Preliminary Design of a Solid-State Thermoelectric Cooling System for Small Satellite Sensors

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   The growth of small satellites, including Cubesats, is rapidly increasing, with the number of small satellites in orbit being forecasted to double in the coming years. With the explosion of small satellites, SpaceWorks projects that 64% of small satellites will perform earth sensing missions between 2017 and 2019. As small satellites are increasingly being used for these remote sensing missions, the payloads on board become more complex, resulting in increased heat production. With this in mind, the cooling of sensors in small satellites, like Cubesats, is an increasing problem with more sensitive and capable payloads in smaller platforms. The dissipation of heat in these sensors is difficult within the Cubesat platform, among other small satellites. Thermal noise, from sensor heat, can decrease Signal to Noise Ratio (SNR) levels, lowering the quality of data gathered. SNR levels are often increased with either larger lenses, a solution often impossible with small satellites, or with direct active cooling of the sensor. Cryocoolers are often used to actively cool sensors, but require moving parts, induces vibration onto the payload, and with respect to cryostats, can limit the mission lifetime. The use of a solid-state thermoelectric module, utilizing the Peltier Effect, can significantly reduce mass and mission lifetime from a cooling system. Previous research into integrating thermoelectric modules focused on feedback control systems. This paper discusses the Electric Thermal Cooling for Small Satellites (EThCoSS) system, utilizing a thermoelectric module and a Cubesat compatible heat dissipation method. The EThCoSS system is expected to increase SNR levels by at least two-fold, decreasing dark current in CMOS and CCD sensors to near zero. The design involves a single-stage thermoelectric module, coupled with a radiator and thermal straps. The system is being prototyped using a CPU liquid cooler to benchmark improved SNR levels and the needed performance from the radiator to operate in space. The design will be tested to demonstrate the results for at least doubling SNR from operating temperatures and to sufficiently dissipate heat from the thermoelectric module. The design, development, and testing aspects will be presented at the conference.

Nomenclature

AS	=	Actual Signal (number of electrons)
CCD	=	Charge-Coupled Device
CMOS	=	Complementary Metal-Oxide Semiconductor
COTS	=	Commercial Off The Shelf
D0	=	Dark Noise at Zero Degrees Celsius
DN	=	Dark Noise (number of electrons)
MOCI	=	Mapping and Ocean Color Imager Satellite
MWIR	=	Medium Wave Infrared
OBJ	=	Object Flux (electrons/pixel/minute)
QFD	=	Quality Function Deployment

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RN	=	Read Nosie (number of electrons)
SNR	=	Signal-To-Noise Ratio
$SPOC$	=	SPectral Ocean Color Satellite
$SWIR$	=	Short Wave Infrared
TEC	=	Thermoelectric Cooler.
t_{sub}	=	Exposure Time (minutes)

I. Introduction

WITH the introduction of Cubesats by Bob Twiggs and Jordi Puig-Suari in 1999, the small satellite industry has embraced the standardized satellite bus for a variety of purposes and missions. Cubesats, and their standard platform, are based off the combination of single units, or "U's". A single unit Cubesat, called a 1U, has dimensions of 10 cm x 10 cm x 11 cm. Larger Cubesats are also able to be created, including 3U and 6U Cubesats, with dimensions of 10 cm x 10 cm x 33 cm and 10 cm x 20 cm x 33 cm, respectively. The standard platform now enables universities and companies to develop satellites rapidly and at very low costs, enabling increased access to space. A variety of new missions and increased frequency of mission types, like earth observation missions and constellations, are now viable due to this standard satellite system. Between 2009 and 2016, approximately 43% of small satellites performed Earth observation or remote sensing missions. The number of small satellites performing those same missions is expected to increase to 64% between 2017 and 2019 (Ref. 1). A majority of these earth sensing missions have payloads which utilize payloads with CMOS and CCD sensors. CMOS and CCD sensors work by converting photons into electrons, the efficiency of this conversion is referred to as the Quantum Efficiency of a sensor. Sensor performance can be characterized by this Quantum Efficiency. The newly created electrons are held in wells, found in both CMOS and CCD sensors. These wells cannot hold an infinite amount of electrons, and the maximum amount of electrons each well can hold is called the well capacity. When a well becomes full, electrons overflow into other wells, resulting in a blooming effect. This blooming effect can be mitigated with larger wells, but this can translate into poorer data, as wells may not become as filled as necessary to provide a necessary gain.

