mill CNC by student members of the RHOK-SAT team.

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The AMUs were designed and provided by Colin Mann from The Aerospace Corporation in El Segundo, California.

The satellite structure and subsystems were provided by ISISpace in Delft, Netherlands.

Other student contributors to the project include Dang Nguyen, Anas Matar, Marouf Mohammad Paul, and Zheng Yu Wong. Past contributors include Mark Ellenberger, Giuliana Hofheins, Elijah Matlock, Johane Boff, and Raeba Roy.

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