

ALARA Shield

Final Report

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1 Introduction

1.1 Problem Definition

Outside of the Earth's magnetic field, astronauts are subjected to harmful levels of cosmic radiation. In order to prepare for long term manned missions to the moon, mars, or other destinations, alternate means of radiation shielding must be developed. Our goal is to design an apparatus to test the shielding capabilities of basalt against space radiation. This apparatus will be launched in a DemoSat balloon in November, and as such, must conform to certain DemoSat standards. To accomplish this, we have done some background research to help guide our design.

1.2 Background

1.2.1 Radiation Overview

When humans leave the protective shielding of Earth's magnetic field, they are subjected to harmful cosmic radiation. The most harmful category of radiation is ionizing radiation. This consists of particles or photons that have enough energy to completely ionize an atom by stripping the electrons from the atomic nucleus. When ionizing radiation passes through a material or a human, it has enough energy to ionize the material, leaving behind significant damage [13]. There are two main sources of ionizing radiation in interplanetary space: galactic cosmic rays (GCR) and solar energetic particles.

Galactic cosmic radiation originates from outside the solar system and consists of atomic nuclei that have had all of their electrons stripped away. They have most likely been accelerated to nearly

the speed of light by supernova remnants. When they travel through interstellar space, the particles interact with thin gasses and high energy gamma radiation [4]. Galactic cosmic radiation typically has energies between 100 MeV and 10 GeV, with the frequency of particles decreasing as the energy level increases [11]. Because mars and the moon has very little atmosphere and magnetic field, this high energy radiation poses a serious health risk to long term lunar or martian missions [17]. Studies have shown that long term exposure to GCR has lead to increased risk of radiation related cancers, leukemia, and melanoma [9].

Solar energetic particles are atoms that are associated with solar flares. They are accelerated away from the sun due to solar wind and are carried outwards towards the heliosphere [4]. The flux of solar energetic particles and their average energy depends on the current position in the solar cycle, a periodic 11-year cycle of solar activity. During the peak of solar activity, the radiation can reach energy levels of 10 MeV to 150 MeV [15].

Overall, it seems that GCR poses the most threat to manned lunar or mars missions because it is at a higher energy and is more constant than solar energetic particles. Therefore, we should focus our device on the detection of galactic cosmic radiation.

1.2.2 Current Radiation Protection

When dealing with radiation, typical strategies include increasing the distance from the source, minimizing time of the exposure and using radiation shielding [7]. Materials that are chosen for radiation protection typically have smaller atomic number [16]. Currently, aluminum seems to be the preference for structural support on the space station. In tests done to determine materials to help minimize radiation for flight crews, it was found that a graphite composite material appeared to have the most capability, by an order of magnitude, in reducing the number of neutrons below the proton knockout region at approximately 200 keV/gm, compared to aluminum or titanium. However the gamma ray shielding efficiency of the composite is not as great as that of titanium, but these fission-based gamma rays do not exist in the high-altitude environment [16]. This is helpful since these tests were focusing on high atmospheric radiation which is what we will encounter in our high energy balloon flight. Overall it seems that there has not been a clear solution to help reduce the radiation that astronauts or pilots see besides limiting their exposure time.

1.2.3 Lunar and Martian Basalt as Shielding Mechanism

Multiple studies suggest the possibility and effectiveness of using lunar basalt regolith for radiation shielding. One study created a model of the lunar radiation environment in order to test the different possibilities [6], without having to execute the actual experiment. It allowed ideas that would not work to be thrown out before they were tested. Another study in the Journal of Radiation Measurements tested the effectiveness of lunar basalt regolith and simulant as shielding by hitting it with lasers that were made to model the types of radiation that would be experienced in space (galactic cosmic radiation – GCR) [12]. The results of this study suggest that around half of a meter of regolith is necessary for sufficient shielding.

With this in mind, it was helpful to look at studies of the shielding capabilities of lunar lava

tubes. A study reported in the Journal of Radiation Research showed that lava tubes on the moon are an ideal place to protect humans on the moon from GCR and solar particle events (SPE) [5]. The results of this study that any layer of regolith thicker than 1 meter will block all SPE radiation, and any layer thicker than 6 meters will block all GCR radiation.

There have been fewer studies on the radiation shielding capabilities of Martian regolith. However, since the properties of lunar and martian basalt are similar, we can most likely say that the radiation shielding potential of Martian regolith is also quite high. Based on a study done by NASA, the raw regolith on the moon and mars score quite high compared to other options for radiation shielding in space [3].

Based on this research, it seems very promising to use the regolith available on the moon or mars as a shield for future people who are working or living there. That said, in order to obtain complete protection, it will be necessary to find a way of creating a shield that is multiple meters thick.

1.2.4 Sensors

Many radiation sensors exist, however most are not viable for use in space. Silicon radiation detectors look promising [10], however come with the downside of needing to be run through a spectral analyzer both before and after the test. This is especially worrisome if our design breaks after the balloon lands on Earth, though can be mitigated with careful design testing. Not to mention, the effectiveness of silicon-based PM readings drops off dramatically once they're put in cold, space-like conditions [2]. NASA's Crew Radiation Detectors [14], which were used to monitor radiation on the ISS, suffer from the same issue of needing an external analyzer. We also briefly considered using a photomultiplier tube (PMT), which yields very accurate results [8], but are ultimately far too fragile to implement in a crash-based design.

What we need is a portable, lightweight, preferably wireless spectrometer as described in E.M. Becker's paper [1]. Though the one designed in the paper would be ideal, the closest thing to it on the market is something like the GR1® Spectrometry System. However, since it needs to be connected to a computer, and more importantly costs between \$10,000 and \$20,000, we cannot incorporate this, or any other industrial microspectrometer, into our design.

What seems most promising for a low-cost, easy-installation setup is several Arduino-interfaced Geiger counters, which run around \$100 per unit. We could layer these counters under different thicknesses of basalt, along with a dedicated backup counter that records ticks. We could then measure general radiation dosage under different basalt thicknesses.

2 Solution Description

Our task is to test the radiation shielding capabilities of Mars regolith. A rendering of our final design is shown below in Figure 1. This design incorporates a number of components, which

are labeled in Figure 2. These components are grouped into two subsystems: mechanical and electrical. An exploded view is also included below in Figure 3. This system is built to withstand the various physical requirements of DemoSat, and uses Geiger counters covered in regolith to measure radiation through Counts Per Minute (CPM). This setup gives three different comparison curves and one baseline curve with no regolith. The solution also includes an Arduino interface with the counters, an OpenLog data recording device, and a non-electronic heating system, all of which will be discussed in greater detail below.