Figure 1. CMOS Sensor Blooming. *An example of sensor bloom is seen here. The number of electrons converted from the sun overflow into surrounding pixels, producing the hazy shape of the sun.*

Additionally, CMOS and CCD sensor performance can be defined through SNR, which is a function of the total signal received by a sensor. Generally speaking, SNR can be calculated with the following formula:

$$SNR = \frac{AS}{\sqrt{AS + RN^2 + DN^2}} \, [6]$$

(1)

Given this equation, it can be seen that dark current noise is a large contributing factor to noise at long duration exposures. Read noise is a constant, as that is inherently part of the way the sensor reads electrons, and is not associated with time. Dark current noise is the result of remnant thermal energy in the silicon of the CMOS and CCD sensors, and is a function of the exposure time measured in electrons/second. As exposure time increases, dark noise can begin to play a large role in decreasing SNR levels, resulting in poorer quality data (Ref. 2). When this occurs in spectrometer payloads, SNR can be boosted in post-processing with binning. The process of binning results in a loss of resolution, both spectrally and spatially.

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[6] https://www.photometrics.com/resources/whitepapers/signal-to-noise.php

Cooling of CMOS and CCD sensors offers a potential solution to providing higher quality data and preserving high spectral and spatial resolutions. Since dark current noise is a result of thermal energy, lowering the temperature of CMOS and CCD sensors allows the dark current to be reduced. This means that smaller wells can continue to be used, without the risk of blooming due to dark current noise, and that long exposures can be taken with preservation of data. This type of data is applicable to night-time earth sensing missions, where high sensitivity and long exposure times can lead to high noise. Cooling CMOS and CCD sensors essentially opens the possibility of continuing spectroscopy data gathering during nighttime.

Additionally, the infrared bands are a large focus of study for weather satellites and other remote sensing missions. To detect MWIR wavelengths and larger, CMOS and CCD sensors are required to be cooled. The blackbody radiation of the sensor itself can be picked up at MWIR wavelengths, and cooling the sensor mitigates these effects (Ref. 3).

II. Design Requirements

With the rapid growth of small satellites with remote earth sensing payloads, more sophisticated and complex payloads are expected. These payloads demand higher resolution and better quality data, a demand which is difficult to fit within the Cubesat platform. A side-effect of these higher quality payloads is the SNR, due to the limited size constraints and increased heat from sensors. A potential way to increase SNR is through the use of larger lenses, to let additional light into the sensor, thereby increasing SNR. This solution proves near impossible to implement, as larger lenses cannot always fit with the Cubesat platform. Cooling the complex sensors to retain high spectral and spatial resolution, as well as preserving high quality data, is necessary in the coming years to maintain the miniaturization of satellite technology.

Current missions which could benefit from sensor cooling include the University of Georgia's Small Satellite Research Laboratory's two Cubesats, SPOC and MOCI. Both of these missions use CMOS Sensors to collect images and data of Earth from LEO.

SPOC's primary objective is to perform a hyperspectral analysis of vegetation heath, primary productivity, ocean productivity, near-coastal sediment, organic matter, and mapping the production of shelf water and salt marshes. The data gathered from SPOC will then be used to create a Georgia coastal imagery library. The current payload configuration for SPOC results in a low SNR, and on-board binning is performed to increase SNR. The binning results in a loss in important spatial and spectral resolution of data. A cooling system on-board SPOC would greatly increase resolution of data.

