Measuring Radiation with Respect to Altitude Using Kevlar Shielding, Non-Oxidizing Heating Agents for Stratospheric Operation of Thermal Sensitive Equipment, and Live Data Transmission

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April 2025

Abstract

This project presents a high-altitude balloon payload designed to measure gamma radiation across varying altitudes while evaluating Kevlar's effectiveness as a shielding material. Here we demonstrate a lightweight, low-power solution for thermal regulation and radiation protection, by integrating Kevlar shielding and a passive heating system. We present a payload design which offers a practical framework for safeguarding sensitive electronics in aerospace contexts. Additionally, we successfully implement real-time data transmission in a compact platform, contributing to the advancement of high-altitude research methods. With these findings we aim to support future development of compact, self-regulating scientific instruments for near-space applications.

Introduction

Radiation at high altitudes can pose health risks to aviation crews, astronauts, and can damage delicate electronics onboard spacecraft or high-altitude balloons. A 2016 study from NASA found that airline crew members are exposed to about double the radiation levels than the average person. When exposed, cells in the human body are targeted by radiation which can damage DNA, causing mutations that can lead to cancer. It can also damage arteries in the heart, and harm blood vessels (NASA, 2018).

Cosmic radiation has the potential to damage delicate electronic components of spacecraft or high-altitude balloons. Over time, exposure to ionizing radiation such as gamma rays or protons can cause degradation of semiconductor materials, leading to performance issues in both analog and digital electronics (Fleetwood, 2013; Pellish, 2017).

These risks highlight the importance of effective shielding materials. This project uses Kevlar as a radiation shielding material on a high-altitude balloon payload. A study from Tripathi, Wilson, and Cucinotta (2008) has shown that Kevlar can provide up to 90% of the effectiveness of polyethylene, a widely recognized material for radiation shielding.

In the process of collecting this data, the effectiveness of a sodium acetate solutions exothermic reaction will also be tested as a temperature regulator for the electronic components. This is the same reaction used in reusable hand warmers. Using the phase change data for sodium acetate trihydrate from NIST which states that the enthalpy of fusion of sodium acetate trihydrate is 20.250 kJ/mol (molar mass 137.09 g/mol), we can predict that 100g of sodium acetate will produce an exothermic reaction that can reach up to roughly 67 degrees Celsius. One advantage of using sodium acetate trihydrate in a high-altitude payload is that the reaction does not require oxygen since it is a crystallization reaction.

Our objective is to gather radiation data from high altitudes while assessing the effectiveness of Kevlar shielding for radiation protection using sodium acetate trihydrate as a heating solution for stratospheric operation of thermal sensitive equipment.

Parts List

Part	Cost
Heavy Weight Aramid Protective Kevlar Fabric - Military Grade	$34.07
MightyOhm™ Geiger Counter kit with SBM-20 Geiger tube X2	$199.90
Lithium-Ion Cylindrical Battery - 3.7v 2200mAh	$9.95
THERMWELL Products Frost King P350CW Polyethylene Sheeting	$14.00

Sodium Acetate Trihydrate (100g)	$6.00
Adafruit Feather RP2350	$12.50
Adafruit LoRa Radio FeatherWing™	$19.95
SparkFun™ 9DoF IMU Breakout - ISM330DHCX, MMC5983MA	$39.95
Humidity and Temperature Sensor - DHT20 with I2C	$6.50
SparkFun™ Qwiic BMP581 Pressure Sensor	$19.95

Other materials: flight tube, foam panels, insulation sheet, cotton coiling, silicone conformal coating

