Colorado Space Grant Consortium

ARAPAHOE COMMUNITY COLLEGE DEMOSAT

Team µ2.0

Figure 1: Team Picture - From left to right, Segev Morgan, Ryan Ennis, Caleb Christenson, Henry Weigel (advisor), Jennifer Jones (advisor), Rachel Smith, Tori Axelson

Written by:

Caleb Christenson, Tori Axelson, Ryan Ennis, Evan Lugo, Santana Padilla, Melissa Marshall, Segev Morgan, Rachel Smith, George Trubnikov

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1.0 Mission Overview

For our project we wanted to build 4 detectors capable of detecting muons. This project is a continuation of from last years demosat project that unfortunately did not succeed in its objective. Both this years project and last years followed a muon detector design from MIT's CosmicWatch program (Przewłocki & Frankiewicz, 2017). To contribute to our goal we decided to run our two detectors in coincidence mode where there are 2 detectors with one on top of the other where the detector on top is the "master" and the detector on the bottom is the "slave. If the master detector detects a muon and the slave does not, only the master detector will record it, and if the slave detector detects a muon and the master does not, neither will record the data. This mode allows us to determine directionality. The main goal of this mission was to test special relativity by showing length contraction and time dilation by building detectors capable of "seeing" different charged particles bombarding our planet; record the data from them and analyze it. These effects can be noticed when the objects are moving with a high speed relative to each other. In other words, when their velocity is a significant fraction of the speed of light. Detecting muons in the upper layers of the atmosphere where they are formed and comparing this data to the one on the ground can help us see the relationship between the altitude and the number of detected muons. Essentially, the higher the balloon goes, the more muons are detected (until a certain altitude). At the same time, the average lifetime of muons in the lab does not correspond to the distance they would be able to travel and be detected on the ground. This is where the special relativity comes into play: the faster the muons move, the longer they live from the ground's frame of reference. Hence, they are able to travel a longer distance from the latter's frame of reference, while this distance does not appear to be as long from the muons' frame of reference. That being said, Einstein's special relativity will be tested via this experiment. A secondary goal of this experiment was to build a lightweight and reusable payload, that would be able to withstand the difficulties of a low pressure, low temperature environment.

2.0 Requirements Flow Down

- Level 0 requirements
    - Remain within a budget of $1000
    - Payload must be below or at 1000 grams
    - Equipment must survive launch, flight, and landing conditions
        - Must withstand a drop of 10 feet
        - Must survive the whip test
        - Must withstand low air pressure
        - Must withstand temperatures of less than 60 degrees Celsius
    - Structure must include flight string attachments
- Level 1 Requirements
    - Have one functional charged particle detector
    - Battery must continue to operate
        - Battery must able to operate below -20 degrees Celsius
        - Battery must stay powered for the entire flight
    - At least one detector must save data to the SD card

- Level 2 Requirements
    - Detectors must run (master and slave) mode
    - Both SD cards must save data
    - Have two functional charged particle detectors
    - Structure must be lightweight
    - Structure must be reusable
    - Have a lightweight battery system

3.0 Design

Functional Block Diagram:

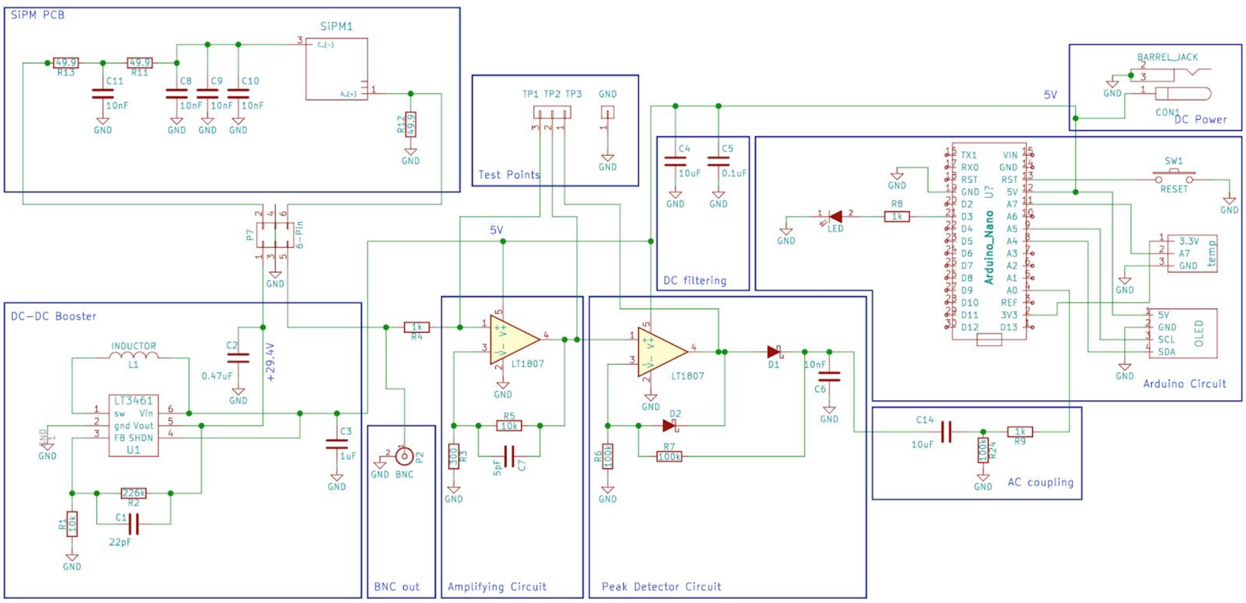

Figure 2: Electronics diagram of the CosmicWatch detector. Source: CosmicWatch, MIT
http://cosmicwatch.lns.mit.edu/detector#steps

