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Thermal and Ultraviolet Modeling, Balancing, and Sensing

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ABSTRACT

A modeling system and a set of sensor arrays is proposed for demonstrating the thermal behaviors of a nanosat in extremely low earth orbit (ELEO). The Thermal and Ultraviolet Modeling, Balancing, and Sensing project (ThUMBS) is the proposed system, with the primary goal of ensuring the safe operating temperature of the second generation Taylor Satellite (TSAT) 2 -unit CubeSat in ELEO. A secondary goal consists of observing the behavior and influences of this temperature for use and analysis in future studies. ThUMBS is comprised of a modeling subsystem to ensure a 220 K - 310 K target operating range, a thermal sensor array with 0.5 K resolution, and a UV sensor array capable of monitoring incoming radiation from A-, B-, and C-bands of UV. Tertiary goals include passive observation with the UV arrays of phenomena such as lightning strikes and solar flares. A summary of the system level overview of the proposed ThUMBS project is outlined in this paper, and an educational focus on documentation of deliverables and assumptions, as well as the process of optimization to meet project goals is discussed. Implementation of such a regimented documentation protocol coupled with the software modeling used throughout is believed to be of benefit to enhancing student learning and their overall appreciation of the technological advancements made in the applied sciences.

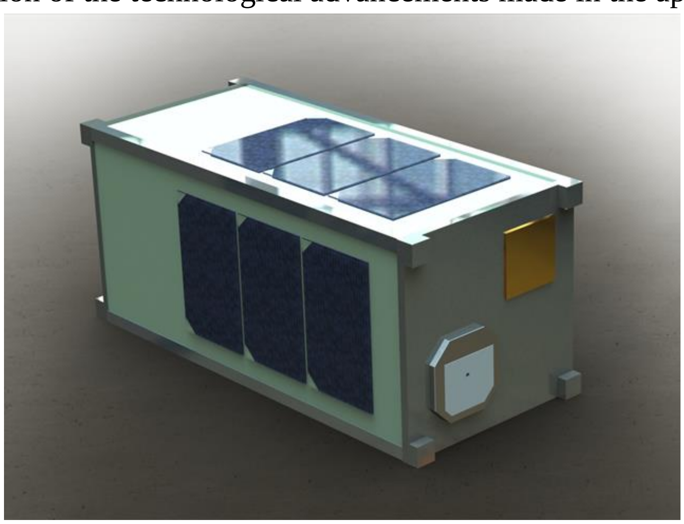

Figure 1: SolidWorks 3D model of TSAT.

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INTRODUCTION

The Taylor Satellite (TSAT) project includes the Thermal and Ultraviolet Modeling, Balancing, and Sensing (ThUMBS) subsystem that is scheduled to launch with NASA in the summer of 2013, and will be set into a decaying orbit as it spirals through ELEO, tumbling at first before gaining stability, and eventually combusting at the end of its mission. The resulting flight path will expose TSAT to temperature extremes — both high and low — which may endanger the safe performance of the numerous sensitive instruments on board. This necessitates the thermal modeling of the satellite, as well as potential alterations to the surface materials to ensure safe thermal equilibrium.

Due to the complex and occasionally unpredictable nature of the thermal environment, mere modeling of the satellite would render an incomplete design. The addition of a thermal sensor array serves not only to confirm the validity of the model for future use, but also its potential to convey raw data on phenomena that are otherwise more difficult to calculate, such as the thermal reaction to solar flares and eclipses, and aspects pertaining to atmospheric re-entry.

The raw data captured by the thermal array is difficult to interpret without context, necessitating, therefore, the implementation of a simple UV sensor array. By measuring incoming UV radiation from the Sun during the initial tumbling of the satellite, the Sun's actual radiation intensity can be calculated in relation to the satellite's temperature. Similarly, any solar flares observed by the UV array can be compared to any temperature spikes measured by the thermal array.

The ability to compare data between the ThUMBS project and other TSAT projects offers a unique opportunity to make validating observations. For instance, any UV flashes believed to be from lightning strikes can be compared to the incidence of VLF "whistlers" created by lightning, as measured on the E-field and VLF sensor project (see Orvis et al., 2013[1]).