Payload Structure

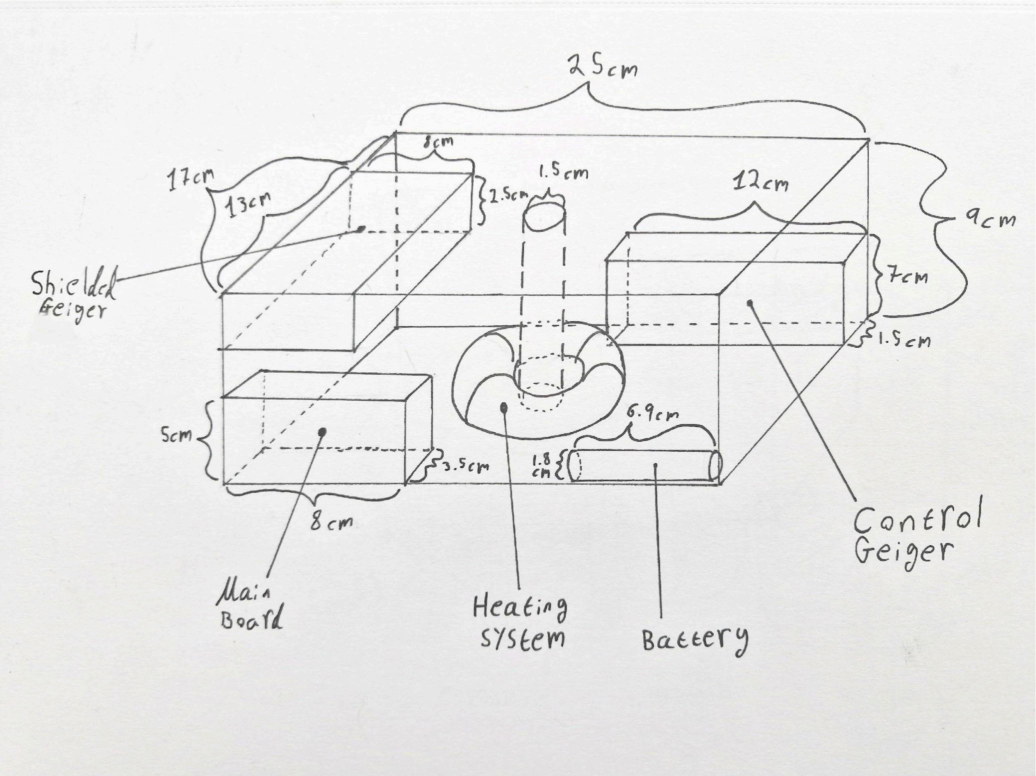

Figure 1

The payload housing was constructed with a focus on thermal insulation and structural integrity. The walls of the payload were made of lightweight foam panels with a thickness of 0.5 cm and layered internally with insulation of 0.5 cm. These panels helped maintain internal temperatures within an acceptable range despite the estimated ~-55 C temperature at peak altitudes.

A flight tube ran vertically through the center of the payload, where a string is pulled through to attach our payload to the balloon.

For our electronics' temperature regulation, a ~100 g sodium acetate solution was hydrated and sealed in layers of polyethylene with a heating gun. The sealed solution was wrapped around the flight tube in a donut shape to create a center of mass in the middle of the housing. Avoiding Uneven weight distribution and distributing heat uniformly inside the payload. Additionally, to avoid contamination from the solution in the case of leakage, the bottom of the solution structure was lined with cotton. Effectively ensuring any leakage will be absorbed in the cotton, minimizing damage.

Kevlar was applied at a uniform thickness of 0.5 cm around the experimental(shielded) Geiger Counter, providing a balance between radiation shielding and the payload's mass limits.

To further preserve the balance of the payload and enhance the reliability of radiation measurements, the two Geiger counters were installed on opposite sides of the payload in a fashion that the Geiger-Müller tubes are furthest apart from each other and as close to the exterior of the payload as possible. This placement allows for the best possible reliability of radiation reading between control and experimental sensors, minimizing internal interference from unrelated subsystems.

Additionally, the lithium-ion battery was placed on the same panel as the main board as the most effective way to maintain even weight distribution while minimizing cable clutter.

A layer of silicone conformal coating was applied to the internal electronics to protect against moisture from our thermal sodium acetate solution shall the container burst, and any potential moisture sources. All while barely changing weight. All exposed conducting wire elements were sealed with electrical tape to avoid problems in the case of leakage from the heating system.

On the exterior of the payload on the panel behind the main board (see fig 1), lays the broadcast antenna pointed down, and secured with a zip tie.

To ensure maximum insulation and minimal external leakage (Leakage of liquids from our payload to payloads below) in the case of the heating systems failure, any cable, switch, zip tie or other such hole in the payload was sealed shut with hot glue and glazed with silicone conformal coating. A small opening was left at one of the top panels' seams of the payload so as to not risk external leakage while allowing for pressure regulation during ascent and descent.

Theoretical background

Radiation

Cosmic radiation at high altitude mostly consists of gamma radiation. We expect our sensors to only measure gamma radiation due to the inability of other detectable particles to pierce your configuration; namely low energy beta particles and alpha particles which cannot pierce the Geiger tubes' hull.