MOCI's mission primarily focuses on Structure from Motion (SfM), an imaging technique for estimating three-dimensional structures from two-dimensional image sequences, to generate 3D point clouds of Earth's surface, and secondly on gathering ocean color data and track the health of the Georgia coast. Cooling of MOCI's CMOS sensor would permit better spatial resolution, resulting in more accurate, less noisy point clouds, and consequently more accurate and detailed representation of structures on earth.

Another potential customer is an American Earth imaging company called Planet. This company designs and manufactures 3U Cubesats called Doves, which have been delivered into orbit since 2013. Planet's Dove Cubesats utilize CCD sensors. The "Doves" are deployed into orbit in flocks, together they form a satellite constellation that continuously scans Earth and provides a complete image of it. The images gathered by the Doves provide up-to-date information relevant to climate monitoring, crop yield prediction, urban planning, and disaster response. Cooling of CCD sensors in the Doves would reduce sensor noise and consequently improve the quality of images. The increase in image quality equates to an increase in profit margin for Planet and better data for their customers.

Although the core requirement of the system is to provide cooling capability to a CMOS or CCD sensor, using a TEC, there are chief specific system requirements. The first system requirement is that it has to be modular. With the system being modular, the system can be easily adapted and attached to different Cubesat payloads, without causing large changes to mission designs. The second system requirement is that the system must adhere to existing standards, including AIAA, ASME, and NASA low-outgassing requirements. By following these requirements, this system can see a shortened development cycle for a quicker integration into real Cubesat missions. The third system requirement is that there will be no moving parts when the system is in operation. In order to reduce the risk of failure, and to increase the mission lifetime of Cubesats, solid-state components will be used. This requirement essentially dictates the use of a TEC for active cooling capability. The fourth system requirement is that the system needs to be operable in a near-vacuum environment. This requirement limits heat dissipation techniques to only radiation and conduction, eliminating the use of convection or fans. The fifth system requirement is that the system must conform to the Cubesat form factor. By complying with the Cubesat form factor, the system can be integrated into more missions. Since the Cubesat form factor is one of the smallest standards for satellites, the ability to

Relative Weight	Weight	Requirement
7.3	4.0	Modular Design
9.1	5.0	No Structural Compromises
14.5	8.0	Adheres to NASA Low-Outgassing Requirements
5.5	3.0	No Moving Parts
18.2	10.0	Operational in Near Vacuum
16.4	9.0	Conforms to Cubesat Standard
3.6	2.0	Low Cost
1.8	1.0	Short Manufacturing Time
10.9	6.0	Low Sensor Temperature
12.7	7.0	High Heat Dissipation Rate

Table 1. List of System Requirements. *The requirements were weighted to determine the importance of each requirement. Weights are a result of the QFD study.*

translate the system into a larger satellite can be done easily. The final system requirement dictates that the system shall increase SNR by two. These requirements, among others which were excluded for clarity, can be found in Table 1.

A QFD study was performed to develop these requirements and determine which of these requirements are the most important to pursue. The study found that the ability to operate in near-vacuum and conforming to the Cubesat form factor are of the most important requirements. Throughout the design process, these two requirements will be followed. The result of the requirement weighing can be found in Table 1. This study also looked at competitor systems, which are discussed in Section III. The study found that TECs as a cooling mechanism are a good middle ground between cooling ability of active systems, and the size of passive systems.

III. Feasibility Study of Cooling Systems

A trade study was performed to investigate the available options to cool a sensor on a Cubesat. Cooling systems can be divided into two categories: passive thermal control and active thermal control. Passive thermal control takes advantage of material properties to either promote or reduce the amount of heat transfer across a thermal gradient. Active thermal control generally requires a power source and a feedback control mechanism, and will always introduce additional energy to a closed system. Driving criteria in this trade study look at the size compatibility with Cubesats, the coldest temperature reachable, and risk to mission success and lifetime.