THERMAL MODELING

Concept

A primary goal for the thermal modeling is to determine that the wide temperature fluctuations encountered during the mission — as observed with similar small satellites in ELEO (see Bauer et al., 2012[2]) — do not compromise the designed performance of TSAT or any of the delicate instrumentation on board. To do this, simulations of the heat and light sources and various materials on both the inside and outside of the satellite must be created to account for the day and night cycles. Due to the size, power, and weight constraints, any thermal protection must be a passive system, i.e. one that does not involve moving parts or a power source to function.

The governing equations (see Lazar et al., 2002[3]) are:

$$P_{out} = \epsilon\sigma A_{out}T^4$$

$$P_{in} = P_{sun}\alpha A_{in} + P_{waste}$$

Where

$$P_{out} = heat\ loss\ over\ time\ due\ to\ radiation$$

$$\epsilon = emissivity\ of\ surface\ material$$

$$\sigma = Stephan - Boltzmann\ constant$$

$$A_{out} = effective\ radiating\ surface\ area$$

$$P_{in} = heat\ incoming\ over\ time$$

$$Psun = power\ per\ area\ incoming\ due\ to\ solar\ radiation$$

$$\alpha = absorptivity\ of\ surface\ material$$

$$A_{in} = area\ affected\ by\ radiation$$

$$P_{waste} = heat\ over\ time\ generated\ by\ electronics$$

Simulink Modeling

The commercially available software known as Simulink was used as the primary analytical tool to model the thermal effects on TSAT. As can be seen in Figure 2, the model calculates the worst case temperature scenarios by simulating the hot and cold temperature extremes of TSAT, based on the balance of power absorbed versus power lost. The power received by a radiating source is scaled by the affected surface area and the average absorptivity for that area. The power lost is based on the temperature and average emissivity for the radiating area. The model in Figure 2 is the hot case analysis with no surface modifications.

As seen in Table 1, the addition of surfaces with high emissivity/absorptivity ratios reduces the hot case temperature, but also lowers the cold case temperature far below the safe operating range. The conclusion, thus, is that the high-emissivity of the radiative thermal protection is insufficient to adequately control TSAT’s thermal environment.