In order to effectively analyze our data, we must first cross reference it to past experiments to ensure the validity of our measurements. Past experiments such as (Space Weather Ballooning) measuring gamma radiation as a function of altitude measured the point at which gamma radiation reaches its peak dosage rate (For high altitude flight), after which dosage rate declines. This point is called the Regner-Pfotzer maximum (RP). (Space weather ballooning - Phillips - 2016 - space weather) found the average RP to be at 20.4 km ± 0.4 km with an average width of 7.8 km ± 0.8 km, defined as the full width at 90% of the peak. We chose to compare this paper with ours due to its similarity in latitude as (Space weather ballooning - Phillips - 2016 - space weather) was conducted in Bishop, California. With a latitude between 36.5°N and 37.5°N. Approximately 2 degrees off our latitude at launch: 39.6° (EOSS, 2025).

Radiation dosage is defined as a unit of energy absorbed per unit of mass that absorbed said energy. For this experiment, the radiation dosage unit which we found to be most meaningful is Sieverts, which is a unit of Joules per kilogram of human tissue. This is a unit of equivalent dose, which is not a purely physical unit, but rather one that depends on the property of the specific radiation.

A study aboard the International Space Station (Narici et al., 2017) measures radiation dosage reduction for Kevlar tiles of area density 5 [g/cm^2] and 10 [g/cm^2]. Finding a nonlinear relation between area density and dosage reduction and an equivalent dosage reduction of ~20%for the 5 [g/cm^2] Kevlar tiled sensors. Our sensors have a shielding of 0.026 [g/cm^2] ± 0.003[g/cm^2], which leads us to believe our fractional dosage reduction should be significantly worse than the 20% measured in the mentioned experiment.

For calibration of the radiation sensors with each other, we used a radiation source emitting primarily gamma radiation. However, we could not calibrate them to get a unit accurate reading of Sieverts. As such, this experiment can only tell us about the differences between radiation readings, not actual total dosage.

Transmission

Live data transmission on high altitude payloads remains an active area of interest to designers of such systems. The benefits of live data transmission are numerous. Live data transmission allows scientists to interpret and act upon data in a much timelier manner. In addition, it lowers the risks posed by payload failures and payload landing locations that prove unrecoverable (at least in a timely manner). While these benefits are great the associated constraints imposed on any live data transmission system are significant. Any feasible data transmission system must consider factors including range, power consumption, data rate, reliability, cost, and weight. Additionally, any solution should, if possible, not require specific regulatory considerations from any regulating body. All these constraints lead to the consideration of a LoRa® based transmission system (IEEE HNICEM, 2019).

LoRa® is a radio communication protocol utilizing spread spectrum modulation owned by SEMTECH®. LoRa® modulation is based on chirp spread spectrum modulation hereafter referred to as CSS. CSS exhibits ideal properties for low power mobile communications. Due to the bandwidth used by CSS it remains resilient to multipath losses even at low powers. In addition, the “chirp” used by CSS makes it resilient to the doppler effect (SEMTECH, 2015).

LoRa® presents numerous ideal properties for high altitude payloads. First, its modulation scheme allows for link budgets upwards of 160dbm. Additionally, it remains error free at high signal to noise ratios (SNR) due to its wide bandwidth and forward error correction. Second, the modulation scheme and high sensitivity result in low power consumption. Third, LoRa® chips remain light and cost effective due to their widespread use. Finally, LoRa® takes advantage of the ISM band which means it does not require specific licensing (SEMTECH, 2015).

Heating system

To regulate the temperature on the inside of the payload at high altitudes, a contained exothermic reaction was triggered during flight. This reaction included the rehydration of a sodium acetate solution. As the solution crystallized, the heat released was transferred from a sealed polyethylene container to the interior of the payload via conduction.

When sodium acetate trihydrate is dehydrated, it will dissolve in water at around 79 degrees Celsius. It is then cooled back to 20 degrees Celsius and when agitated, crystallization occurs and heat is released (University of Washington, Department of Chemistry, n.d.). This process is reversible, allowing the solution to be reused through repeated cycles of dehydration and rehydration, which is a similar process to that found in reusable hand warmers. A major benefit of the crystallization of sodium acetate reaction during flight is that this reaction produces heat without requiring oxygen.

Maintaining an appropriate temperature range for electronic components at high altitudes is very important to the effectiveness of sensor data collection. The limitations for interior temperature in our payload were to not drop below –20 degrees Celsius, to ensure the reliable performance from all components in the system

$$C_2H_3NaO_2 + 3H_2O = C_2H_3NaO_2 \cdot 3H_2O$$

Enthalpy of one full mol of reaction: -39.56 Kj/mol

ENGINEERING

Thermal Management Subsystem

We constructed our thermal system by sealing two sheets of polyethylene plastic together making a bag-like structure which served as a perfect container for our solution. We used polyethylene plastic because it has high durability. The durability addresses our need to withstand expansion due to atmospheric pressure. We sealed the edges using a concentrated stream air at 260 degrees Celsius fusing the plastic together. This was repeated for each edge and on each side of the container. This created an airtight seal that was able to contain our solution and withstand the expansion from atmospheric pressure as well as impact within the payload. We did go through multiple testing phases with this concept. The main concern that we needed to address was preventing the bag from leaking. We refined this process through testing and found that the double sealing technique was the most effective at creating an airtight container. We also found that 260 degrees Celsius is the optimal temperature for sealing the polyethylene sheets. For example, if more heat was used it would melt right through, and less heat would not effectively seal the bag.