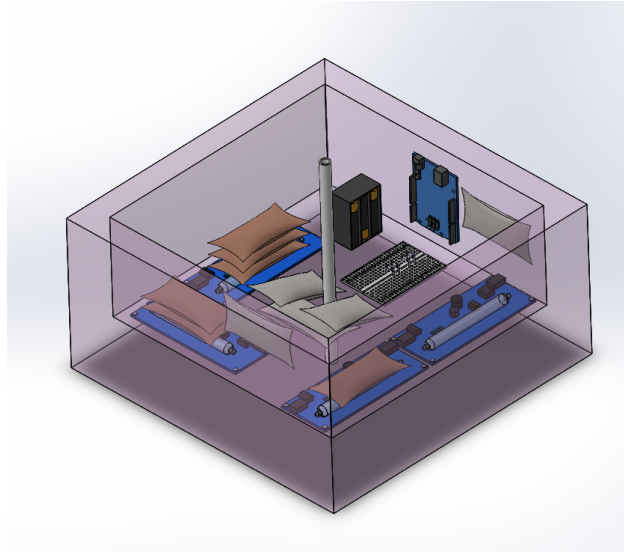


Figure 1: Isometric view of final design.

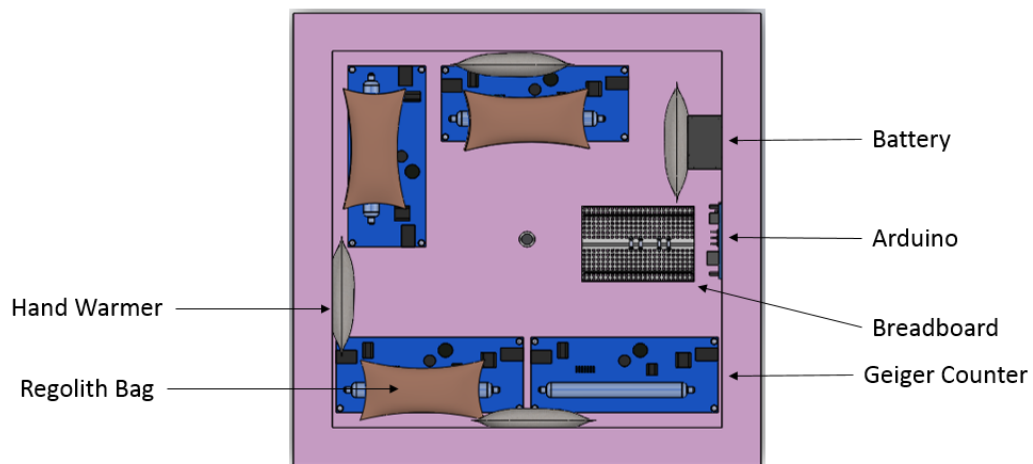


Figure 2: Top view of design showing labeled components.

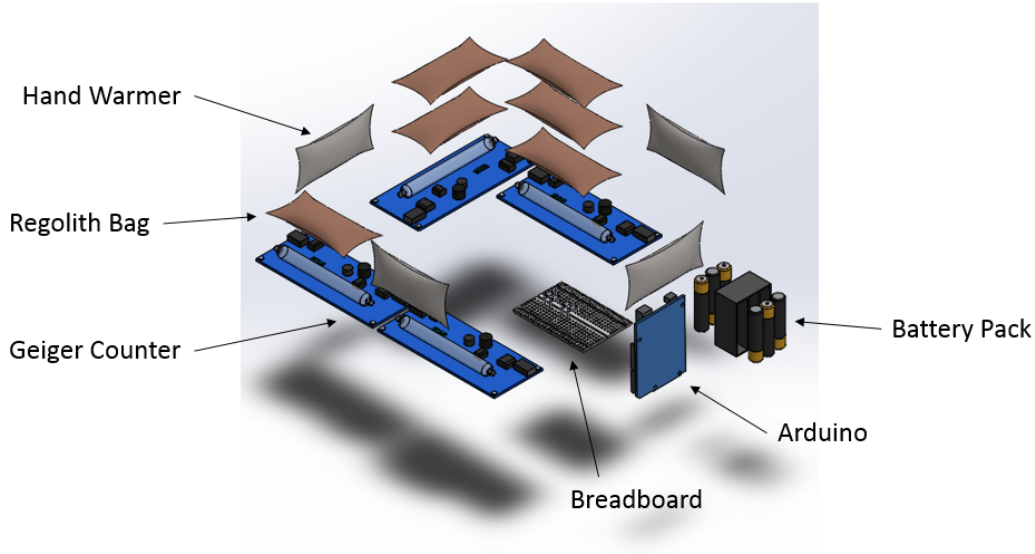


Figure 3: Exploded view showing labeled components.

3 Mechanical Subsystem

3.1 Outer Shell

The electrical components and regolith bags are housed inside of a box made out of extruded polystyrene, a durable foam resistant to moisture [19]. The dimensions of the box are 35cm by 35cm by 18cm. Insulation is used as an outer shell to protect the electronics against the freezing temperatures found at high altitudes. Additionally, the insulation is 5 centimeters thick, providing sufficient shock resistance in the event that the outer shell impacts the ground at speeds approaching terminal velocity. Gorilla Glue was used to hold together the multiple pieces of extruded polystyrene, as it bonds well to the insulation. Because the glue expands once it solidifies, it also serves to fill in the gaps between the insulation, creating a fully sealed thermal envelope.

Figure 4 shows a SolidWorks sketch of the outer shell.

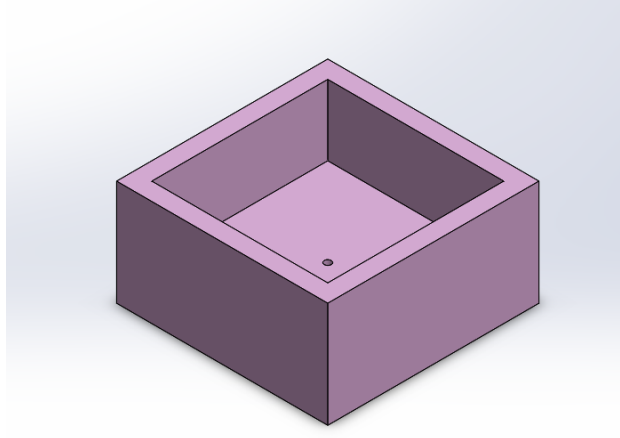


Figure 4: Isometric view of outer shell.