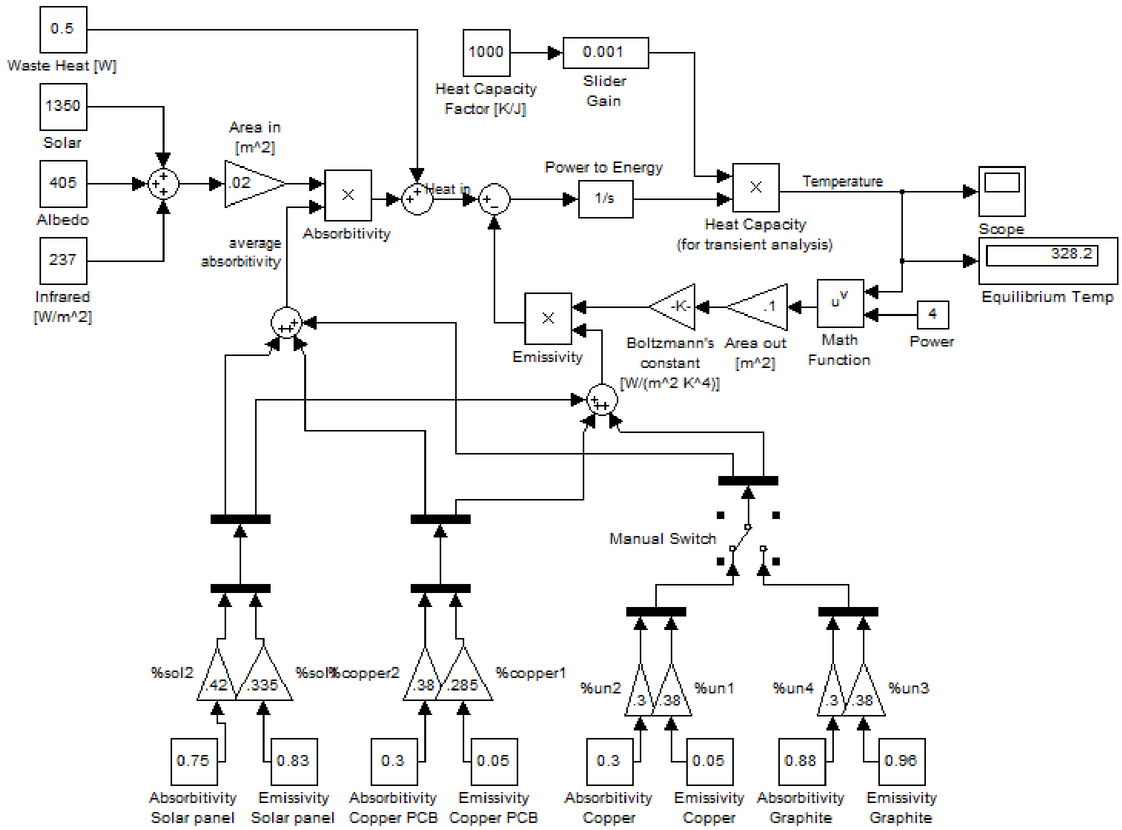


Figure 2: Simulink thermal model.

Table 1: List of results of the Simulink model.

	Without modifications	With graphite-based surfaces
Hot case	328.2 K	294.8 K
Cold case	241.4 K	208.4 K

SolidWorks Modeling

The limitations of a block diagram calculator such as Simulink are fairly apparent: it is inefficient at calculating with internal thermal resistances and transient characteristics in complicated bodies. For this purpose, the program SolidWorks was used.

In SolidWorks, a simple model of the satellite and its flight hardware was created, using blocks to represent the largest student sensors and devices on board (Figure 3). Several thermal simulations were performed using different thermal protection designs (not pictured) until a satisfactory proof-of-concept version was found (Figures 4, 5).

As seen in the Simulink model, applying surfaces with high emissivity/absorptivity ratios lowers not only maximum temperatures, but also minimum temperatures as well[3]. In this version, instead of applying a carbon-based high emissivity surface to the outer shell of the satellite, an insulating surface is placed between the high-absorptivity solar panels and the copper shell, creating a buffer zone which alleviates extreme temperatures[2] and slows the rate of temperature change during transient analysis in comparison to high-emissivity elements.

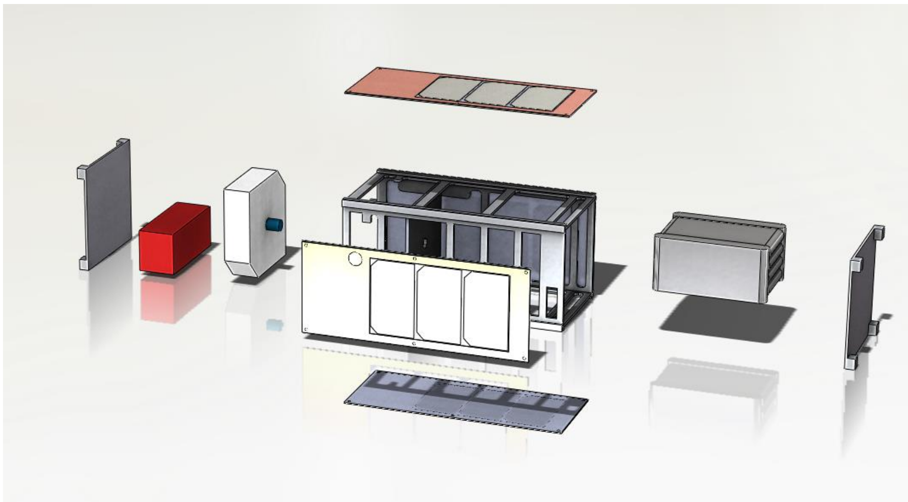
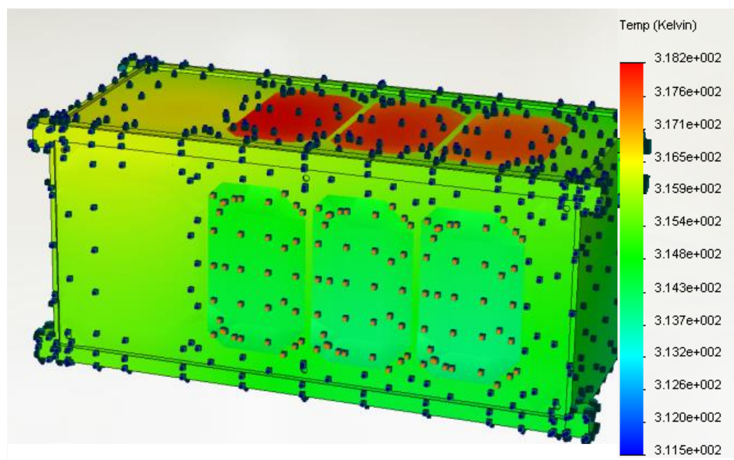
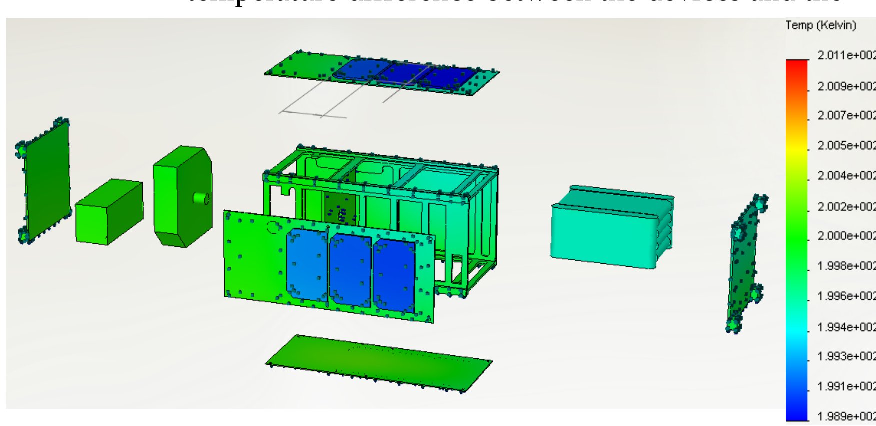