While we did not synthesize the chemical compound from scratch, we invested significant time into testing and optimizing the chemical reactions involved. This is the part of the thermal heating system that would theoretically heat our payload. Some challenges we faced included using correct mole ratios, which in turn dampened the effectiveness of the thermal output. I will demonstrate this challenge with annotated calculations below.

$$60g\ NaC_2H_3O_2 \times \frac{1\ mol\ NaC_2H_3O_2}{82.034\ g} \times \frac{-39.56\ KJ}{1\ mol\ NaC_2H_3O_2} = \ -\ 28.87KJ$$

Given the equation above we know that the energy output of the reaction should be 28.87KJ. However, there are other factors to consider such as the presence of limiting and excess reagent.

For example, if we have excess water and the solution becomes ultra saturated then we lose energy output to that reaction.

$$60g\ NaC_2H_3O_2 \times \frac{1\ mol\ NaC_2H_3O_2}{82.034g\ NaC_2H_3O_2} \times \frac{3\ mol\ H_2O}{1\ mol\ NaC_2H_3O_2} \times \frac{18.015g\ H_2O}{1\ mol\ H_2O} = 39.52gH_2O$$

$$40g\ H_2O \times \frac{1\ mol\ H_2O}{18.015\ g\ H_2O} \times \frac{1\ mol\ NaC_2H_3O_2}{3\ mol\ H_2O} \times \frac{82.034g\ NaC_2H_3O_2}{1\ mol\ NaC_2H_3O_2} = 60.71g\ NaC_2H_3O_2$$

Given the calculations above using what we had for our masses as the initial amounts of grams doing some basic stoichiometry you can see what the perfect number of grams would have been for the alternate chemical to make the ideal output of heat energy. However not much heat energy was lost considering that the difference in mass is less than a gram in either case. The heating system was still successful in keeping our payload warm, which is the main concern, it's just the struggle to get precise measurements which dampened the effectiveness but by a virtually negligible amount.

Data Transmission system

The data transmission system is based on the RFM95W chipset. This chipset allows for sending and receiving of LoRa® packets. The underlying software driver used is the Radiohead library. This combination allows for easy and reliable data transmission. The radios were tuned to maximize the range of transmissions. This was achieved by using a bandwidth of 125Khz, a coding rate of 4/5, and a spreading factor of 2048 chips/symbol. The link budget was calculated using the max transmission power of 20dBm, 10dBi antennas on each side, and the maximum sensitivity at our spreading factor of –136dBm. For propagation losses we used both a model based on pure free space path loss with an added term for atmospheric absorption, and a model based on the Egli model. Both models predicted more than enough range, but each is not perfectly fitted for this use case. For example, the Egli model has a large weight on the height of each station. In addition, each model fails to account for more complicated atmospheric effects like cloud cover and ducting.

After the range considerations were taken into account our settings left us with a data rate of approximately 70 bits per second. The method for packing all of our sensor data into packets we used was simply to pack a raw c-struct into big endian ordered bytes which were then decoded on the ground station. This allowed us to pack 6dof IMU data (6 floats), humidity (1 float), external temp (1 float), pressure (1 float), internal temp (1 float), Geiger data (2 floats), and sequence (1 uint32). This data, along with a 4-byte header used for addressing by Radiohead, put our required data rate to transmit 1 packet per second at 56 bytes per second.

TESTING

The system includes two Geiger counters—one shielded in Kevlar and one exposed—as well as a thermal management system using sodium acetate trihydrate, which releases latent heat upon crystallization to maintain operational temperature. Real-time data on radiation, pressure, and humidity is transmitted via radio.

Testing included vacuum chamber simulations to validate the thermal system's stability and confirm the sodium acetate's ability to maintain temperatures above the Geiger counters' minimum operating threshold. Signal integrity assessments ensured reliable radio transmission at altitude. Anticipated data trends include decreasing radiation levels inside the Kevlar-shielded compartment compared to the unshielded control, as well as correlations between radiation intensity and atmospheric pressure.