3.2 Regolith Containment

To contain the regolith, small 6cm by 3.5cm jewelry bags are used. To determine the relationship between the amount of regolith used and its radiation shielding capabilities, a different number of regolith bags are placed on each counter. One Geiger counter is not covered by any regolith to provide a base case, and the other three counters are covered with one, two, and three bags respectively. Each bag is filled with the same amount of regolith to ensure that each counter is covered by a known amount of regolith. The bags are attached to the Geiger counters with electrical tape.

Figure 5 shows a rendering of a Geiger counter covered with two regolith bags.

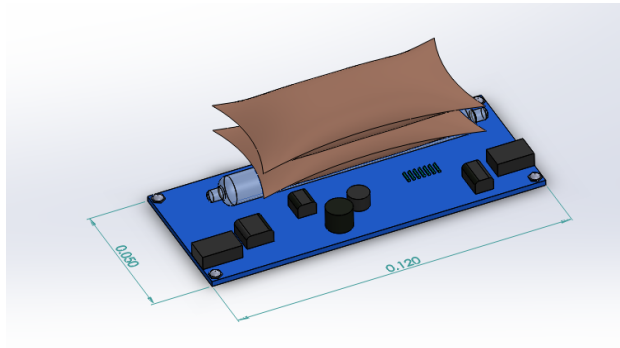


Figure 5: Rendering of Geiger counter with two regolith bags attached.

3.3 Heating

Four Hothands hand warmers are used to heat the system during flight. They are able to provide up to 10 hours of 130 °F to 140 °F heat [18]. One is attached directly to the battery, and the other three are attached to the walls. They are air activated so before launch they will need to be shaken

and taped into the box. The outer shell is air tight so there should be enough oxygen to keep the hand warmers working for the 2 hour flight.

Figure 6 shows the location of the four hand warmers. Three are attached to the inner walls of the shell using electrical tape, and one is taped directly to the battery pack to ensure that it will stay warm for the duration of the flight.

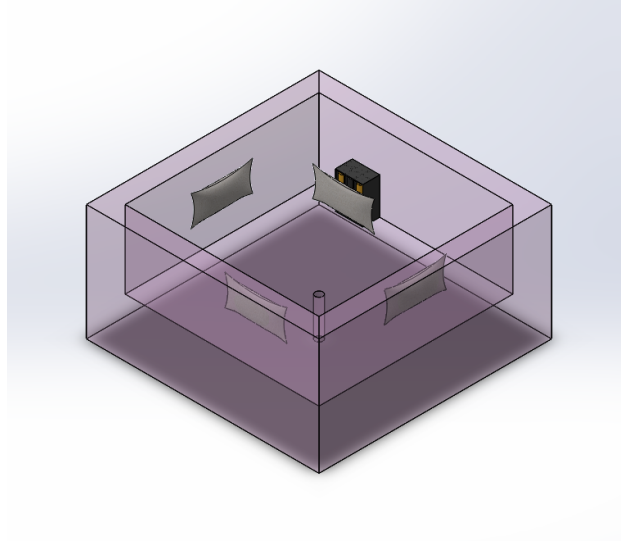


Figure 6: Isometric view of shell showing location of the four hand warmers.

3.4 Sizes and Weights

Table 1: The size and weight of each component

Component	Size(cm)	Weight (g)
Outer Shell	35 x 35 x 18 with 5 walls	300
Balloon Attachment Tube	$15\frac{1}{4} \times 1\frac{1}{4}$	50
Regolith Containment	$6 \times 3\frac{1}{2} \times 2$	60
Geiger Counter	$12 \times 5 \times 0.2$	150
Arduino Board	$11 \times 5 \times 0.5$	130
AAA Batteries	$3.5 \times 2.2 \times 4.75$	200

3.5 Test Results

3.5.1 The Drop Test

In order to simulate the possible landing conditions the payload could experience, the payload was dropped from 15 feet[20]. Figure 7 shows the dummy weight used in order to ensure that the electronics would not be damaged in the event of our structure failing.



Figure 7: Dummy load placed in outer shell for drop test.

The payload was then thrown off a second story balcony with a parabolic trajectory as seen in figure 8.



Figure 8: Payload during the drop test.

The payload landed without any serious injury to the outer shell, so the test was deemed a success.

3.5.2 The Swing Test

The payload also underwent a "Swing Test" in order to simulate the maximum g's it may encounter during the flight. For this test we put a backup arduino unit with some other electrical components into the box to ensure that the actual electronics used in the flight will not be damaged. This can be seen in figure 9



Figure 9: Dummy electronics placed in outer shell for swing test.

A rope was tied through the payload, and it was spun overhead as seen in figure 10. It then collided with a tarp room divider in order to impart a directional change.

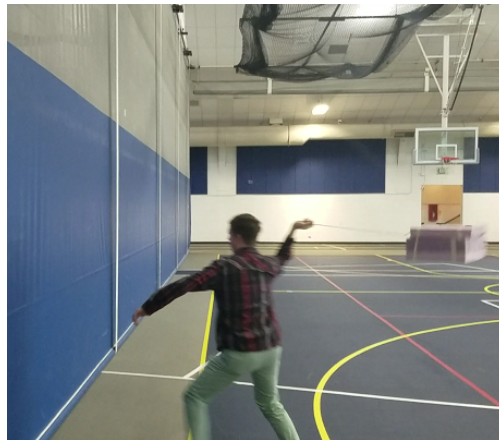


Figure 10: Payload during swing test before colliding with room divider.

The electronics were tested that night, and there appeared to be no damage to them. Therefore, the swing test was deemed a success as well.

4 Electrical Subsystem

The electrical subsystem consists of an Arduino Uno attached to four geiger counters, an OpenLog data logger with microSD, and a SparkFun Pressure/Temperature breakout board (MPL3115A2). The entire system is shown in Figure 11. The Arduino is run by 6 AAA 1.5V batteries, rated at 1000 mAh. For a four-hour flight, this setups yields 250 mA of consumption. Table 2 shows the net expected power consumption of the system.

Table 2: Power Consumption

Item	Current Consumption (mA)
Geiger Counter x4	120
Arduino Uno	30
OpenLog	6
Altimeter	2
Total	158

For memory usage, the microSD card used has 8GB of memory, while every line of data stored contains five 32-bit integers, with the expected run time being 4 hours. At one data point per minute, 240 lines of data are expected, yielding a net cost of 38.4 Kb. The microSD space proves more than sufficient for storing the data we need.