This is the electronics block diagram for the CosmicWatch Muon detectors; two of these were flown in our structure, along with a USB battery pack. One of the detectors functioned as the master detector, which communicated to the slave detector when it detected a muon, allowing the slave detector to register the same detection event. The master detector sat above the slave detector and both detectors were connected to each other through 3.5mm jacks. Included in MIT CosmicWatch's code was the functionality to set the detectors up in master/slave mode. Not every muon will pass through both detectors (some will decay in between and others will come in at too high an angle for the second detector to catch), so we expect the slave detector to count lower muon rates than the master detector for the same altitude.

Battery:

We wanted to create a custom battery to power our experiment. The battery needed to run the experiment for more than three hours and needed to continue to operate during the cold temperatures the payload will experience. After researching battery types we decided to use a lithium-ion battery because they can operate at -20C before their performance is affected. Most the lithium-ion batteries we found output 3.7 volts, our detectors needed 5 volts to run. We used a voltage setup circuit that was designed to take 3.7 volts to 5 volts to get the required voltage. During testing our battery lasted for seven hours average

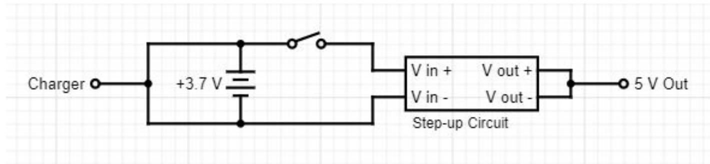

Figure 3: Battery Circuit Diagram

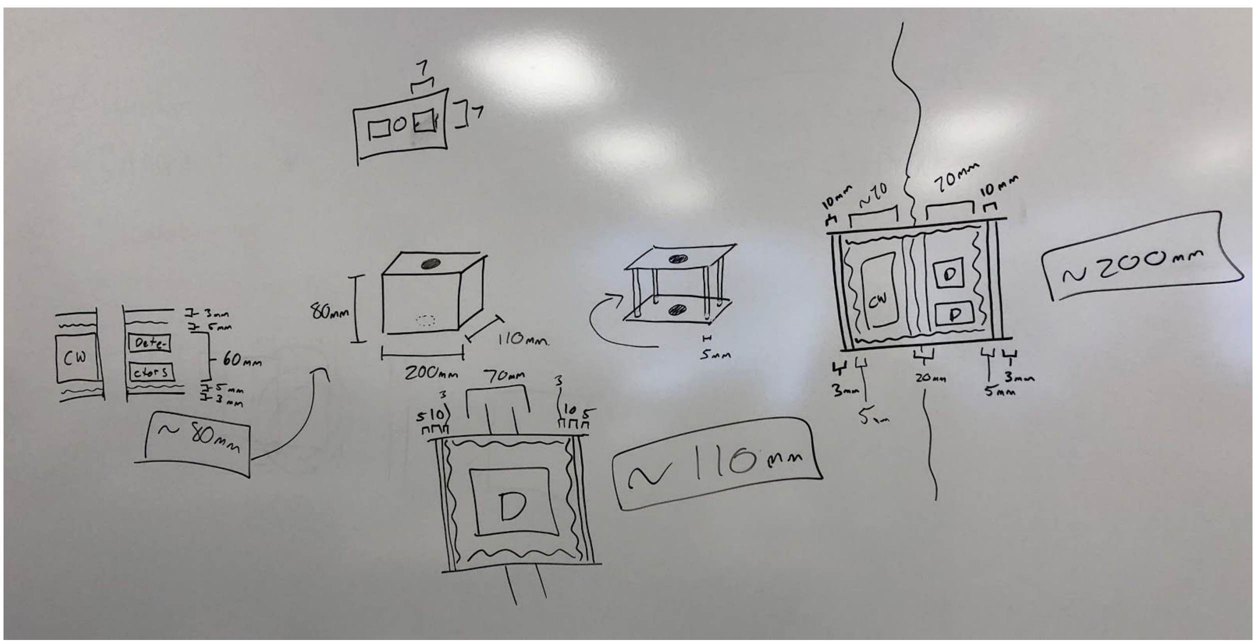

Figure 4: First Iteration of the Structure

Structural Aspects:

Our payload was composed of two rectangular boxes made of foam core which were fit inside each other with a layer of aerogel blanket in between. The outer box was covered with aluminum tape to ensure it stayed together. The top of the box acted as a lid to open the payload. Inside the box was a small shelf made out of foam core glued to the base of the payload for the detectors to sit on. The structure was designed with room for the tube to run through the center and out the lid with a washer secured on the outside. The washer not only secured the aerogel blanket inside the structure and prevented the tube from being dislodged but also helped prevent the payload from opening in case of extreme structural trauma. To open the payload, we removed the top paperclip from the tube to unlock the lid. The paperclip and the aluminum tape ensured that the payload would not come open during the duration of the launch.

