Third Time's The Charm: The Cosmic Watch Project And Faculty Muon Shielding

Team Members

Abi Hurairah
Emre Berna
Indra Vezbergaite
Mario Meléndez Romay
Mathias Enrique Perazo
Nils Thiessen

Supervisor

Chad Ellington

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1. Introduction

Knowledge of the existence of cosmic rays and thereby the generation of short-lived, subatomic particles has fundamentally challenged the physicist's view of the world. Uncovering their mysteries proved paramount in various crucial discoveries in galactic astronomy, particle physics, and enhancing our understanding of Earth's magnetic field. It is therefore all the more surprising to realize that the discovery of this phenomenon was accidental.

When Viktor Hess conducted his balloon ascents between 1911 and 1912, the primary intention was to verify whether the penetrating radiation, apparently causing the ionization of the gasses in an electroscope chamber, was due to radiation from Earth. The results indicated that after reaching an altitude of around 600 meters, there was a steady increase in radiation positively correlating with height, leading Hess to ascribe these occurrences a cosmic origin. (Bruno Rossi, 1964)
Although there had been similar conclusions made by the likes of Pacini, only after Hess's revelations and later studies did scientists acknowledge cosmic rays as the source of this mysterious radiation. (De Angelis, 2012)

This finding had a tremendous impact, and it is a common understanding nowadays that the majority of the radiation raining down on Earth's surface arrives in the form of heavy, unstable leptons called muons (Particle Data Group, 2018, pp. 424–430). These particles have been measured in a wide range of experiments, where one approach done by the Cosmic Watch group was the design and construction of a small, inexpensive device capable of detecting high energy charged particles as well as gamma rays (Przewłocki & Frankiewicz, 2017).

Building on the efforts of the previous groups, whose progress was affected by the lack of supplies among other factors, the aim of this project was to build several Desktop Cosmic Watch Muon Detectors. These could then be used for several purposes, including the determination of absorption levels of buildings or natural caves, as well as creating underground geological structure mappings by absorbance-geophysical density correlations. The aim of this paper is to elaborate on the background theory of these muon detectors and cosmic rays, demonstrate its function and explain the corresponding results.
Furthermore, an experiment will be conducted, comparing the rates of muons and their intensities between rooftop and underground measurements of a building. The expected outcome is that the rooftop rate will approximate to the usual muon rate at sea level, while the floors of the building will gradually decrease the amount of muons and their energies.

2. Theoretical Background

Cosmic rays are high energy particles that travel through the universe to eventually reach us, and are produced by different cosmological processes. A fraction of the cosmic rays that reach Earth are generated by the Sun, and are referred to as solar winds, although the vast majority originate from outside the solar system through processes such as supernovae, the remnants of one, as well as other unknown sources. (Institute of Physics, n.d.)

Although the composition of cosmic rays varies depending on their source, they are mainly composed of ionized Hydrogen nuclei (~89%), ionized Helium nuclei(~10%) and heavier nuclei (1%) (CERN, 2019). In addition to the previously mentioned charged particles, they also contain high energy gamma rays, the particles that make up cosmic rays are known as primary particles.

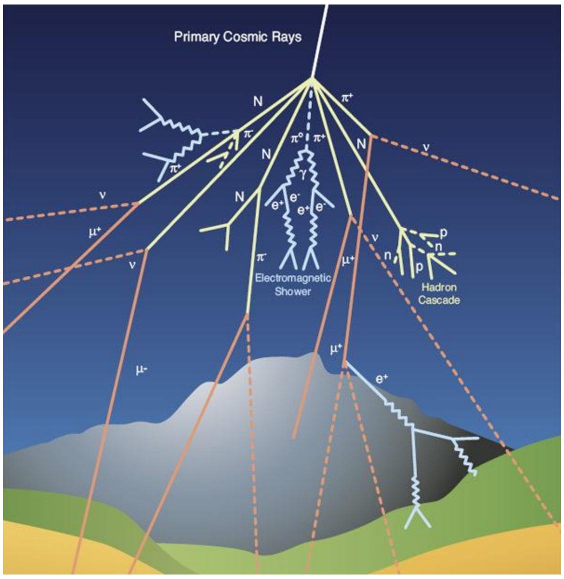

Figure [1]: Diagram of the chain reaction generated by a cosmic ray hitting the atmosphere (CERN, 2019)