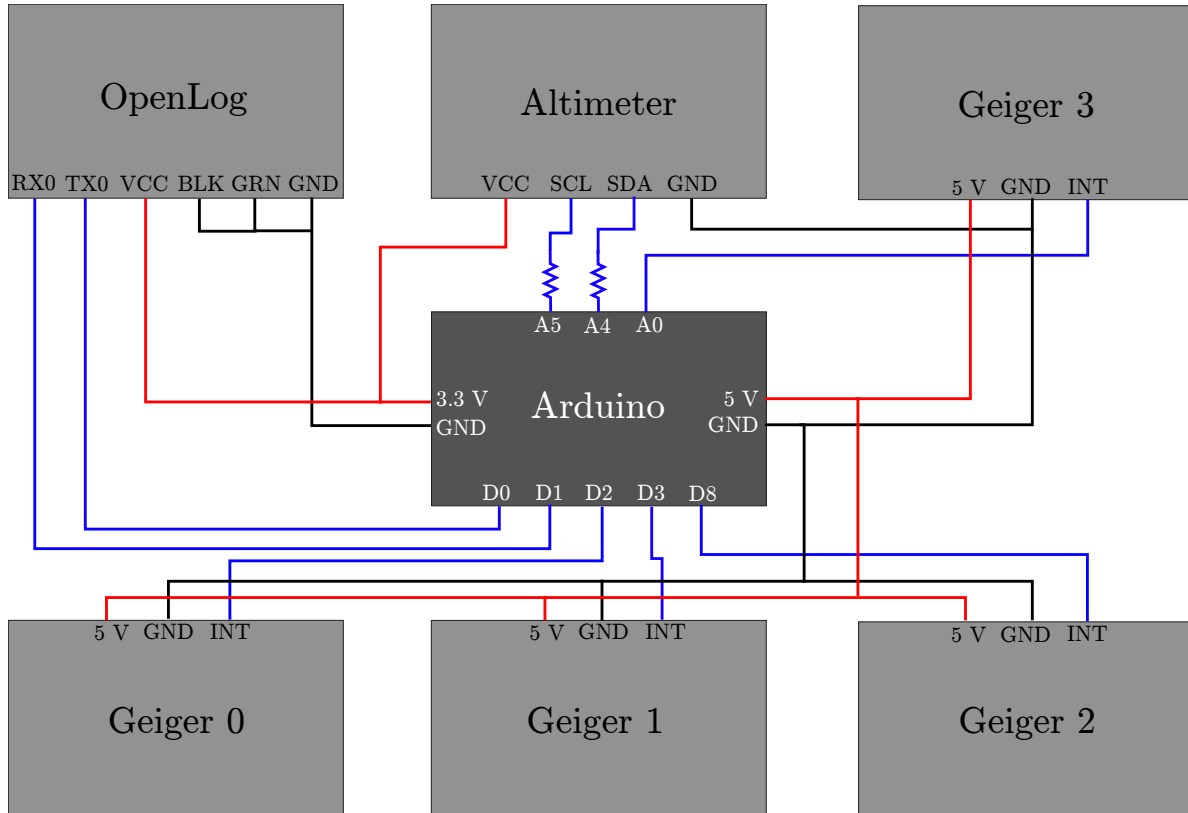


Figure 11: Block diagram of electronic subsystem.

4.1 Arduino and Geiger Counters

An Arduino Uno is used to run the geiger counters, altimeter, and SD card storage system. The board draws 30mA, and runs off 6 1.5V AAA batteries.

Four geiger counters are used to test a range of regolith options. All of the counters are hooked up similarly, as Figure 12 shows. Each counter runs off of the Arduino's 5V output, and is also attached to the GND of the board. Each board consumes 30mA, for a total of 120mA.

Each board's interrupt pin is attached to a different pin on the Arduino. Those pins are D2, D3, D8, and A0 on the board. The Arduino Uno has both external interrupts and pin-switch interrupts [21]. Pins D2 and D3 are external, meaning they are set up in hardware to be interrupt-enabled. Every other pin on the board can be enabled to be interrupted in software, but comes with the downside that there are only 3 unique interrupt routines that can be used. This means that a pin change (such as from high to low) on D0-D7 calls one unique interrupt function, no matter which pin actually changed. The same is true for pins D8-D13 and A0-A5. We technically had 3 interrupt vectors available, since D2 and D3 use their own hardware-based interrupts, but we did not want to overload the software D0-D7 interrupt vector handler. Because of this, we chose pins D8 and A0 as our pins for the other two boards.