Radiation Shielding Testing

Our radiation sensors were not properly zeroed to the sievert unit but rather zeroed against each other near a radiation source of Cobalt-60. Such that they both had identical readings over a period with an uncertainty of ~±5%. Due to time limitations, we could not leave the radiation sensors long enough around the radiation sources to achieve better accuracy.

Transmission Testing

Our radio transmission testing was mainly comprised of reliability testing. We tested the ground station and payload code in order to fine tune the timings between them. This increased the consistency of received data. After this reliability testing, we did limited testing on range. This testing was performed in an open field but was fundamentally flawed due to the fact that we could not simulate the elevation of the payload.

Thermal Management Subsystem Stability Testing

Evaluation of the structural integrity and stability of Sodium Acetate when sealed in an airtight plastic membrane when exposed to gradual depressurization when entering the upper atmosphere. The predicted air pressure at 90,000 feet is 0.48 inHg.

When using Sodium Acetate, the solution must be given water to hydrate, then boiled down to a slightly viscous clear liquid. This state is considered “primed” and ready to activate. During this time of being a liquid it will need to be in this form until it is activated. It will then be placed in an airtight sealed plastic membrane with a small amount of air inside it to be used as a catalyst for the exothermic reaction.

A small pneumatic 3-gallon Vevor™ vacuum chamber was used to simulate low pressure environments like that at upper atmosphere. To simulate the “primed” Sodium Acetate Compound, water was placed in an air-tight sealed plastic membrane with about 20 percent air occupying the rest of the bag. The simulation membrane and liquid were placed inside the chamber and sealed. Upon activating the vacuum chamber there was no obvious leaking or structural damage caused to the membrane, other than progressive bloating until the chamber reached a maximum internal pressure of 1.2362 inHg (0.04131 atm). This amount was derived from subtracting from the normal atmospheric pressure of the testing location at Longmont, Colorado. Once the chamber reached its maximum internal pressure it was left on for 30 minutes to simulate the time it would take to be stuck at high altitude. After 30 minutes the chamber was slowly re-pressurized and returned to normal. No deformations or leaking was observed, and it was deemed a success as it held integrity throughout the entire experiment.

RESULTS

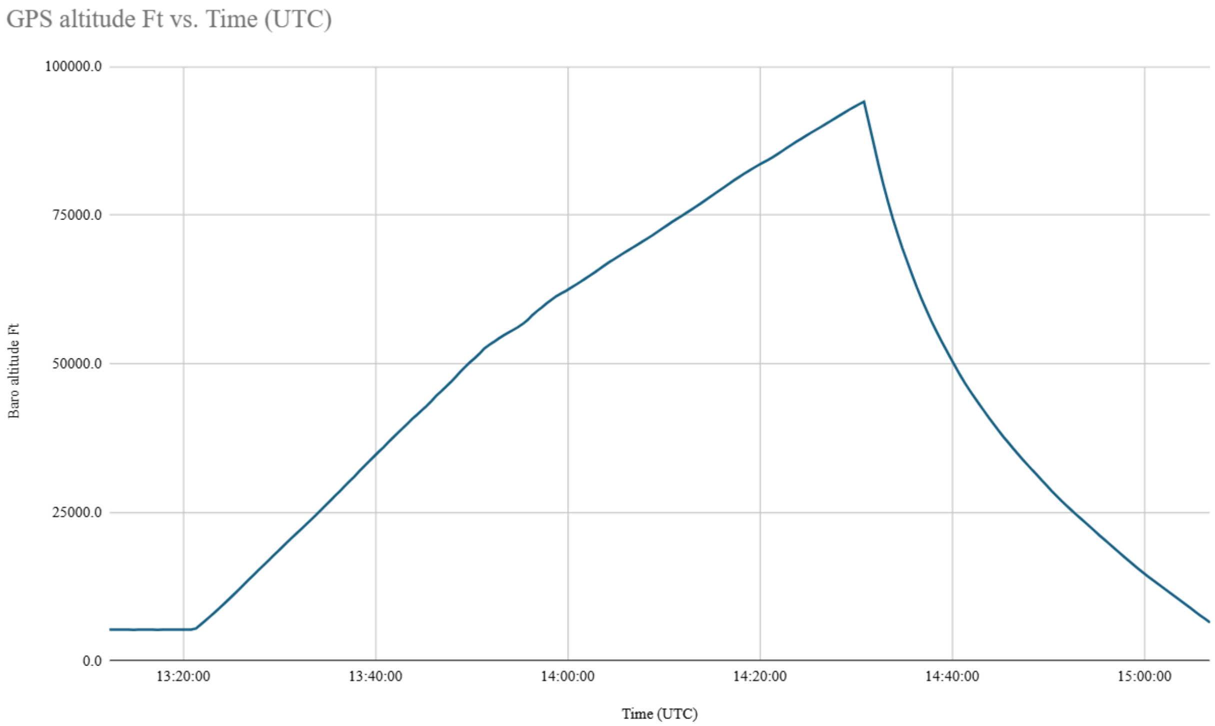

Figure 2

Figure-2 was plotted from the GPS altitude data provided by the EOSS 371 launch. EOSS logged new data every 30 seconds while our data logging system reported every 1 second.