A. Passive Cooling Systems

Thermal heat sinks that contain phase change materials or materials with a high thermally conductivity can be used to control the temperature of a Cubesat. The phase change heat sink takes the thermal energy directly from the object and stores it as latent heat of fusion or sublimation. Because phase changes require large amounts of energy, this allows more heat to be stored than a regular heat sink. Thermal Management Technologies has developed a phase change thermal heat sink for Cubesats. This device is capable of storing energy in a phase change, letting heat escape or put back into the satellite.

Most current heat sinks currently in use however use a high thermally conductive material to store thermal energy. While gold, silver, and copper have the best thermal properties for this task, usually aluminum is used for this task due to its lower cost. Heat sinks usually are paired with heat pipes, but heat pipes are not widely commercially available for Cubesats.

Application of a patch of material to the surface of a different material is an often used example of passive thermal control. For example, applying patches of different materials such as aluminum, gold, silver, and copper with differing thermal conductivities on the exterior of the CubeSat can allow for thermal control, as different materials have different thermal properties. These material patches can control the internal temperature of the CubeSat, much like insulation.

An additional thermal control mechanism is known as louvers. In essence, louvers are shutters that can be opened and closed and are typically found on large satellites. This allows for heat to be retained or shed via radiation by opening and closing of the louvers. This technology is being miniaturized by NASA Goddard for use on Cubesats. Louvers are planned to be tested on a Cubesat platform with the Dellingr Mission, which is due to launch within the year. If successful, NASA Goddard partners could use the technology, or the technology could be licensed out for production for use in future Cubesat missions (Ref. 4).

Although passive cooling systems can typically be easily fit to Cubesat missions, passive cooling cannot cool a device or sensor to below ambient temperatures. This means that passive cooling systems are not ideal when cooling

requires a temperature below that of the satellite. The cooling of sensors to increase SNR typically requires the sensor to be cooled to sub-zero temperatures, especially when dealing with MWIR operations. For this reason, passive cooling systems are typically not used for these types of applications.

B. Active Cooling Systems

Although passive cooling systems cannot cool components or sensors to below ambient temperatures, active cooling system are able to perform deep cooling on satellites. But, due to power and size constraints, active thermal control units have not been developed as heavily as passive thermal control mechanisms for Cubesat missions. Cryocoolers are often used in larger satellites. Space qualified cryocoolers have been extensively developed for large military and commercial satellites, and CubeSat compatible Stirling Cryocoolers are available upon special order from a select number of companies, like Iris Technology. This means that these devices are not very modular and can cost a lot. These cryocoolers are able to reach a healthy range of temperatures and heat loads, from 95 K at 10W heat load to 10 K at 250 mW heat load, but the input power required to operate is significant, sometimes up to 500W. Despite some special cryocoolers available for Cubesats, such as the mLCCE developed by Iris Technology, the state-of-the-art of cryocoolers simply is not compatible with the CubeSat platform. Because cryocoolers involve complex thermodynamic processes, it's difficult to downscale cryocoolers to the Cubesat platform, and maintain their effectiveness. As cryocoolers get smaller, effects of the miniaturization can make a cryocooler less effective (Ref. 5). Although direct research into the decrease in effectiveness with miniaturization of cryocoolers has not been performed, cryocoolers have other qualities which make them unsuitable for Cubesats. Cryocoolers make use of motor systems, which can vibrate payloads. Although research has been shown that a low-vibration cryocooler can be developed for satellites, these systems are difficult to implement in the Cubesat platform because of the decrease in effectiveness with miniaturization (Ref. 6). Cryocoolers always make use of moving parts, which inherently increase mission risk. Although Cubesat missions are heralded for taking on unnecessary risk, cryocooler risk directly jeopardizes the operation of onboard payloads, which calls into question the use of cryocoolers, no matter the mission.