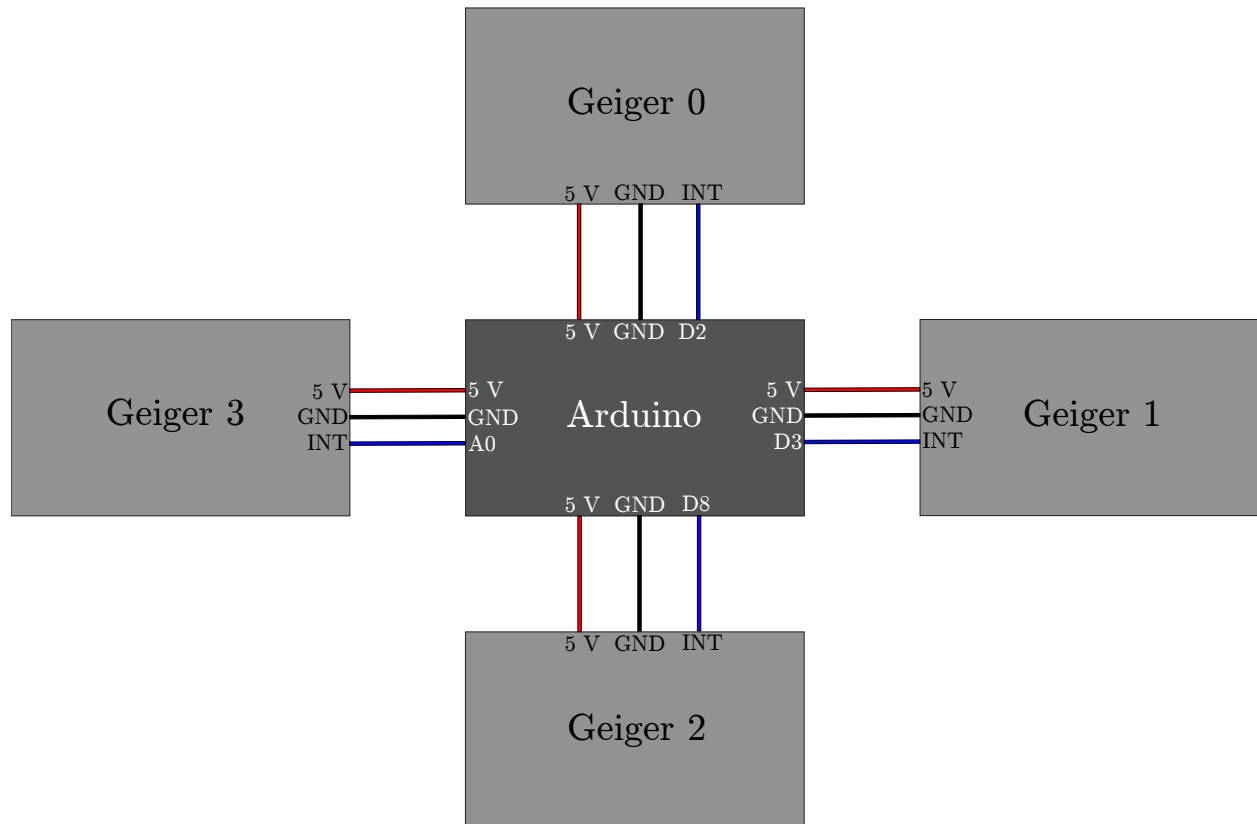


Figure 12: Geiger counter hookup schematic.

Shown below is the implementation of the schematic on one board.

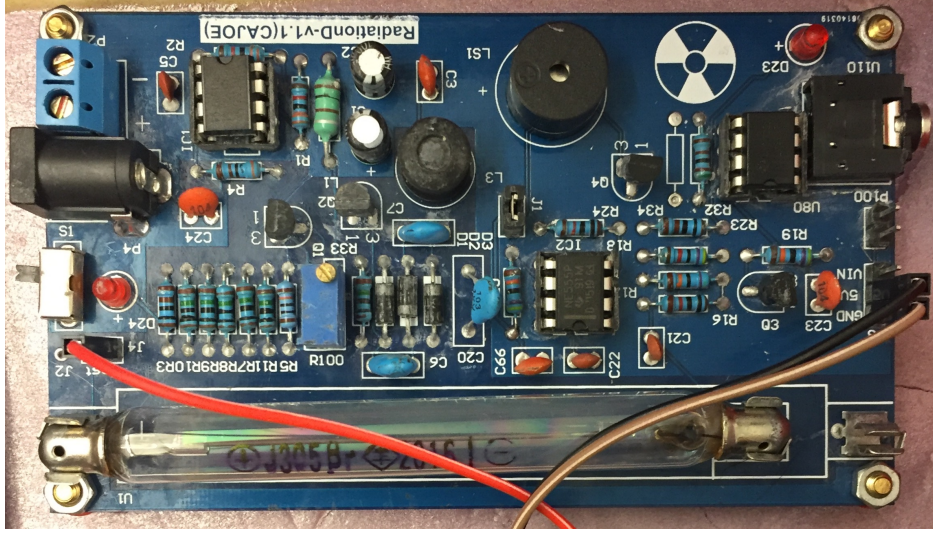


Figure 13: Picture of the physical setup of one of the geiger counters.

4.2 Meteorology Data

A SparkFun Altitude/Pressure Sensor Breakout (MPL3115A2) is used to collect meteorology data [22]. While temperature data is not used in the code, it was logged regardless as a way to debug failures. For example, during our first freeze test, after we pulled data out, we noticed it was corrupted. However, the temperature data was fine, and it showed that the first iteration of heaters were not working well enough to keep the geiger counters operational. Figure 14 shows the hookup used for the altimeter. Note that the two $330\ \Omega$ resistors are used to interface the 3.3V I2C connection on the breakout with the 5V I2C on the Arduino. It draws 2 mA of current.

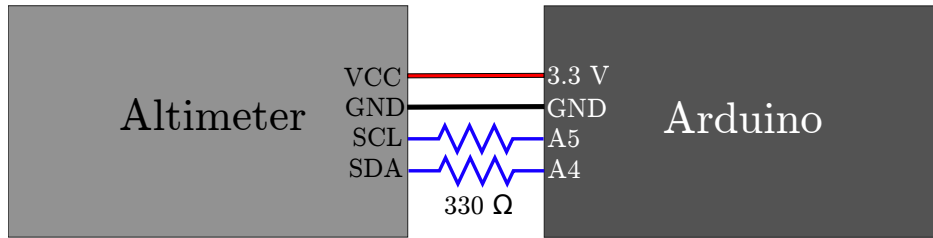


Figure 14: Altimeter hookup schematic.

4.3 Information Storage

An OpenLog with a microSD card is used to log gathered data. The OpenLog interfaces with the Arduino using RX-TX, as shown in Figure 15. The OpenLog draws 6mA of current.

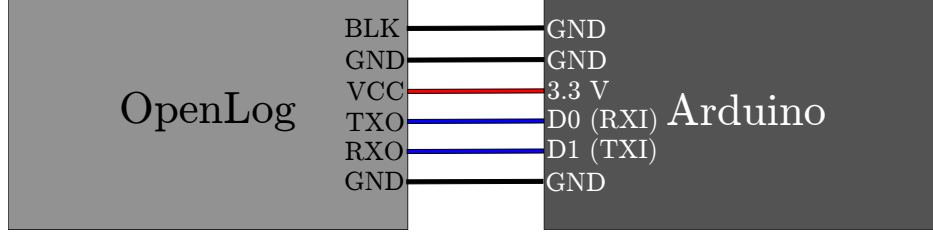


Figure 15: OpenLog hookup schematic.

4.4 Code

The code is very simple in order to facilitate minimal power and memory usage. Whenever radiation hits a geiger counter, it sends a pulse through its INT line, which the Arduino can interpret as an interrupt [23]. The software we wrote uses interrupt handlers to increment integer counters inside the Arduino. Once a minute passes, all relevant data is written to the SD card, and all of the counters are reset back to 0. This goes on indefinitely until the battery dies. In the Appendix, Figure 19 shows a broad overview of the program. Below Figure 19 is the full code.

4.5 Freeze Test Results

Shown below is a table of data from a 3.5-hour freeze test. The box was put into a freezer which operated at about -10 °C, which we considered sufficient to simulate atmospheric temperatures. The electronics operated well the whole time, confirming that the batteries would be able to last through the 2.5-hour flight, that the geiger counters, Arduino, and OpenLog will work under typical payload temperatures, and that our heating system provided sufficient heat to keep everything operating.