The Spaceloft Aerogel blanket, which was acting as a non-toxic insulator, is designed to withstand up to 200 degrees Celsius and has a thermal conductivity of 14 $mW\ m^{-1}\ K^{-1}$. The Aerogel was purchased from a website specializing in aerogel products. With the theme of this year's launch being sustainability and light in density, materials were chosen carefully to ensure that our payload would not weigh more than the 1-kilogram limitation.

Detector 1 weighs 78.7g, detector 2 weighs 80.0g, and the power and wire and battery systems weight is 50g. The structure itself weighs 400g, totaling the entire payload weight to 610 grams with the original battery. With our old battery in the payload and our structure weighing less than we planned, we came in at a weight of 655 grams.

Greenest and Lightest Payload Competition Analysis:

Since there was a competition to be as “green” as possible and to keep the payload as light as possible, we adjusted our goals in an attempt to participate in the competition. In terms of our recyclability/reusability, we performed quite averagely.

We decided to make the structure of our payload as reusable as possible by building it out of airplane plywood or using a 3D print material. These materials were quite recyclable and very reusable. However, due to a miscommunication, our payload could not be made of these materials in time, so we went with a standard foam core material. We could potentially reuse this same structure for another launch, but it is not nearly as recyclable as our other candidates.

Our electronics also had the goal of reusability. Since this payload experiment was our second attempt to detect Muons in upper atmospheric conditions, we decided to reuse as much of our previously used Muon detector parts as possible. In fact, one Muon detector was fully functioning from the previous payload, so we reused that detector for this semester. We also stripped one of the previous detectors for parts and created a hybrid Muon detector for this semester’s payload. This gave us a huge boost in reusability for our electronics.

One huge boost towards recyclability was our aerogel blanket. Our aerogel blanket had phenomenal insulative properties, but it also was 100% recyclable.

In terms of how “light” our payload was, we performed averagely as well. Our structure was incredibly light because it was made of foam core and aerogel. The structure ended up weighing 225 grams, which was substantially lighter than we originally calculated. However, one of the setbacks we had was the battery; we originally planned on using a super light, efficient battery for our detectors, but this battery did not work on the day of the flight. We, unfortunately, had to reuse the same battery from last semester, which was substantially heavier than the alternative, making our payload 655 grams before flight.

Overall, if we had communicated more effectively and set up for multiple points of failure then we would have had a greater chance at winning the “greenest/lightest” payload competition. Even though we did not win, the competition gave us incentive to think creatively to overcome our typical challenges.

4.0 Management

1. Project Management:
    a. Caleb
2. Science Team:
    a. Ryan
    b. George
    c. Santana

3. Programming Team:
    a. Melissa
    b. Ryan
    c. Caleb
4. Structure Team:
    a. Santana
    b. Tori
    c. Rachel
5. Electronics Team:
    a. Ryan
    b. Caleb
    c. Segev

5.0 Budget

Predicted Weight

- Battery:50 grams
- Detectors:160 grams
- Structure:400 grams
- Total predicted weight:610 grams

Actual Weight

- Battery: 255 grams
- Detectors:160 grams
- Structure: 240 grams
- Total Weight: 655 grams

Budget:

Detector Purchasing List

Item	Name	Required	Estimated 1	Amount	Unit Cost	Cost	Shipping	Total Cost	Arrived
1	0 Ohm resistor	15	$0.69	15	$0.04	$0.57	$8.99	$9.56	15
2	49.9 Ohm resistor	12	$0.63	12	$0.04	$0.52	$0.00	$0.52	12
3	249 Ohm resistor	6	$0.51	10	$0.05	$0.51	$0.00	$0.51	10
4	1K resistor	12	$0.63	12	$0.04	$0.52	$0.00	$0.52	12
5	10k resistor	15	$0.86	15	$0.04	$0.65	$0.00	$0.65	15
6	24.9k resistor	6	$0.28	10	$0.03	$0.27	$0.00	$0.27	10
7	100k resistor	9	$0.79	10	$0.08	$0.79	$0.00	$0.79	10
8	226k resistor	6	$0.43	10	$0.04	$0.43	$0.00	$0.43	10
9	10pF capacitor	6	$2.52	6	$0.42	$2.52	$0.00	$2.52	6
10	22pF capacitor	6	$0.84	6	$0.84	$5.04	$8.99	$14.03	6
11	0.47uF capacitor	6	$2.40	6	$0.40	$2.40	$0.00	$2.40	6
12	20 nF capacitor	18	$0.96	18	$0.05	$0.86	$0.00	$0.86	18
13	0.1uF capacitor	12	$1.74	12	$0.14	$1.63	$0.00	$1.63	12
14	1uF capacitor	9	$1.08	10	$0.11	$1.08	$0.00	$1.08	10
15	10nF capacitor	12	$2.13	12	$0.17	$1.98	$0.00	$1.98	12
16	10uF capacitor	9	$2.16	10	$0.22	$2.16	$0.00	$2.16	10
17	Feritte bead	6	$0.60	6	$0.10	$0.60	$0.00	$0.60	6
18	47uH inductor	3	$1.08	3	$0.36	$1.08	$0.00	$1.08	3
19	Schottky diode	6	$2.10	6	$0.35	$2.10	$0.00	$2.10	6
20	4 pin header for OLED	3	$1.68	3	$0.56	$1.68	$0.00	$1.68	3
21	6-pin connector	3	$1.77	3	$0.59	$1.77	$0.00	$1.77	3
22	6pin header	3	$1.89	3	$0.63	$1.89	$0.00	$1.89	3
23	Reset button	3	$0.69	3	$0.23	$0.69	$0.00	$0.69	3
24	3.5mm coincidence jack	3	$3.69	3	$1.23	$3.69	$0.00	$3.69	3
25	BNC header + Nut	3	$4.59	3	$1.53	$4.59	$0.00	$4.59	3
26	3.3 V regulator	3	$1.26	3	$0.42	$1.26	$0.00	$1.26	3
27	Standoff for SiPM PCB	6	$0.40	6	$0.48	$2.88	$7.35	$10.23	6
28	Standoff threaded screws 0-80	0	$0.00			$0.00		$0.00	
29	Plastic scintillator screws	0	$0.00			$0.00		$0.00	
30	LT-3461 DC-DC Booster	3	$13.44	3	$4.02	$12.06	$0.00	$12.06	3
31	LT 1807 Op-Amp	3	$24.06	3	$7.43	$22.29	$0.00	$22.29	3
32	Non-Inverting Buffer	3	$1.38	3	$0.46	$1.38	$0.00	$1.38	3
33	5mm LED	0	$0.00			$0.00		$0.00	
34	Arduino Nano	0	$0.00			$0.00		$0.00	
35	Temperature sensor	0	$0.00			$0.00		$0.00	
36	microSD card socket	0	$0.00			$0.00		$0.00	
37	OLED screen	0	$0.00			$0.00		$0.00	
38	SiPM	3	$219.00	3	$72.92	$218.76	$9.79	$228.55	3
39	Plastic scintillator	3	$90.00	3	$30.00	$90.00	$0.00	$90.00	3
40	PCB	3	$127.00	3	$24.82	$74.46	$19.00	$93.46	3
41	LT 1807 Op-Amp - Right Size	3	$22.29	3	$7.30	$21.90	$16.99	$38.89	3
42	#54 drill bit for scintillators	1	$18.14	1	$19.20	$19.20	$0.00	$19.20	
43	#54 drill bit for scintillators	1	$19.88	12	$1.66	$19.88	$7.98	$27.86	12
44	LT1807IS8#PBF Op-Amp	5	$36.50	5	$7.30	$36.50	$18.99	$55.49	5
45	LT3461AES6#TRMPBFCT-ND DC-DC	3	$12.93	3	$4.31	$12.93	$0.00	$12.93	3
46	12x48 Aerogel spaloft blanket 5mm	1	$100.00	1	$100.00	$100.00	$56.28	$156.28	
47	Gloves - large	1	$9.75	1	$9.75	$9.75	$0.00	$9.75	
48	Dusk Masks	1	$19.75	1	$18.76	$18.76	$0.00	$18.76	
		Total:	$752.52		Totals:	$702.02	$154.36	$856.38	

Other potential purchases

Item	Name	Required	Price for to	Amount	Unit Cost	Cost	Shipping	Total Cost	Arrived
1	microSD Card	3	$18.30	3	$6.09	$18.27	$0.00	$18.27	3
2	Battery	1	$5.95	1	$5.95	$5.95	$7.81	$13.76	1
3	Converter	1	$7.92	1	$7.29	$7.29	$0.00	$7.29	1
5	Battery Cable	2	$5.90	2	$2.95	$5.90	$0.00	$5.90	2
6	Usb Splitter	1	$5.99	1	$5.99	$5.99	$0.00	$5.99	1
7	Electric Switch	1	$1.99	1	$6.45	$6.45	$0.00	$6.45	1
		Total:	$46.05		Totals:	#REF!	$0.00	$57.66	
		Total:	$798.57				Total w/ Ship	$914.04	
	Total part count:	237							
	Small Electronics Cost	$447.73							
	Structure cost	$437.07							
	Total Cost	$884.80							

Figure 5: This is our final parts list. It contains the source of the items, in addition to what and how many of them were used.