Students at UC Irvine are currently developing a system to variably control emissivity of a radiator, they have dubbed their system the Variable Surface Emissivity Radiator (Ref. 7). By passing a voltage across titanium dioxide, which is applied to the radiator, the color and the emissivity of the radiator can be adjusted. This phenomenon can limit or maximize radiative heat transfer. Although considered passive, the system utilizes the varying of an electric voltage, which is inherently active.

TECs are a technology which uses the Peltier Effect to remove heat from a device or sensor. As a current passes through a series of semiconductors, heat is transferred from both sides of the semiconductors. The exact physics of the TEC is described later in this paper. TECs are solid-state, not involving any moving parts, and are as thin as a piece of bacon. Being solid-state, TECs can operate without risk of damaging the payload, and do not experience fatigue as cryocoolers do. The size and lightweight nature of TECs make them easy to integrated onto payloads, especially in the Cubesat platform. A team at the University of Maryland performed research into the use of a TEC onboard a Cubesat, but mainly focused on control mechanisms for the TEC, rather than heat dissipation design (Ref. 8). TECs do have power consumption concerns, however these can be minimized with proper design of heat dissipation mechanisms.

C. Trade Study Decision

Although passive cooling systems are easy to implement on the Cubesat platform, their inability to cool devices and sensors to below ambient temperatures is a significant drawback, which throws out primary cooling systems as the primary method of cooling a sensor. Cryocoolers offer the most cooling capability for satellite sensors, but these systems often are difficult to integrate onto Cubesats because of their shape and moving parts. With a cryocooler's moving parts, fatigue is expected and can decrease mission lifetime. TECs offer a small and lightweight solution to cooling sensors. Because of this, they can be easily integrated onto payloads with little overall changes needed. The solid-state nature of TECs make them suitable for long duration missions. Our trade study found that TECs offer the best solution to cooling a sensor in the Cubesat platform.

IV. Solid-State Cooling Operation

In order to develop requirements for the solid-state cooling operation, specifically requirements tied to thermoelectric modules, the Peltier Effect functions and the governing principles should be understood. TECs work by utilizing the Peltier Effect, which is a counterpart to the Seebeck effect. The Peltier Effect was observed by Jean

Charles Athanase Peltier in 1834, where he found if current is made to flow between a junction between conductors A and B, thermal energy may be generated or removed at that junction.

Looking at a typical TEC (Figure 2), the entire module is made up of a series of n and p-type semiconductors. N-type semiconductors are doped such that they have an excess of electrons, while p-type semiconductors are doped
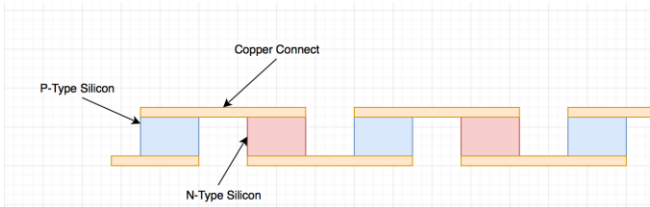

Figure 2. Thermoelectric Module Cutaway. *This illustration shows a cutaway side view of a thermoelectric module.*

such that they have a deficiency in electrons. When current is conducted through the module, taking the path from the p-type semiconductor, through a connect, to the n-type semiconductor, through a second connect, then back to the p-type semiconductor. This can be thought of as the act of forcing electrons out of the p-type semiconductor, passing them through the metal connects, then forcing them into the n-type. Since electrons coming out of the p-type semiconductor comes from below the Fermi level, from the valence band, and the electrons going into the n-type semiconductor has to go above the Fermi level, to be in its conduction band, there is energy required in this process. This energy is drawn in from the p-type - n-type metal interface and dumped out at the n-type - p-type metal interface in the form of thermal energy. We could think of this mechanic as "evaporating" electrons and pulling in energy from the surrounding in the process.