Figure 3: Exploded view of SolidWorks physical model, with internal devices displayed.

All thermal TSAT simulations performed up to this point have been equilibrium calculations (i.e. not transient calculations), and therefore do not involve the thermal inertia of the craft. The actual craft will fly with a 90-minute orbit, and is expected to smoothly transition between regions of cold and hot. This means that the temperature as determined by a transient analysis should fluctuate sinusoidally somewhere between the hot case and cold case temperatures, with extreme temperatures being far less severe (see Arroyo, 2009[4]).



Figures 4 (above), 5 (below): Hot and cold case thermal results for the chosen setup, demonstrating temperature difference between the devices and the



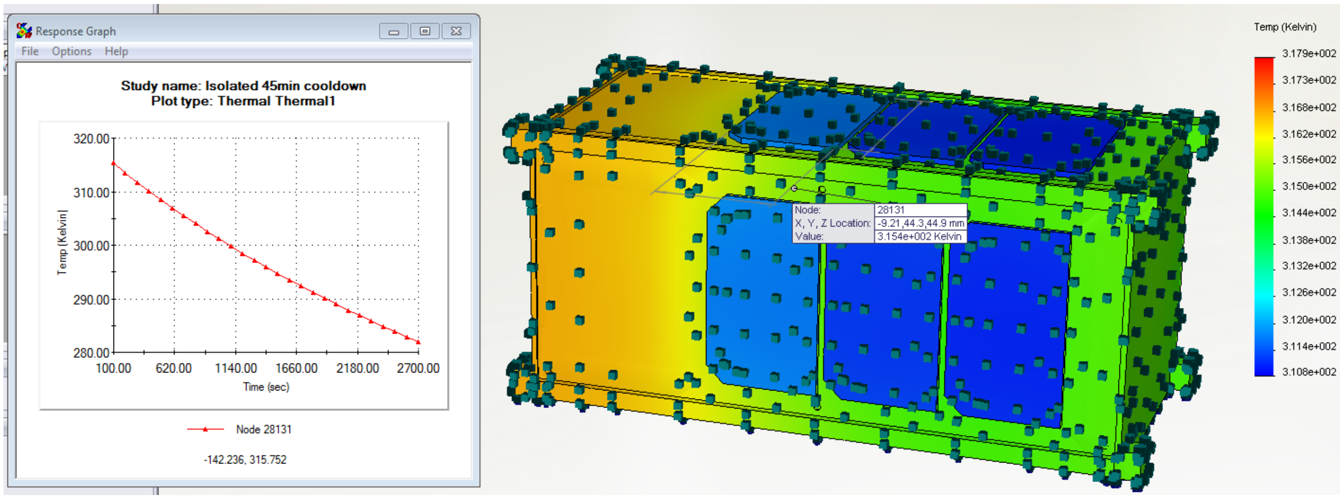


Figure 6: Transient response of TSAT, cooling from hot case temperatures over 30 minutes.