Table 3: Freeze Test Results

Time (minutes)	Sensor 0 CPM	Sensor 1 CPM	Sensor 2 CPM	Sensor 3 CPM	Temperature (°C)
1	32	31	33	18	15
2	13	21	22	19	16
...	...	...	...	...	...
100	26	30	33	27	43
101	25	29	21	18	43
...	...	...	...	...	...
212	24	25	18	18	46
213	22	38	10	17	46

5 Interfaces

The only interfaces between the mechanical and electrical subsystem involve attaching the regolith bags to the geiger counters and the geiger counters to the outer shell. The regolith bags will be wrapped in electrical tape to add additional structural support so that the bags do not rupture

during the flight. The regolith bags will then be secured to the Geiger counters by wrapping electrical tape around both the bags and the counters in three different places along the length of the counter. All of the wires are hot glued in place so that they will not detach during the flight. Finally, the geiger counters, arduino, and breadboard are all attached to the outer shell using a combination of hot glue and super glue.

6 Results

The data collected shows a trend that corresponds closely with our predictions. There appears to be a positive relationship between the amount of regolith used and the shielding capabilities. This can be seen in Figure 16 below, showing the counts per minute of the four geiger counters as a function of altitude.

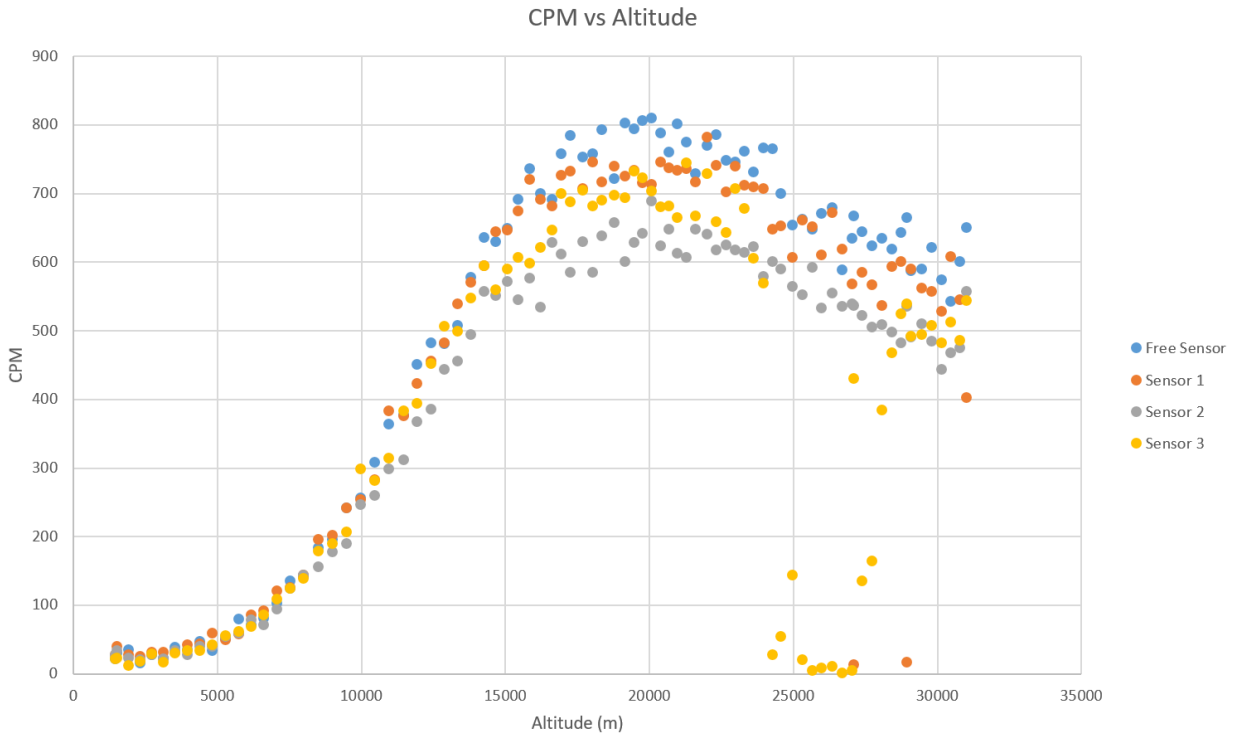


Figure 16: Graph of counts per minute as a function of altitude.

As can be seen in this graph, the geiger counter with no shielding recorded the most counts per minute. This implies that it was struck with more radiation than any of the other shielded geiger counters. This trend continues, as the geiger counter with one bag of regolith (sensor 1) recorded less counts per minute than the free counter, but more than the counter with two bags of regolith (sensor 2). However, there is a discrepancy in the data for sensor 3, which was the geiger counter with three bags of regolith shielding. The data showed that this counter recorded more counts per minute than the counter with only two bags of regolith shielding (sensor 2), which does not follow the trend displayed between the other three sensors. This could be for a number of reasons. One possible explanation for this is that the payload was swung around with lots of force during the takeoff and landing of the balloon, which could have knocked over the third counter. This means

that the radiation coming from outside the atmosphere would no longer be passing through the bags of regolith, but rather hitting the counter fairly directly. Another possibility is that the third counter had some power issues. This is supported by the fact that at around 25,000 meters, the counter stopped working entirely.

These graphs also demonstrate that all four sensors recorded a decrease in radiation above 20,000 meters. This is due to the fact that the geiger counters were most likely picking up secondary rays rather than primary rays at lower altitudes. Secondary rays are only created when primary rays from space collide with particles in the atmosphere and scatter into lower energy (secondary) particles. The primary rays were probably so high energy that they passed right through the geiger counters. Once the payload got above 20,000 meters, most of the secondary particle scattering was occurring below it, so the sensors didn't record as much radiation as they did at lower altitudes [24].

The data shown above can also be represented in a graph of counts per minutes as a function of time, as seen in Figure 17. The graph looks very similar to the graph of counts per minute as a function of altitude because the altitude was increasing steadily with time.