Budget: $1,000

Structure Cost: $437.07
Electronics Cost: $447.73
Other Costs: $29.24
Total Cost: $914.04

6.0 Test Plan and Results

We first tested the structure to ensure that it would not only survive the impact but also survive the lack of pressure and low temperature. We used four main tests to test the structure of the payload. The first was the drop test; we first placed our payload inside a large plastic bag to ensure that excess aerogel would not escape into the environment should the structure fail. We then dropped our payload structure onto concrete from twenty feet up. The payload survived with minimum scratches and dents. We then performed the whip test; we again placed the payload into a large plastic bag and swung it above our heads as fast as we could. The payload did not sustain any damage whatsoever, and our electronics inside were still secure. Since we wrapped the payload in a bag, it was technically a half-whip test; the original whip test was meant to use a rope through the payload in an effort to test the structure's integrity through the tube opening. Instead, our whip test was meant to see if the aerogel would leak out of the payload.

After the drop and whip test, we moved on to the vacuum test, in which we placed our small payload in an environment one-tenth normal atmospheric pressures. We wanted to make sure the Aerogel would not outgas, or be affected in any other way by the incredibly low pressure it would encounter during launch. No issues arose from this test. Finally, we wanted to test the insulative properties of our aerogel/payload by performing a cold test. We placed our payload in a box filled with dry ice, reaching close to negative 78 degrees Celsius directly on our payload. The container itself reached a minimum of negative 13 degrees Celsius, but the inside of the payload only reached a minimum of negative six degrees Celcius. This was a phenomenal test result of the Aerogel insulative properties. Our battery can handle about negative 20 degrees Celsius, so our battery continued to function inside the container. Our battery lasted the entire duration of the cold test, which was conducted for over 3 hours.

As far as electronic testing goes, we ran the battery for an average period of 6 hours powering the two detectors. This confirmed that the experiment would run for the entirety of the flight. Each detector was exposed to yellowcake uranium as well to confirm that they were properly reading charged particles.

7.0 Expected Results

We expected to see higher muon counts at higher altitudes of measurements, once the detectors got closer to where the muons were created in the atmosphere. Our data was stored to digital memory in the form of text files on an SD card. MIT CosmicWatch provided a special Python program designed to gather the data stored on an SD card through the Arduino Nano on the muon detector. We tested this multiple times to ensure that our SD card write functionality was working when the detectors were set in SD mode. This involved plugging the Arduino Nano into a computer through a USB COM Port and running the specialized Python program. Then, the data was imported into Excel so we could analyze it in graph form.

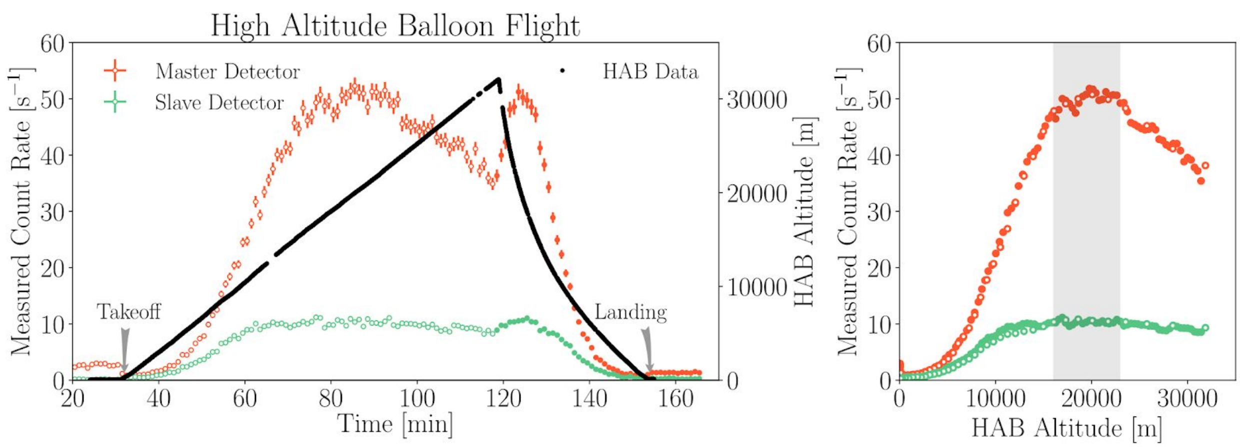

Figure 6: Data from MIT CosmicWatch High Altitude Balloon Flight. from S. Anaxi (personal communication, November 8, 2018)

8.0 Launch and Recovery

The plan for launch and recovery involved each member of the team who was able to attend the launch. One member, Rachel, was selected to stay with the payload for the duration of the day leading up to the launch, ensuring nothing would happen to it. This team member was also responsible for running with the payload during the launch.

Our team volunteered to test the new ground tracking system provided by EOSS. The system involved having a computer and antenna that received data directly from the balloons telemetry data. We were then able to connect to the computer with our phones and view the data. During the chase, we were able to maintain contact with our balloon until it popped. We lost contact with the balloon after it passed below our horizon and regained contact as we approached the landing site.