The transient temperature profile of TSAT as it cools over a 45 minute period (half of its 90-minute day/night cycle) is shown in Figure 6. The model imitates what would happen if the satellite was raised to its hottest temperature before being instantaneously introduced into cold surroundings, similar to what would happen if the Sun was to suddenly be eclipsed. As seen, the temperature drops by 35 K to a minimum of 282 K, still well within a safe operating range, in spite of the cooling rate being feasibly taken to be a maximum.

Recommendations for Future Research

Even while constrained to small available surfaces and mass, a CubeSat's thermal equilibrium can be adequately controlled without requiring an active cooling system.

Due to the limitations in modeling, a full-orbit transient analysis was impractical. For any future CubeSat missions, more etailed and optimized models are recommended for the sake of performing full-orbit analysis (see Reiss et al., 2012[5]).

Judging from these results, any future CubeSat missions from Taylor University at this point will carry some form of insulative thermal protection instead of radiative surfaces.

THERMAL SENSING

Concept

The purpose of the thermal sensor array is to actively measure the temperature of TSAT, not only to validate the thermal model, but also to account for phenomena not readily modeled, such as any temperature spikes from solar flares and the temperature of the satellite in its final phase when it begins to combust. Such phenomena are more difficult to model adequately, but can provide valuable information for future missions, such as an indication of the lowest altitude at which the satellite can safely fly, and whether any further effort must be taken to protect more delicate instruments from temperature spikes.

Physical Aspect

To measure the temperature, TSAT contains thermal diodes at various points of interest. Specifically, there are a total of ten which are thermally coupled to the interior wall of the satellite's shell, plus an additional six that are affixed to various detectors, amplifiers, and processors.

Electrical Aspect

The electrical aspect of the thermal array is designed to meet the required 0.5 K resolution and offer basic shut-off failure mitigation. Each thermal diode is provided with a +5 V source, and the signal relayed back to the primary circuitry. Due to the large number of signals, multiplexers (or "muxes") are used to allow the processor to handle the data one signal at a time. After the signal is muxed, the current from the thermal diodes is driven across a sensing resistor. Due to the relatively low resulting voltage span and consequently low resolution, the signal is then amplified and offset using a high-precision instrumentational amplifier.