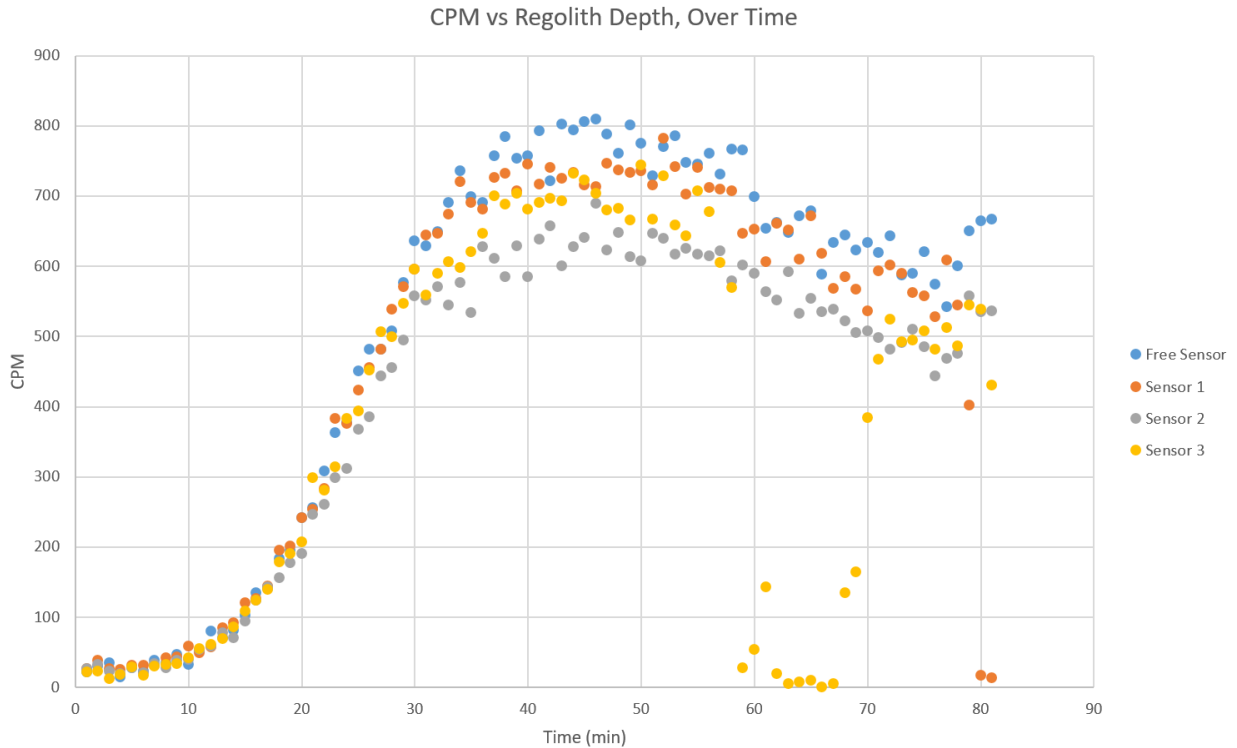


Figure 17: Graph of counts per minute as a function of time.

The recorded temperature data is also consistent with our predictions, i.e., the temperature slowly decreases as the time in flight increases (which is positively correlated with altitude). This data can be seen in Figure 18.

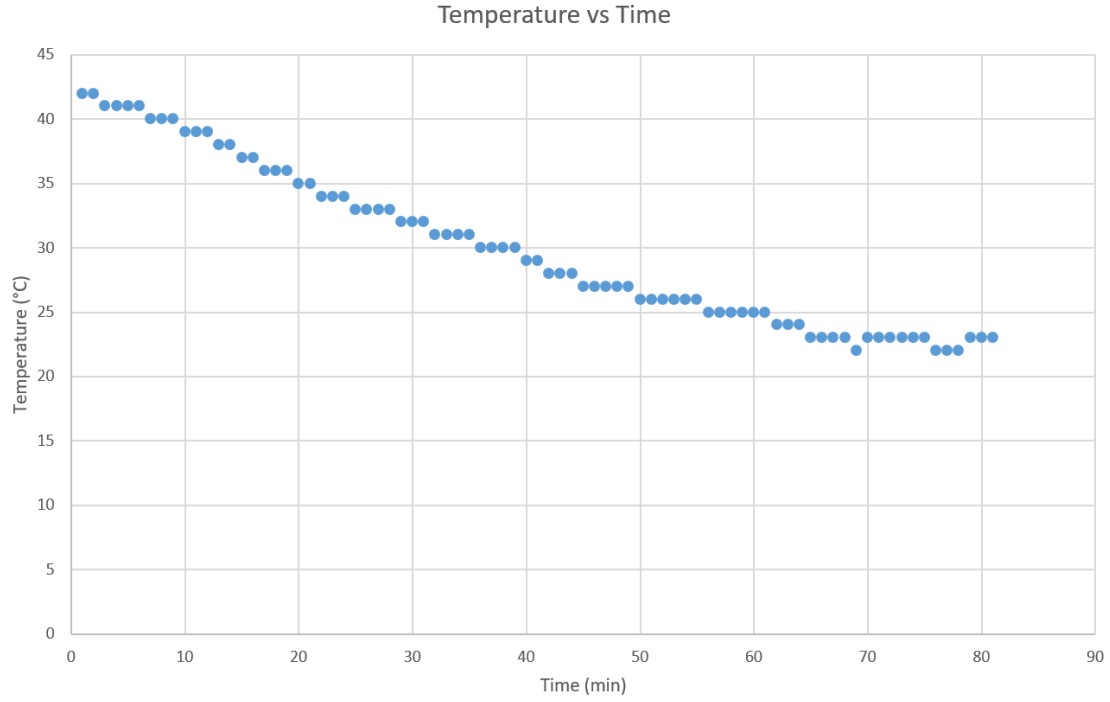


Figure 18: Graph of temperature inside of the payload as a function of time.

Finally, given below in Table 4 is a portion of the actual data collected from the four geiger counters and the temperature sensor.

Table 4: Sample of Actual Data Collected.

Altitude (m)	Free Sensor	Sensor 1	Sensor 2	Sensor 3	Temperature(°C)
10463.9	308	283	260	281	34
10963.1	363	383	298	314	34
11466.8	377	376	312	383	34
11947.0	450	423	367	394	33
12432.9	482	455	385	452	33
12891.5	481	482	443	506	33
13363.9	507	539	455	499	33
13823.8	577	570	494	547	32
14278.1	636	595	557	595	32
14666.1	629	644	551	559	32
15072.3	649	646	571	589	31

7 Summary

Based on our final launch data, we would change minor aspects of our design in order to gain maximum accuracy. To address the discrepancy in our data, we would suggest that future implementations of this project improve on the methods used to secure the electronics and sensors in the box. For example, a piece of plywood could be bolted to the bottom of the box and have the electronics bolted to it. This would ensure that the geiger counters could not be knocked over and have radiation hit the counter directly instead of passing through the bags of regolith. In addition, this may also improve the issues we encountered with power since the wires would be less likely to come loose. Another design aspect to address the power issue is to solder the electronic connections instead of hot gluing wires into the breadboard. The pre-flight tests were extremely helpful in confirming the high likelihood that our payload would survive the launch and landing. If any design modifications are made, the tests should be repeated.