The plan for recovering the payload was for every member attending the launch to help retrieve the payload, and make observations about the condition of the payload before picking it up. The payload appeared to have sustained no visible damage, with the entire structure still intact. The package was then opened on the site after being detached from the balloon so the physical condition of the inside of the payload could be evaluated. This needed to be done before running any other tests. Inside the payload, everything was still in place; nothing had been jostled or damaged due to how we packed our structure. The detectors were both functioning at the time of opening the payload and were subsequently disconnected from power. The data was later retrieved from the Arduinos with the special Python program.

Figure 7: Our Payload after the flight

9.0 Results, Analysis, and Conclusions

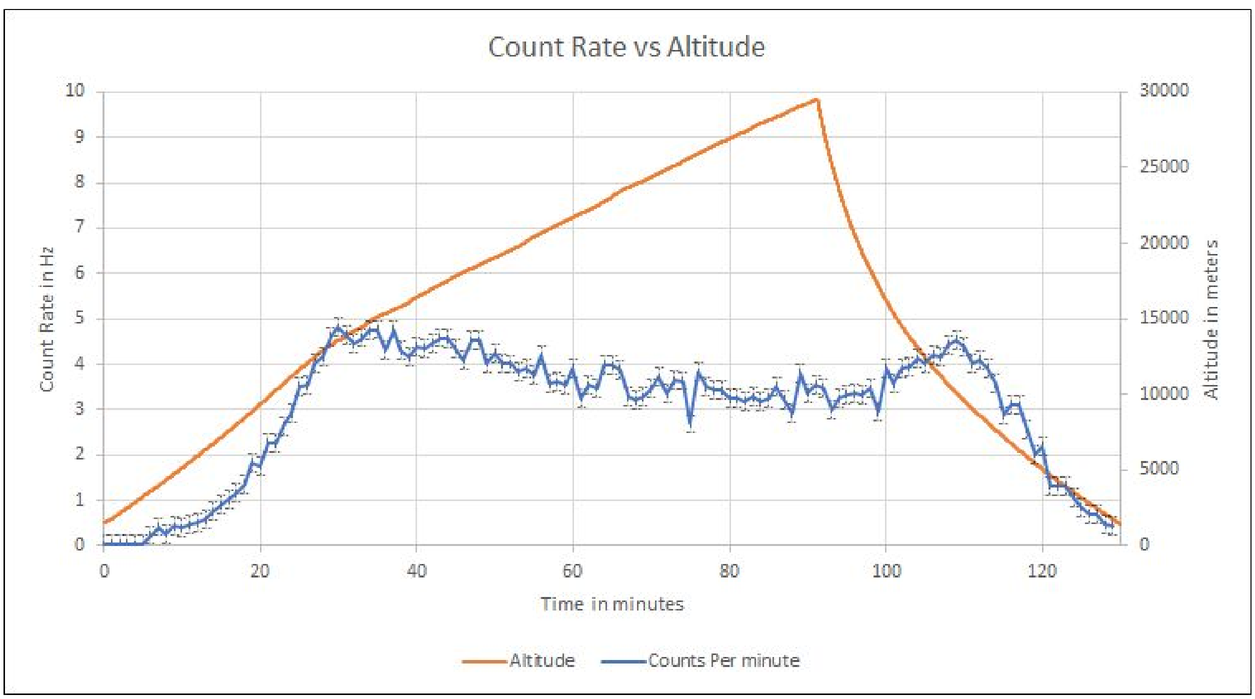

Figure 8: Our data from the flight, count rate in blue and altitude in orange.

To get the data in this graph we had to align the altitude data which had data in 1 second intervals and our data which had no real set interval since our detectors only recorded data when a muon was detected. In order for us to line up this data we averaged out the altitude data by adding up 60 rows of data and dividing it, effectively getting altitude data every 1 minute. The data for the muon count rate is also in minutes so we could line up the data in a reliable manner. With the system we used for data collection, we did not have a way to turn the detectors on right before flight, so we had to plug them into the battery and then seal the payload, which led to a large amount of unnecessary data, so we had to adjust the graph to only use data from the time of launch. To get a base ground reading we took the data 60 seconds prior to the flight and divided it by 60 to get an average count rate in minutes, we know that the orientation was somewhat correct because one member of our team was holding the payload in the correct orientation right before lift off. Unfortunately due to 2 of the detectors not working, we were unable to have an extra set of 2 detectors to have on the ground with us to get a baseline reading for the count rate.

As we can see from the graph obtained from the slave detector, the highest number of muons was detected at the altitude of 15km. Comparing these results to the MIT data, our peak was ~5km smaller. The average lifetime of a muon is ~2.2 μs (Muheim, 2019). At the same time, the speed of a muon is $(2.99 \pm 0.15) \times 10^8$ m/s = 0.99c (Vest, Castilow, & Brown, 2010). If special relativity is not taken into account, the distance that muons are able to travel while they exist is

$$d = 0.99c \cdot 2.2 \times 10^{-6}s = 650m$$

This is not enough to cover 15km, where most of the muons are formed, according to the experiment. However, if we take special relativity into account

$$d = (0.99c)(2.2 \times 10^{-6}s)(1/\sqrt{1 - 0.99^2}) = 4600m$$

$$1/\sqrt{1 - 0.99^2} = \gamma$$

This is the distance that muons are able to travel on average. The value is still smaller than 15 km. Therefore, we detect much fewer muons on the ground.