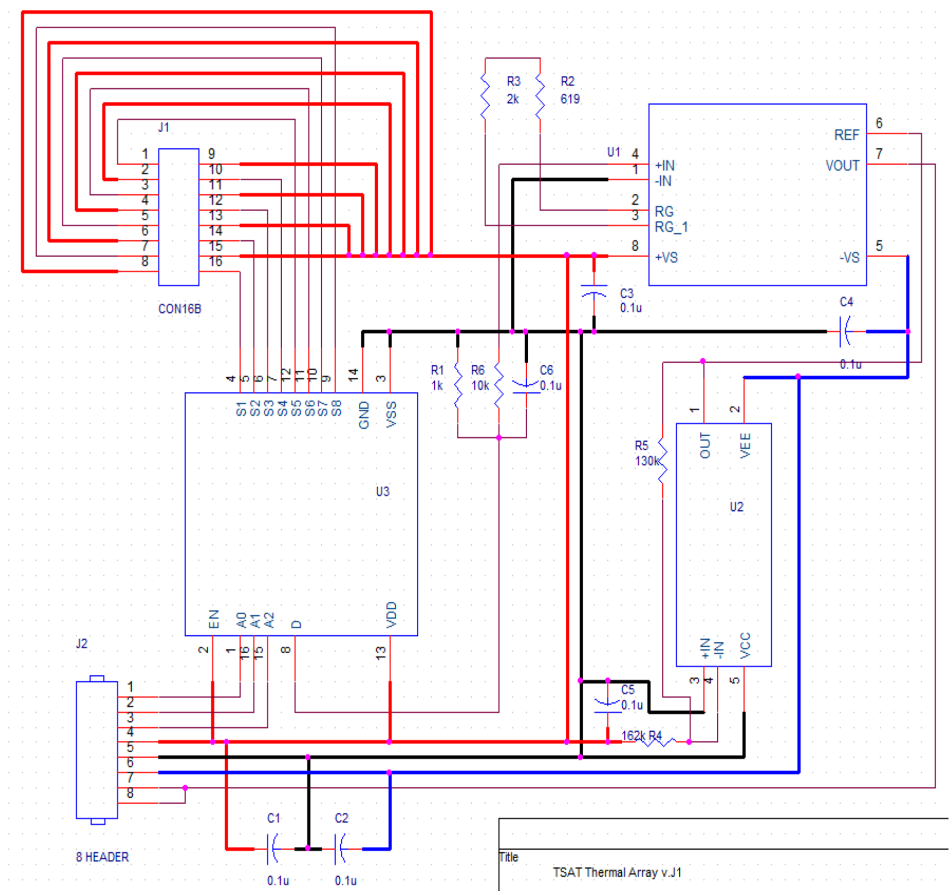
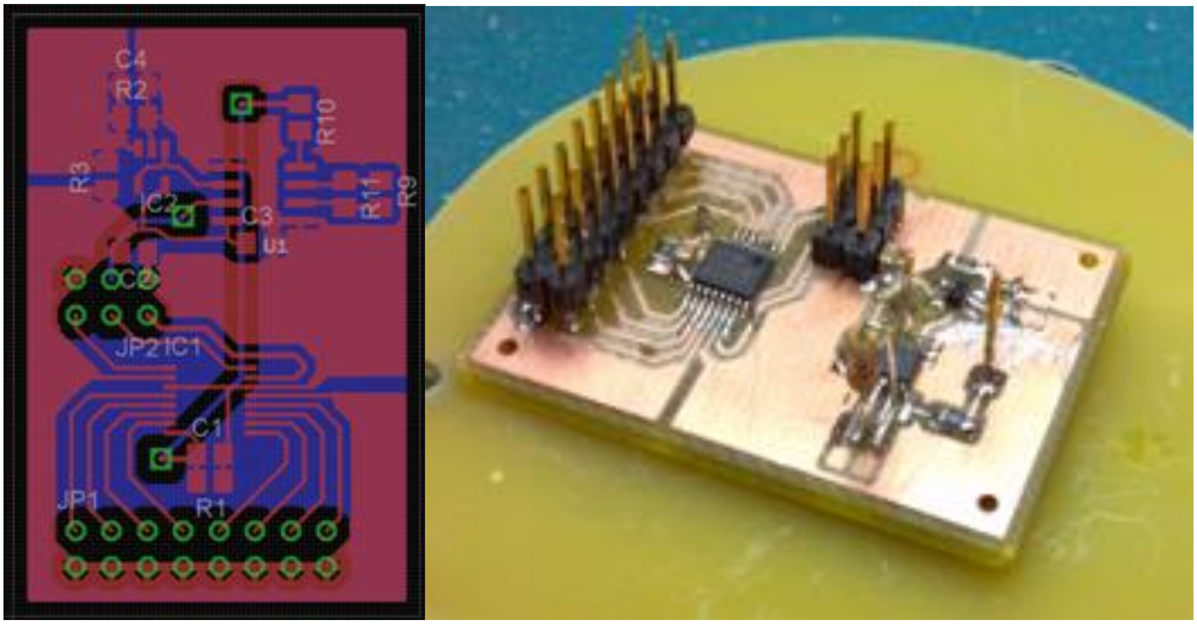


Figure 7: Final prototype of thermal array circuit diagram.



Figures 8, 9: Early prototype of thermal array PCB design and implementation.

Failure Mitigation

Due to the high risk of a thermal diode becoming shorted, several precautions must be taken to ensure that the rest of TSAT is not affected. For instance, due to the fact that the power source of the diodes is an isolated source, in the event of a short being encountered, it can be shut off without shutting the power to any other device. Similarly, the 16 sensor signals are relayed through a pair of identical muxes and amplifiers (i.e. half the total number of sensors per mux), so that if a shorted sensor causes damage to a mux or amplifier, the entire set of thermal sensors will not be lost.

UV SENSING

Concept

The purpose of the UV sensing is to observe the incoming radiation in the UV frequency ranges for comparison to other data sources. As mentioned in the introduction, one interesting comparison of data involves UV radiation spikes to that of "whistlers" on the VLF E-field sensor [1] for identifying lightning strikes. Other potential comparisons may involve the intensity of the aurora to the frequency of incidence of high energy particles striking the on-board solid state detector (SSD), or of solar flares to plasma field density spikes (see McClure et al., 2013[6]).