The data supported the general trends we were expecting; the time and altitude data closely correlated since the altitude was increasing then decreasing as time passed and the temperature slowly decreased as time passed since we were getting higher in the atmosphere. Since the data supports the general expected trends, we are confident that with the small design aspect changes, this apparatus will be able to accurately test the shielding capabilities of basalt against space radiation.

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8 Appendix

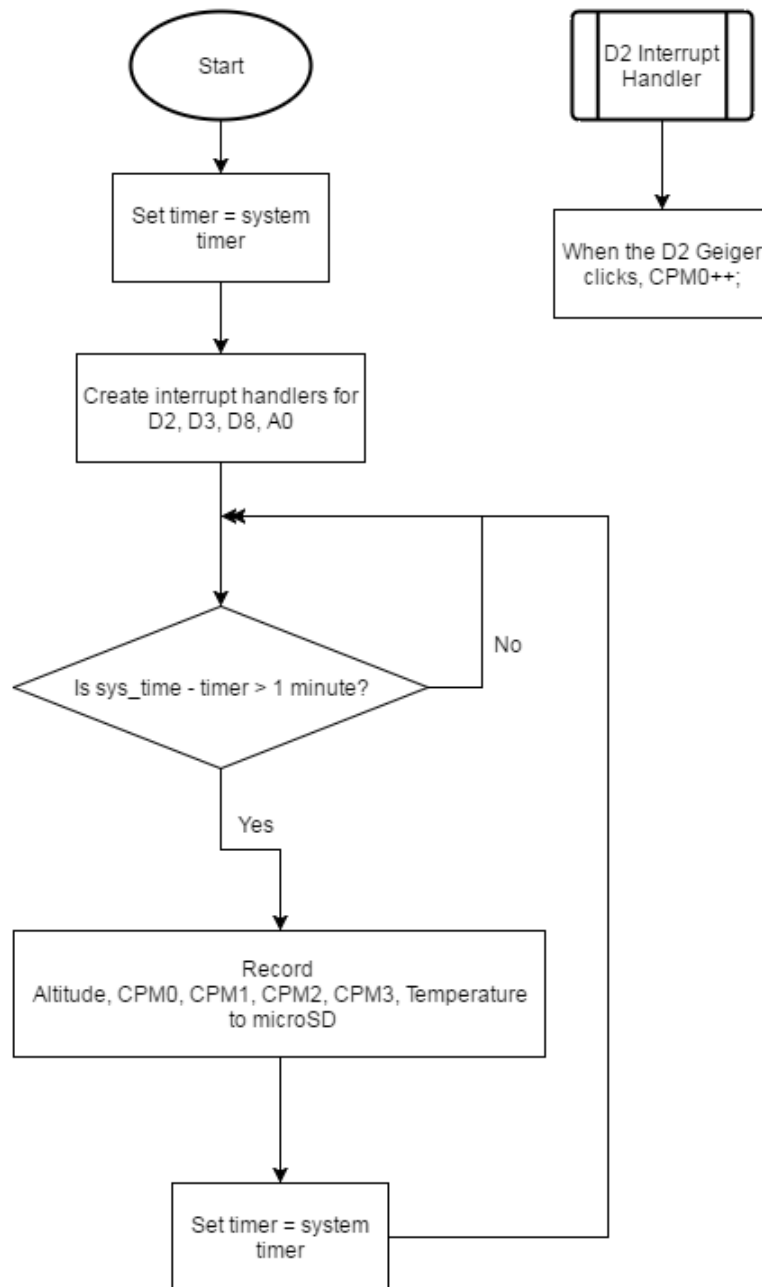


Figure 19: Code Flowchart.

```

#include <Wire.h>
#include "SparkFunMPL3115A2.h"
#include<SPI.h>

#define sensorFree 2
#define sensor1 3
#define sensor2 8
#define sensor3 6
MPL3115A2 myPressure;
unsigned int altitude; //max altitude ~30000m
int temperature;
volatile long cpmFree = 0;
volatile long cpm1 = 0;
volatile long cpm2 = 0;
volatile long cpm3 = 0;
unsigned long timer = 0;
const unsigned long interval = 60000;

void pciSetup(byte pin) //pin change interrupt initializer
{
    *digitalPinToPCMSK(pin) |= bit (digitalPinToPCMSKbit(pin)); // enable pin
    PCIFR  |= bit (digitalPinToPCICRbit(pin)); // clear any outstanding interrupt
    PCICR  |= bit (digitalPinToPCICRbit(pin)); // enable interrupt for the group
}

ISR (PCINT0_vect) //D8 aka sensor2
{
    cpm2++;
}

ISR (PCINT2_vect) //A0, note there may be problem with externals
{
    cpm3++;
} //note that for both of these interrupts, we need to halve them. We get a high-
    low-high pulse from geigers => 2 pin changes per pulse

void setup() {
    Wire.begin(); // Join i2c bus
    Serial.begin(9600);
    pciSetup(sensor2); //set up PCI
    pciSetup(sensor3);
    myPressure.begin(); // Get sensor online
    //Configure the sensor
    pinMode(sensorFree,INPUT_PULLUP); //set each sensor output as Arduino input
    pinMode(sensor1,INPUT_PULLUP);
    pinMode(sensor2,INPUT_PULLUP);
    pinMode(sensor3,INPUT_PULLUP);

    myPressure.setModeAltimeter(); // Measure altitude above sea level in meters
    myPressure.setOversampleRate(7); // Set Oversample to the recommended 128
    myPressure.enableEventFlags(); // Enable all three pressure and temp event flags

    attachInterrupt(digitalPinToInterrupt(sensorFree),addTickFree,FALLING); //Create
        external interrupts
    attachInterrupt(digitalPinToInterrupt(sensor1),addTick1,FALLING);
    delay(2000);
}

void loop()

```

```

{
  altitude = (unsigned int)myPressure.readAltitude();
  temperature = (int)myPressure.readTemp();
  if (millis()-timer >= interval) //If 1 minute has passed
  {
    Serial.print(altitude);
    Serial.print(",");
    Serial.print(cpmFree);
    Serial.print(",");
    Serial.print(cpm1);
    Serial.print(",");
    Serial.print(cpm2/2);
    Serial.print(",");
    Serial.print(cpm3/2);
    Serial.print(",");
    Serial.print(temperature);
    Serial.println();
    Serial.flush();
    cpmFree = 0; //reset our counters
    cpm1 = 0;
    cpm2 = 0;
    cpm3 = 0;
    timer = millis(); //reset our timer
  }
}

void addTickFree() //external interrupt handlers
{
  cpmFree++;
}

void addTick1()
{
  cpm1++;
}

```