When approaching Earth, the charged particles in cosmic rays may be deflected by properties of the solar system, especially the Earth's and the Sun's magnetic fields, which cause certain areas of our planet to get higher levels of radiation. Once they enter Earth's atmosphere, the particles may be affected by some of its properties, such as temperature. However, most will interact with the atomic nuclei at high altitudes, mainly nitrogen and oxygen. These collisions break some of the nuclei and several secondary-particles are generated as shown in Figure 1. Pions are the most abundant secondary-particles emerging from these processes. These particles, consisting of a quark and antiquark, are classified as mesons and depending on their quark-composition, pions can be neutrally, positively or negatively charged. With a short half-life, they quickly decay, and depending on their charge they will either produce muons or antimuons along with their respective neutrinos (Sutton, 2023). However, neutral pions typically decay into gamma rays. Muons belong to the family of leptons, which consists of the electron, muon and tau. All these particles share similar properties and differ mainly by their mass (a muon is about 207 times heavier than the electron) (nmi3, n.d.).

2.1 Importance of the Discovery of Cosmic Rays

Detecting cosmic rays is crucial as it provides important insight on our universe. It is through the observation of cosmic rays that scientists have been able to identify some elementary particles such as the muon. In fact, this is how the first known antimatter, the positron, was discovered. (Lerner, 2023)

Moreover, it provided great insight into the environment in our solar system. For example, by observing the trajectories and energy distributions of these rays it is possible to extract information about the magnetic fields they encountered on their way to Earth. On the same note, as the majority of cosmic rays are believed to have an origin beyond our solar system, they provide great insight on the study of the massive objects in which they are generated as well as providing scientist with a way to study particles produced in collisions of much higher energy than what can be reached with current particle accelerators. It is on some rare occasions possible to detect and study matter from beyond our solar system, if not beyond our galaxy. (Lerner, 2023)

Furthermore, because some cosmic rays emerge from stars, supernovae, black holes and other extreme places in the universe, they provide scientists with a rare window of opportunity to learn about these processes which otherwise occur at too large a distance to be studied.

2.2 Different Detection Methods

Cosmic rays are thus important in many ways and there are also several different methods used to detect them.
The Compact Muon Solenoid (CMS) detector, a crucial component to the Large Hadron Collider at CERN, is one of them. It is designed to investigate high-energy particle collisions, particularly muons. By measuring the trajectories, energies, and momenta of particles produced in collisions, the CMS detector provides valuable information for understanding the properties of particles, and potentially discovering new phenomena beyond the established theories. (CERN, n.d.)
Another existing detector is the Cosmic Ray Muon Detector or CRMD developed by bachelor students at IUCAA Radio physics lab. As its name implies it is used to detect muons and other particles in cosmic rays. (Team Radio Physics Lab, n.d.)

However for our research and experiment we used the Cosmic Watch muon detector. It is a self-contained apparatus developed by Massachusetts Institute of Technology (MIT) and Polish National Centre for Nuclear Research (NCBJ). (Axani, 2019)
It is meant to be an affordable electronics oriented and undergraduate-level project. This low-powered and extremely portable device uses a Silicon Photomultiplier to detect the energy deposited by charged particles and radiation on a plastic scintillator. (Przewłocki & Frankiewicz, 2017)

3. Structure of the Cosmic Watch

When muons manage to reach Earth's surface, detectors like the Cosmic Watch are able to identify them and process their signal.
This specific desktop muon detector employs a plastic scintillator as a detection medium and a silicon photomultiplier (SiPM) for light collection. The signal produced in the SiPM circuit is transmitted to the main circuit board, permitting the data to be processed by the included Arduino Nano depending on the code that has been uploaded on it. The data can then be accessed through the SD Card module or a connected computer. A fully compiled Cosmic Watch can be seen below in Figure 2.