In addition to data comparisons, the UV sensing array can be used to calculate the speed of rotation of TSAT, by observing the frequency of incidence resulting from UV radiation characteristics of the Sun's rays or the thermal radiation of the Earth (see Kandimala, 2012[7]).

Physical Aspect

In order to effectively measure the incoming radiation, a unidirectionally oriented array consisting of three optical diodes, one for each of the bands (100 - 400 nm wavelengths) of the UV spectrum, are used. These are contained in a single block (see Figure 10) or some similar configuration, with a ± 10° viewing angle. The ideal orientation of this array is either towards the Sun or the Earth, but due to the way TSAT may rotate and settle in unknown orientations, the satellite may stabilize with the sensor array pointing along either vertical axis. The sensor must therefore be able to collect data from a wide variety of orientations.

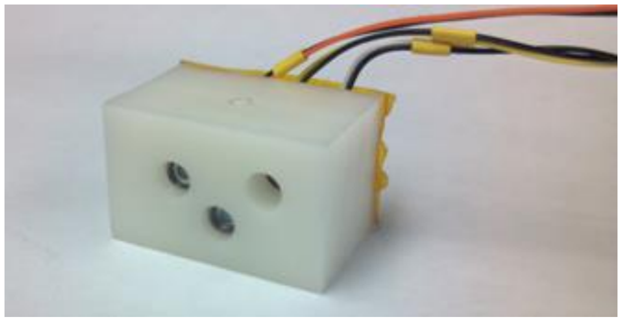


Figure 10: UV array in block

Electrical Aspect

The circuitry of the sensor array consists almost entirely of three transimpedence electrometers, as seen in Figure 9. Due to there being only three UV sensors, muxes are not required, as the resulting increase in signals can be counterproductive.

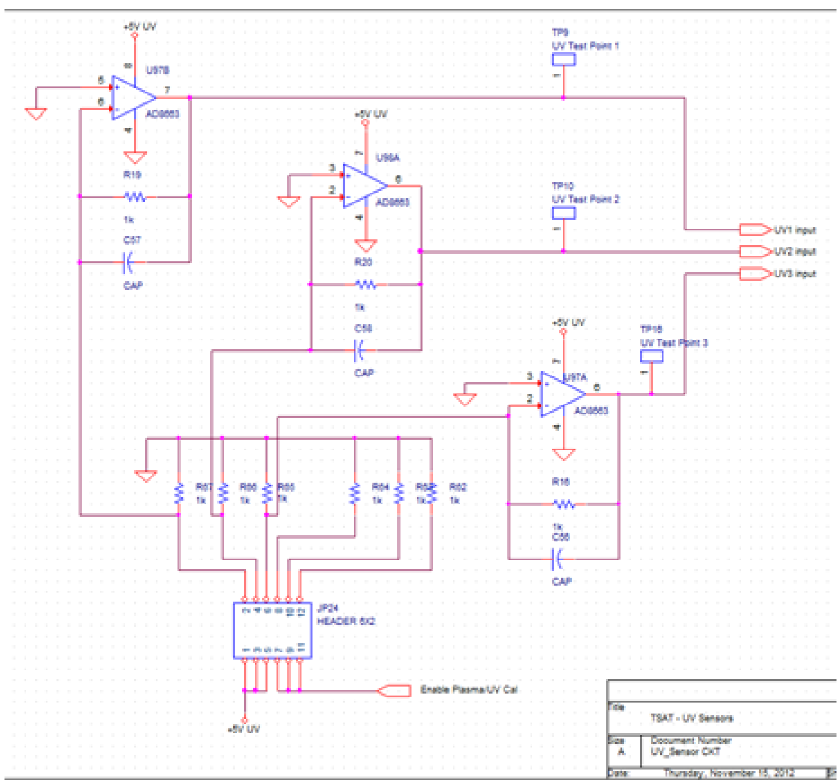


Figure 9: UV sensor shaping amp circuitry.

CONCLUSIONS

In this document, a case was made for requiring insulative thermal protection in CubeSats, demonstrating the temperature extremes that arise from flying in ELEO. In addition, based on the design of the TSAT CubeSat, thermal and UV sensor arrays capable of validating the modeled analytical results from vital in-situ data being collected, will offer invaluable insights into future flights.

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BIOGRAPHICAL INFORMATION

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