Typical specifications from thermoelectric modules include Qmax, DTmax, Vmax, Imax, and dimension A, B, and H. Qmax is the maximum amount of heat that the module can transfer across its surface, this will result in DT (temperature difference) of 0. DTmax is the maximum temperature difference between the two surfaces given that the module does not transport any heat, hence Q = 0. Vmax and Imax are the operating voltage and current of the module. The input voltage to the system can be raised and consequently the current can rise as well. But what Imax really represents is the current at the module's max performance. This means that when any current introduced is higher than Imax, the resistive heating inside the module starts to overcome its ability to transfer heat. Note that these specifications are tested values conducted by TEC manufacturers and are used for system design purpose.

The TEC can be treated as a heat pump and modeled with the following equation:

Figure 3. Sensor Temperature & Arduino Test Stand. *A thermocouple and Arduino were used to characterize sensor temperatures over time with different exposure times. Deconstruction of the Canon XSi is clearly seen.*

$$CP = \frac{Q_h}{W} = \frac{Q_h}{Q_h - Q_C} \Rightarrow \frac{T_h}{T_h - T_C} \, [7]$$

(2)

From this model, CP will increase if Th increases, and decrease if Tc increases. Given a constant Th and constant W, the colder the cold side of the module gets, its ability to carry heat decreases and results in its efficiency decreasing. This will become a problem to this design since the goal is to achieve the coldest temperature in a room temperature environment, which one-node and six-node MATLAB simulations show to be a similar temperature environment in space.
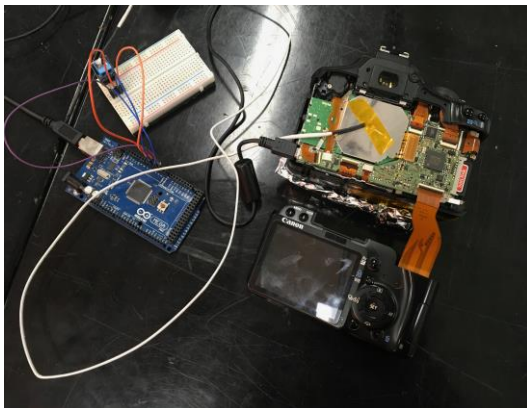
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[7] http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/heatpump.html

When looking at the heat rejection side of the TEC, the heat produced at the hot side of the module (heat waste) is the sum of the power input and the heat removed from the cold side of the module. Taking a look at one TEC being used in the under development prototype model, the CUI CP20351 pulls 15.2 Watts from a sensor, while pulling approximately 30.8 Watts of power. This TEC results in approximately 46 Watts of heat which needs to be dissipated. At the time of writing, the design of the radiator system to accompany the TEC is still under development and has not been finalized. Further testing of the radiator design with the TEC will allow us to generate better design criteria for the development of the radiator. The results of this design are expected to be presented later this year.
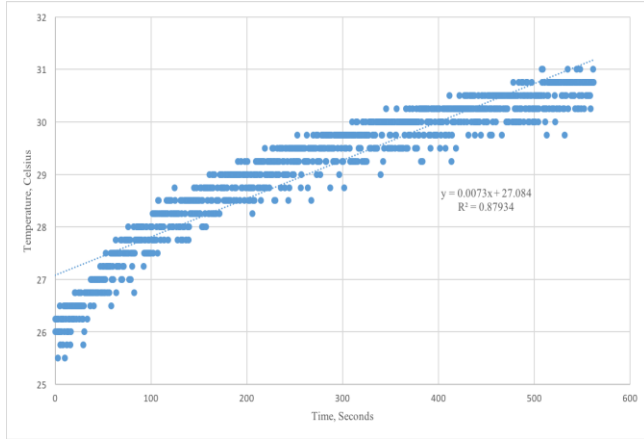