Figure [2]: Top view of a detector without aluminum casing

3.1 The Scintillator

Scintillators are made of a material that absorbs energy and re-emits it in the form of electromagnetic radiation. Typically, there is a distinction between organic and inorganic scintillators. The former are usually grown as crystals, while the latter are either mixed into a liquid or embedded in a plastic, resulting in the inorganic scintillators usually being cheaper.
The scintillator's ability to emit light proportional to the energy deposited on the material makes it useful in particle detection. The average organic scintillator would emit about 10,000 photons per MeV. These devices must be transparent so the light may propagate to the SiPM. An organic plastic scintillator normally requires a transparent base, a fluorescing agent that is able to absorb energy from an incident charged particle and re-emit it in the form of UV light, and a secondary fluorescent agent that absorbs UV and converts it to the visible spectrum. Typically these devices are covered with aluminum foil, which causes the light emitted by the fluorescing agent to travel through the scintillator, rebounding off the foil until it is absorbed, increasing the chance of a photon striking the Photomultiplier.

3.2 The Photomultiplier

A photomultiplier is a commonly used device in particle physics which is capable of producing an electrical signal from the interaction with one single photon. In such a device, photons that strike the SiPM can induce a Geiger discharge on the SiPM microcells, producing a signal that can be further processed. The most commonly used photomultipliers are the photomultiplier tubes (PMTs) (ScienceDirect, n.d.), which cover a relatively large area, have a high rise time and provide excellent current amplification. However, they require a high voltage as well as shielding from magnetic fields, while also having a high spatial sensitivity. For these reasons, Silicon photomultipliers (SiPMs) were used in the context of our project. They have several advantages over PMTs, such as their ability to operate at lower voltages, their insensitivity to magnetic fields, a similar gain to that of the PMT and a peak responsivity near the peak emission of the scintillator. A finished scintillator-SiPM complex is shown below in Figure 3.

Figure [3]: SiPM module and scintillator taped together, ready to be placed on the main PCB

3.3 Main PCB

To bias the SiPM, the Main PCB also supplies 29.5 V to the SiPM module, passing through a low-pass filter before reaching the SiPM itself. The Main PCB consists of multiple sections. One of them is the DC/DC Booster, including a DC/DC Converter set up for turning the 4.6 V supplied by the Arduino Nano into the aforementioned 29.5 V required for the SiPM bias. The incoming signal from the SiPM proceeds over a BNC connector into the following section: the amplifying and peak detector circuit. The operational amplifier (OP-AMP) of this circuit plays a role in boosting the incoming signal and allowing for a peak detector to stretch the peaks of pulses, such that they can be long enough for the Arduino Nano to detect them.

The Arduino Nano will then record the event's timestamp and peak value thanks to its built-in analog-to-digital converter (ADC). The measured ADC value is later converted back to a digital value to calculate the corresponding SiPM peak voltage. If this voltage is above a software defined threshold, the event can be recorded to a MicroSD card or directly into a computer through a USB connection.

A 0.96" OLED screen is placed on the front side of the detector to display the count rate, total number of detections, time elapsed since the start of the count and the intensity of the last detection. Alongside the screen, an LED is installed, lighting up for each occurring detection.