Next, we can calculate the predicted amount of muons that are able to reach the ground (basing it on their half-life) and compare it to the experimental result.

Half-life calculation (where τ is an average lifetime and $T_{1/2}$ is a half-life):

$$\tau = 2.2\mu s = \frac{1}{\lambda}$$

$$\lambda = \frac{ln(2)}{T_{1/2}}$$

$$T_{1/2} = \frac{ln(2)}{\lambda} = \frac{ln(2)}{1/2.2\mu s} = 1.5\mu s$$

According to special relativity, muons will live longer from the ground's perspective. Namely,

$$\Delta t = \frac{\Delta\tau}{\sqrt{1-0.99^2}} = 2.2\mu s \cdot \gamma = 16\mu s$$

N_{left} is how many muons (in %) are left when they reach the ground

$$N_{left} = N_0 e^{-\lambda t} = 100(\%)e^{-(ln(2)/1.5)t}$$

t is the time muons need to reach the ground from their frame of reference. Hence,

$$t = \frac{4600m}{0.99c} = 15.499\mu s$$

$$N_{left} = 100e^{-(\frac{ln(2)}{1.5\mu s})15.499\mu s} = 0.078(\%)$$

As seen on the graph, the number of detected particles at 0 altitude is indeed very small compared to 15 km altitude. In fact, it is very close to 0, which is consistent with 0.078% of the initial number (at 15km).

During our flight we also recorded temperature data. Our detectors had temperature probes on the main pcb board that were collecting temperature data every time a muon was detected. It was important for us to have our temperature recorded due to test our new structure insulation material choice that we decided to go with this year, which was an aerogel blanket insulation.

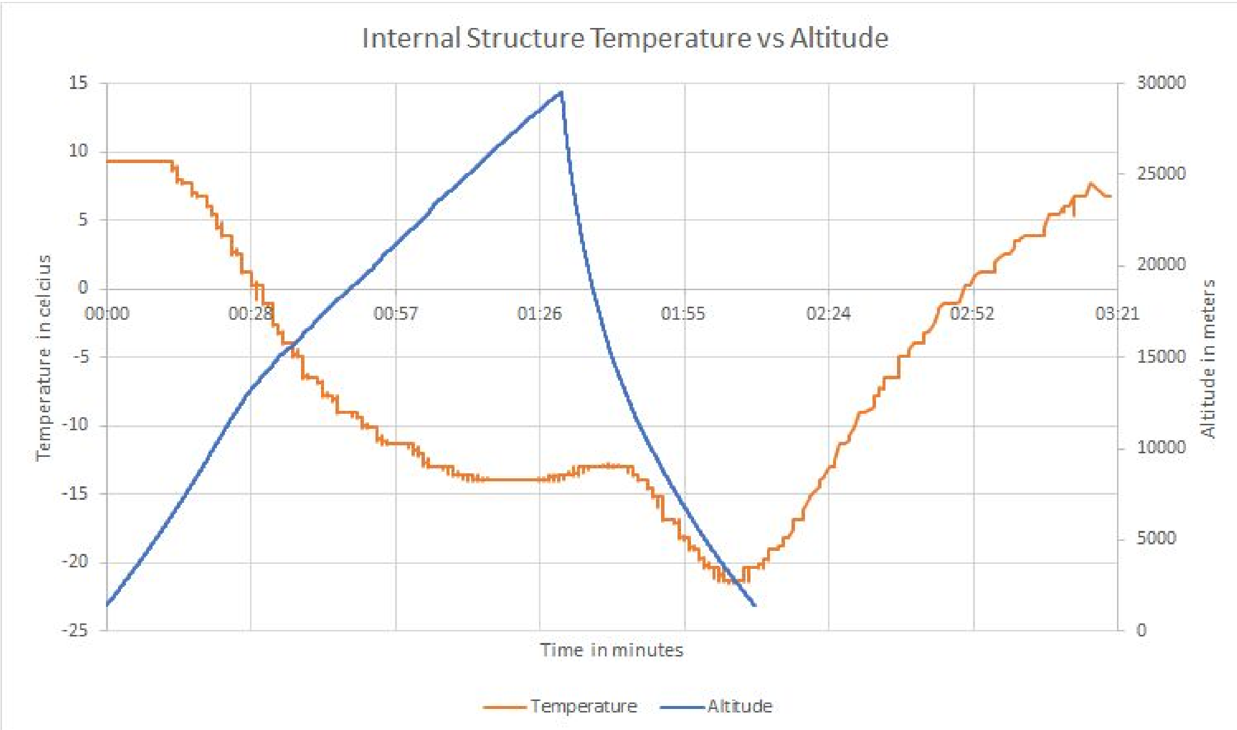

Figure 9: Our temperature over time inside our structure

Failure Analysis:

One important part of our muon detection assembly failed during flight: the SD Card Reader Header on Detector 1, which was our master detector. Because of this, we have no data from our master detector from the flight. We do have data from Detector 2, the slave detector. Because Detector 1 still detected muons during flight, Detector 2 still worked properly; Detector 1 did not record any of its own data. All of our data had to come from Detector 2, and it was this data that we used to make our preceding graphs. The muon count rates of the slave detector are expected to be lower than the master because not every muon that passes through the master also passes through the slave: some muons decay between the detectors and others come in at a high enough angle to pass around the limited surface area of the slave detector. Due to this, we would expect the Detector 1 data, if we had it, to have a higher muon count rate than our results indicate because the master detector would detect all muons that pass through it, meaning that the muons would not all be coming from above.

Another component that failed before flight was our rechargeable lithium-ion battery circuit. The battery was unable to store a charge, so we had to use a backup battery pack that was four times heavier and much bulkier than our circuit battery system. As a result, the electronic components were packed much more tightly than anticipated in our structure, putting Detector 1 at a significant angle in its shelf. This resulted in a smaller detection area relative to muons falling straight down for Detector 1, decreasing the muon count rate for Detector 2. Another thing to consider is that the heavier battery pack would rotate our muon assembly up, introducing another angle that would further reduce our detection area, this time for both detectors. This would account for our small muon detection rate relative to MIT CosmicWatch's slave muon detector detection rate (about ½ of MIT's).

10.0 Ready for Flight

Structurally, the payload could fly again right away. It sustained little to no damage in the flight. Electronically, some elements need to be fixed. For instance, the soldering of the SD card reader on detector 1 needs to be redone to get data. The battery needs resoldering and added strain relief at several points. A spare battery circuit will be kept on hand to ensure that there would be no issues with powering the detectors.

11.0 Conclusions and Lessons Learned

This year our team learned a lot regarding quicker and more efficient ways to build a structure that we can utilize in the future. Experimenting with different designs and learning how long it takes to assemble those different designs led us to the structure we ended up utilizing. The compact and easy-to-assemble rectangular structure is one we know we can use again if we pack the inside of the structure in a similar way, which helps the structure stay balanced during flight. We also learned what materials work better than others and what would be good to use in the future, such as the aerogel for insulation and the foam core as a lightweight material. We would have done a few things differently if we had the opportunity to do the launch over again, such as better preparing for all worst-case scenarios. This would have been helpful and is something we will be sure to do next time by bringing backups for all of our materials and testing all of our electronics and materials more than once. On the morning of the launch, we found ourselves needing to use a backup battery. Thankfully we brought a fully functioning backup from last year's project. Had we better-considered things that could have gone wrong, we would have built another 1200mAh Lithium-Ion battery with our 5v boosters to create a backup battery system, and been able to avoid adding extra weight to our payload.

12.0 Message to Next Year

Our message to the next years Demosat team: This is an opportunity for you to help further the understanding of our planet. Remember there are countless opportunities to learn during the course of the project and to stay open to new ideas. Furthermore, don't forget to enjoy the work and the launch!

There were several aspects to our project that worked and failed. Our slave detector worked while the master detector didn't write any data. Thus, we were only able to collect a fraction of the data we expected to capture. Our original design for the case had to be scrapped due to a communication breakdown between members and we ran out of time to fix any mistakes. We each had different interpretations on how the case should be designed which caused confusion in the team.

When building the electronics there were some parts that we wanted to design further. The battery circuits were loose inside the payload and did not have an independent housing; We had thought about building or printing something but did not. The electronics were not integrated into the structure at all. We had planned on having a button on the outside to turn the detectors on from the outside. We did not account for the fact that we would need 2 buttons because the detectors needed to be turned on in sequence. It also would have been nice to have a led on the outside to indicate the detectors were running.

What could be done differently from this years project is to ensure communication between all participating team members to make sure problems can be solved quickly and early in the development of your satellite, check every single thing done to the payload to make sure every component is in working order. Finally, before going out to launch, do a final test to troubleshoot any lingering problems with the payload.

13.0 References

Muheim, D. F. (2019). *Muon Lifetime Measurement.* Retrieved April 25, 2019, from The University of Edinburgh: https://www2.ph.ed.ac.uk/~muheim/teaching/projects/muon-lifetime.pdf

Vest, B. C., Castilow, J., & Brown, D. J. (2010). Measuring the Speed of a Muon. *Wabash Journal of Physics*(1), 1-3. Retrieved April 25, 2019, from http://www.iontrap.wabash.edu/adlab/papers/S2010_castilow_vest_muon_speed.pdf

Frankiewicz, K., & Przewłocki, P. (2017). *CosmicWatch*. Retrieved April 26, 2019, from http://cosmicwatch.lns.mit.edu/