Figure 4. Temperature of Canon XSi Sensor Over Ten Minutes. *The temperature of the sensor increases with longer exposure times. This plot shows temperature data every .5 seconds for a 10 minute exposure.*

V. Cooling and Sensor Performances

At the time of writing, sensor performance characteristics with cooling are being investigated. Predictions on increases in sensor performance have been performed in Excel and MATLAB, and is presented. Initial data was gathered from a Canon XSi DSLR camera, with sensor temperature data being gathered with a thermocouple and Arduino test stand, as seen in Figure 3. The Arduino test stand polls the thermocouple every .5 seconds, but sometimes misses these steps, resulting in odd lengths of data. To counteract this, temperature ranges were taken from an extension at the hotter end of the range to complete the timings. The sensor was set to ISO 1600, the front of the camera was completely covered in aluminum foil, to keep out all light, and four different exposures were made at one minute, two minutes, five minutes, and ten minutes. A ten-minute plot of temperature for the ten-minute exposure can be seen in Figure 4. During these four long exposures, four separate dark frames were gathered. Each of these dark frames has a certain noise level considered to be the thermal noise level, because of the limited amount of light allowed to enter the system. To analyze the thermal noise levels, ImageJ was used to analyze the Mean Gray Value in each dark frame. The Mean Gray Value is a measure of noise in an image, and holds a linear relationship with exposure time.

To have a better understanding of the SNR improvements that the TEC can unlock for CMOS and CCD sensors, we are able to adjust Equation One to the following:

$$SNR = \frac{OBJ * t_{sub}}{\sqrt{OBJ + D0 * e^{\ln(2)*(T/Td)} * (T/Td) + RN^2}}$$

(3)

Where OBJ is the object flux in electrons/pixel/minute, t_{sub} is the exposure time in minutes, $D0$ is the dark noise at zero degrees C, T and Td are the studied temperature and noise doubling temperature difference, respectively, and *RN* is the read noise in e- RMS.
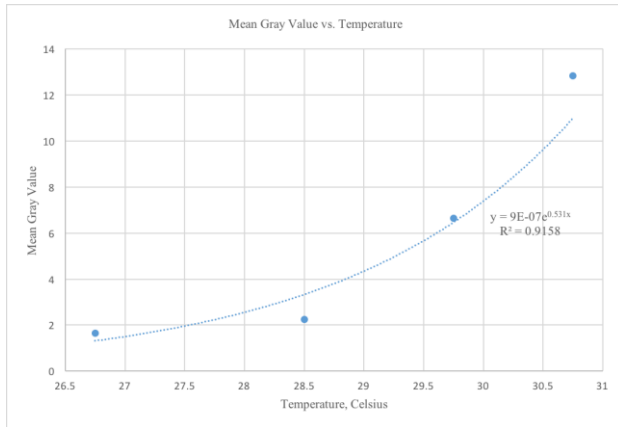
Figure 5. Mean Gray Value vs. Temperature. *Mean Gray Value was determined through ImageJ, and can be interpreted as equivalent to dark noise. Dark noise increases exponentially with increases in temperature.*

Sensor specifications were found online, showing a value for the read noise at 3.6 e- at 1600 ISO, the sensitivity the dark frames were taken[8]. $D0$ is able to be determined by using a model which shows the relationship between Mean Gray Value and Temperature, as seen in Figure 5. Td can also be found in a similar fashion. Future analyses will use more data points for a better regression. For simplicity, an exposure of five minutes is used and an object flux of twenty electrons/pixel/minute. Modeling the formula in MATLAB, we are able to model the SNR at different temperatures, as seen in Figure 6. In this model, it can be seen that there are clear gains of higher SNR with lower temperatures. Seeing that ambient temperatures result in an SNR of around six, being able to double SNR with a TEC is feasible, based off of this data. Since temperatures need only to reach around 10 degrees Celsius, the TEC does not need to work very hard to maintain that

temperature. The current performance benchmarks do not take into account any compatibility with MWIR, however, continued cooling would be required for MWIR operations.