On the backside of the detector, a female USB Mini is installed, allowing not only the transfer of code onto the Arduino, but also for powering the detector. The adjacent reset button is utilized to change the detector´s mode, while also restarting the count of muons. On the same side of the board, the installed 3.5mm jack provides a method to power two detectors at the same time, and if desired, it can serve as a link for setting the two detectors up in coincidence mode, as elaborated on in its respective section. Lastly, a male BNC (Bayonet Neill–Concelman) connection is installed and bridged directly to the SiPM output, with the intention of analyzing the output of the detector as well as providing signals to test the PCBs. After all the previously mentioned components are added onto the board, the completed detector can be put in an aluminum casing with plastic lids to protect the circuit and to obtain a clean and visually appealing final look.

Figure [4]: Top view of the Main PCB

3.4 The Code

The software uploaded to the Arduino Nano was obtained from the Cosmic Watch-related GitHub (Axani, 2018), which contained 3 main pieces of code:
The first code, Naming.ino, gives a unique, changeable name to the detector, which causes the variable det_name to be written on the EEPROM memory of the detector. While the second code, OLED.ino, is used to display the relevant information on the OLED screen, the third and last one, SDCard.ino, enables data collection onto an SD Card.
Unfortunately, due to the limited SRAM and flash storage of the Arduino Nano used in these detectors, only one of the OLED.ino or SDCard.ino codes can be run at the same time.

3.5 Coincidence Mode

An important feature of the Cosmic Watch is found in the Coincidence Mode. Connecting two detectors through the 3.5 mm jacks over a cable and successively pressing their reset buttons allows the one detector to act as a *Master* and the other one as its *Slave*. The *Slave* will only record its signals if the *Master* is triggered in the same time window, roughly 30 µs due to the Arduino Nano's slow ADC sampling rate. Although there is a possibility that two distinct muons hit the detectors during this time interval, an appropriate deduction is that both signals come from the same event, almost certainly distinguishing the muons from the noise. (Axani, 2018)

Whereas alpha particles are already blocked by the aluminum casing and thus not detected at all, beta particles are affected by it, losing energy and dumping even more at the *Master*'s scintillator. Presumably, this should leave insufficient energy to also trigger the *Slave*. Lastly, gamma rays are likely to Compton scatter by passing on energy and momentum to the excited electron at a certain angle, changing the direction of their paths (Boeglin, 2023). Muons are special in the sense that it is highly probable for them to penetrate both the detectors' casing and scintillators without being absorbed or diverted. Their inherent property as a lepton of not interacting over the strong force reduces the probability of muons undergoing high energy collisions with atomic nuclei. Furthermore, due to their high mass, exchanges with the scintillator's electrons have little influence on the muons' energy and movement. (Ling, 2020) Furthermore, muons generated in cosmic rays are produced at energies that are hardly replicable on Earth, be it in the form of a natural or artificial source such as particle accelerators. Hence, a muon detected will certainly be a product of cosmic rays.

The spatial arrangement of the scintillators towards each other determines the angle muons can originate from in order to be detected by both. This and Compton scattering are illustrated below in Figure 5.

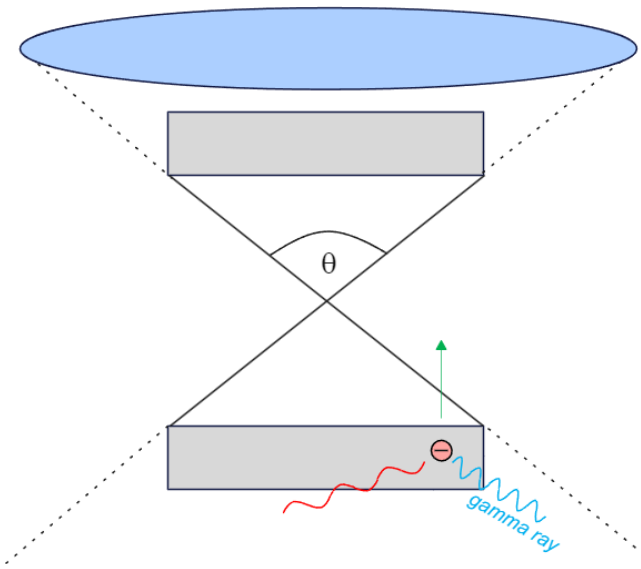

Figure [5]: Diagram demonstrating the effect of Compton scattering as well as the area of muon trajectories covered by both scintillators (gray), as defined by the dotted lines