Figure-3 was data collected from the internal and external temperature sensors during flight. The y-axis has units of degrees Celsius, and the x-axis has units of seconds from launch.

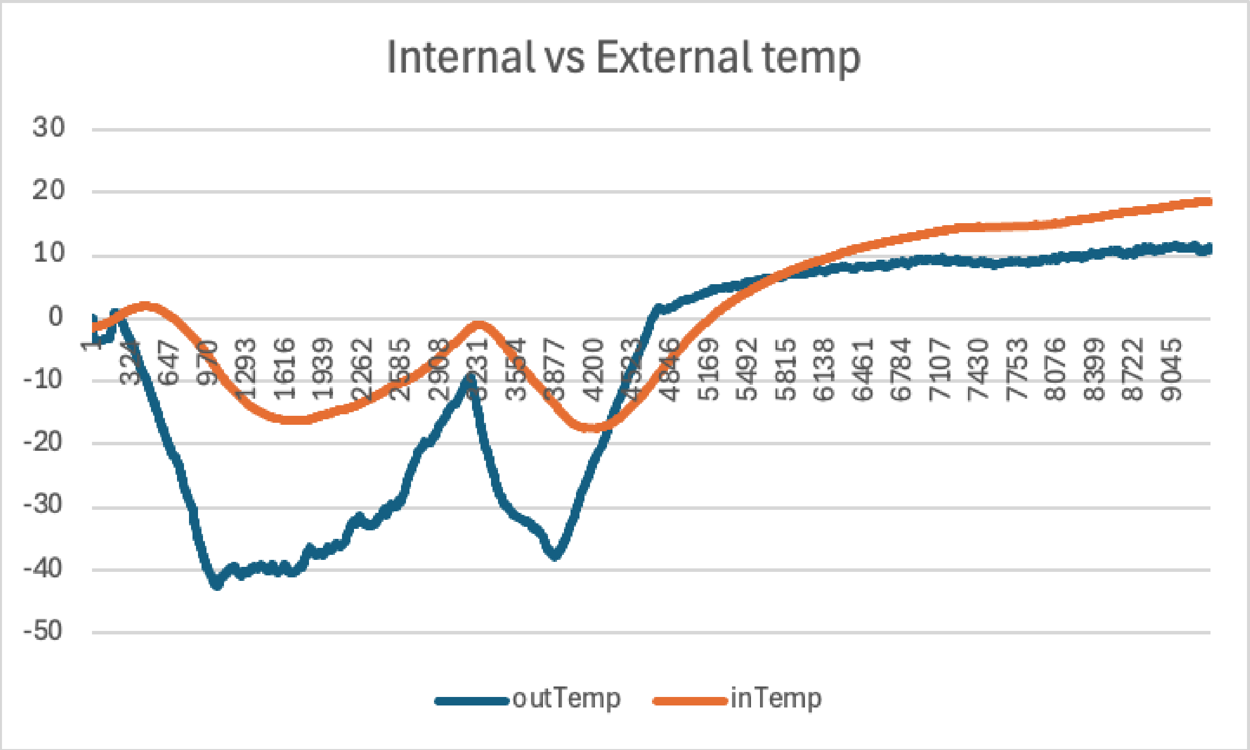

Figure 3

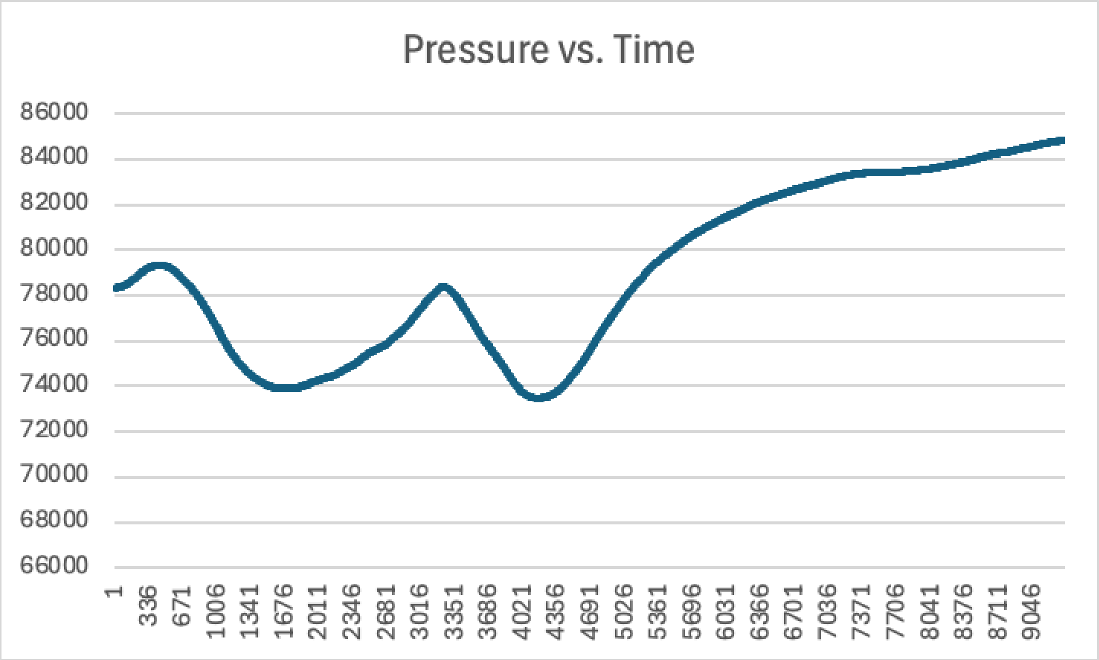

Figure 4

Figure-4 Pressure in kilopascals (kPa) throughout flight.