Although full physical modeling has not occurred, it is clear that performance gains in spectral and spatial resolution can be attained, purely through these mathematical models. Future findings from the physical model will relay valuable information about the accuracy of the mathematical models.
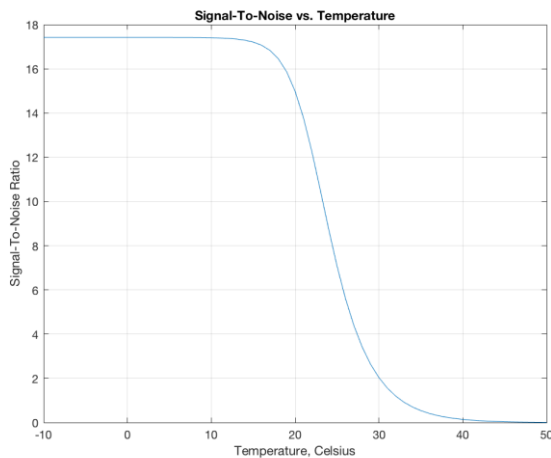

Figure 6. SNR vs. Temperature. *As the temperature decreases, the dark current noise disappears, allowing for increases in signal to translate into higher SNR.*

VI. Prototype Development and Testing

In order to develop the prototype, two different models of TEC will be used. Each of these TECs operate differently, and at different power levels. Each TEC will go through a testing regiment to determine which TEC pulls enough heat to cool the sensor down, while also not pulling large amounts of power, as to be supported on the Cubesat platform. A system of two K-type thermocouples will be used to measure the temperature at the sensor, and at the hot side of the TEC. This system will feed into an Arduino, which regulates power to the TEC and acts as a feedback control system to the TEC. By monitoring the temperature differences on either side of the TEC, the feedback control system will only send enough power to maintain optimal efficiency of the TEC and ensure that the set point of sensor temperature is maintained. The hysteresis for the TEC has not been finalized, but the set point has been preliminarily determined to be 5 degrees Celsius,

based off of Figure 5. The TEC will be interfaced to the sensor with a NASA compliant thermal sheet. This thermal sheet essentially acts as a thermal paste, but is easier to work with and easily complies with NASA standards. The hot side of the TEC will be cooled with a Corsair H75 liquid cooler, for the prototype. The liquid cooler exceeds any radiative capabilities which would be found on a Cubesat, which has been done by design. By controlling the power input to the Corsair H75, it can act as a radiator with almost any Cubesat compatible size. This prototype setup will benchmark the requirements of the radiator, and will supply data on input power for the TEC. Additionally, tweaks to the TEC feedback control can be performed, and can be tested immediately. From the prototype, the team will move forward with implementing the requirements derived from testing to manufacture a radiator system, Cubesat

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[8] http://www.sensorgen.info/CanonEOS-450D.html

compatible control board, and interfacing of the TEC with the rest of the system. A similar test setup will be used with final prototype, with the radiator, instead of the H75 liquid cooler, to verify system operability. Prototype and test results are expected to be presented later this year.

VII. Conclusion

The development of a small satellite compatible thermoelectric module based cooling system is still in progress. Current developments show the theoretical side of the design as being feasible, with system prototyping occurring at the time of writing. With this in mind, the authors are unable to report any final designs or specifications until later this year. The use of a TEC as the main cooling mechanism has many advantages over passive cooling mechanisms and cryocoolers. A TEC is solid-state, meaning that there are no moving parts, making the cooling system particularly well-made for sensitive optical payloads. Additionally, a TEC is able to cool a component to below ambient temperatures, a property that passive coolers cannot attain. System prototyping will include baselining the performance characteristics required by the radiator on the small satellite, and a trade study between heat pipes and heat straps. Future work will include making the TEC more efficient, thereby making the system more viable for use on a power limited Cubesat or small satellite.

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