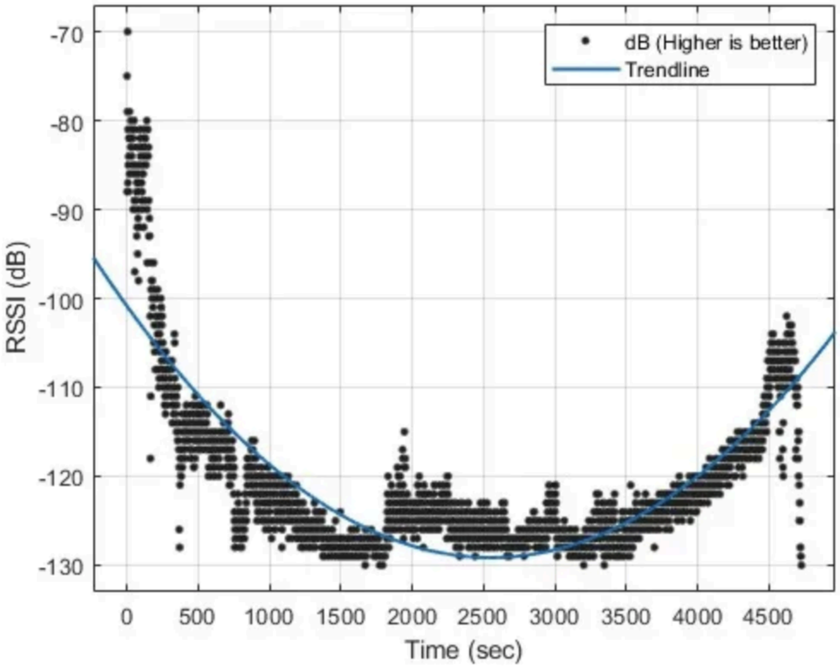

Figure 5

Figure-5 Received Signal Strength Indicator (RSSI) evolved throughout the flight's duration. Note that the theoretical floor on RSSI is –136dBm but our observed floor was closer to –130dBm.

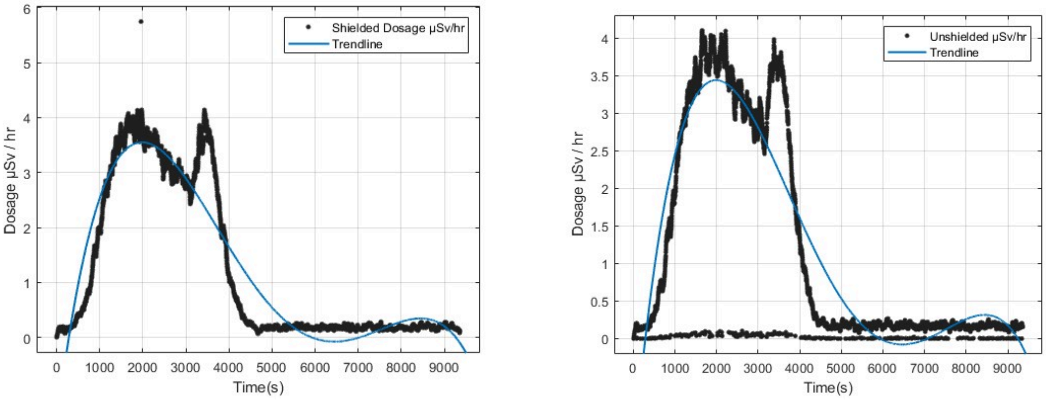

Figure 6

Figure-6 Shows the dosage rate in micro-severts per hour throughout flight.

Conclusion

Data collection was a major success. The on-board backup logging recorded over 9000 data points (many of these were recorded after landing). Investigating the data received from radio transmission we can see that during flight we received about two thirds of the packets transmitted. This left us with a mean time between packets of 1.58 seconds and a max time between packets of 10 seconds during flight. This constitutes a huge success for the radio subsystem. After the payload hit the ground, we saw a sharp decrease in signal strength. This led to us losing connection for a while we closed in with the payload. After we closed in with the payload, we started hearing faint packets again all the way until we retrieved the payload.

When observing data collected from temperature [figure 3] and altitude [figure 2] over time, we can see that the temperature increases by about 20 C° around the time the payload reached its highest altitude of 30. Km. This is explained by the completely calm environment created by the air that exists in the stratosphere. Once the payload has entered this layer, there is little to deflect the direct warmth of the sun, causing the external temperature of the system to reach a second peak.

[figure 3] The internal temperature of the payload remains higher than the external temperature data recorded for most of the flight time. This indicates the effectiveness of our heating solution. The data shows the largest difference between the two readings in the first half of the flight time indicating the interior temperature of the payload was increased by about 30 C°. Our lowest point met by the internal temperature measurement was about -18 C°, while the lowest external temperature reading was -42.5 C°.

Data from our pressure sensor [figure 4] shows fluctuations similar to the Temperature vs. Time graph. An explanation for this could be that the sensor uses temperature data to then calculate pressure. This makes sense because we only expect our pressure to decrease as altitude increases, but instead we are met with peaks and dips in the data. Another possible explanation is the payload entering lower or higher-pressure pockets in the atmosphere.

For figure 6, The radiation of both radiation sensors appears to align with our prediction in terms of the RP. With an average maximum of 15 [Km] ± 3[Km], and an average peak width as defined previously of 5200 [m] ±100 [m]. Although this does not align with collected data from [insert experiment], but so does the latitude not align with said experiment. Additionally, it is known that different atmospheric regions as well as solar storm conditions have different RPs (Space weather ballooning - Phillips - 2016 - space weather). We may not conclude anything from the shielding due to the uncertainty in zeroing with each radiation sensor (5%) being larger than the calculated fractional difference in total radiation dosage. Which was a difference of 5% lower radiation in the *unshielded* sensor, leading us to believe that the results were invalid and not useful.

Our radiation data did not provide us with evidence that a 0.5 cm Kevlar fabric will provide effective radiation shielding at high altitudes. This could be because of the uncertainty in our data collection due to the samples used to calibrate the Geiger counters. Other potential causes include the distance between the Geiger counters, or the thickness of the Kevlar. The Geiger counters were installed inside the payload about 17 cm apart, which could explain why we do not see much of a difference between the readings. It is possible that both Geiger counters were shielded, that neither was shielded because the material wasn't thick enough, or that the data doesn't reflect the shielding's effectiveness due to calibration issues.

The use of an exothermic reaction using 60g of sodium acetate and 40 g of water as a heating system for our high-altitude balloon payload proved to be a success. The goal was to prevent the internal components of the payload from being exposed to temperatures below -20 degrees Celsius. It is shown in our data that the solution was able to keep the temperature inside the payload in this range throughout the entire flight. This goal was achieved without any leakage or damage to electronic components even after flying it in a near-space environment. Sealing the solution in a polyethylene bag using compressed air at 260°C proved to be an effective containment method.

In future experiments we recommend the precise calibration of Geiger counters using a strong radiation isotope as a sample like Cesium-137. Data collection could have been improved by more thorough testing on our pressure sensor, which would have allowed us to replace the specific sensor used once inaccurate data was presented.

Overall, our data did not conclude that the 0.5 cm Kevlar shielding was effective. However, our system for live data transmission was a major success, recording over 9,000 data points over the duration of the flight. Our heating system was also a success, maintaining an internal temperature above 20 degrees Celsius throughout the mission.

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