Depending on the distance between the scintillators, the angle θ covered by both can vary drastically, which can be further influenced by rotating them relative towards each other. In this way, focusing the muon detection on smaller, specified areas could enable information on phenomena such as the east-west asymmetry (Diep et al., 2003). However, due to the relativistic speed of muons, the coincidence window is unable to provide information about which scintillator was hit first.

3.6 Data Acquisition

When an energetic particle sheds its energy in the scintillator and causes the silicon photomultiplier to produce a voltage beyond 15.5 mV, the Arduino will take the next 4 measurements and average them to obtain the pulse amplitude with an analog pin while avoiding recording only the rise of the produced voltage. Signals below 15.5 mV will be considered noise that can be ignored.

The Arduino Nano by itself has no viable solution to store the gathered data. Although writing data into the onboard EEPROM is possible, its rate write cycle is 100,000 (Arduino, n.d.), an amount that can easily be exceeded by only a few long recording sessions. There are several ways to save the data produced by the Cosmic Watch utilizing external hardware.

One option is writing data to an SD Card. By uploading SDCard.ino and inserting a microSD card to the corresponding module, the Arduino Nano will be able to continuously write the data into the aforementioned card in the form of a text file for further data processing. It is important to note that the SDCard library only supports SD Cards that use the FAT16 or FAT32 filesystem, therefore it is only possible to use SD Cards with memory capacities of up to 32 GB for the Arduino Nano.

An alternative method is to establish a serial connection from the computer to the Arduino Nano via the USB ports. The computer will receive data via the serial port that can be read through the Arduino IDE or other programs that can read from the serial port such as PuTTY. This method works with both the program for the SD Card and OLED display.

Table 1 below shows a list of example measurements from one of the detectors.

Event Number	Elapsed Time (ms)	ADC Value	SiPM Voltage (V)	Deadtime (ms)	Temperature (°C)
1	3036453	433	104.37	8518	19.61
2	3048068	334	61.44	8537	20.04
3	3049861	521	150.31	8555	19.61
4	3061495	316	56.81	8572	19.61
5	3064052	304	53.73	8589	19.61
6	3066191	305	53.88	8606	20.04
7	3080081	254	43.77	8624	19.61
8	3090631	240	41.21	8643	19.61
9	3092621	255	43.96	8660	19.61
10	3108923	408	90.57	8678	19.61
11	3112385	65	18.22	8699	20.04
12	3120893	305	53.88	8717	19.61
13	3124358	287	50.23	8734	19.61
14	3125872	313	56.02	8751	19.61
15	3127458	263	45.37	8768	19.61
16	3127621	327	59.28	8785	19.61
17	3128308	496	144.49	8802	19.61
18	3130113	263	45.37	8820	19.61
19	3134747	415	95.00	8837	20.04
20	3143517	300	52.79	8855	19.61
21	3148983	255	43.96	8872	20.04
22	3168886	287	50.23	8891	20.04
23	3188579	231	39.55	8910	20.04

Table [1]: Measurements from a Cosmic Watch muon detector

4. Methods

4.1. Building the Cosmic Watch

The Cosmic Watch Project has previously been attempted twice by Maastricht University students, both attempts failing to produce a finalized, functioning Cosmic Watch. Their efforts left us with various spare components and necessary tools. Seven unfinished circuit boards were a part of those components left behind from previous groups.

These boards were tested to see if any of them could be fixed, worked on and completed. It was found out that five of them were irreparable. For the other two boards, one had all of the parts but was not providing the correct voltage throughout the circuit. After troubleshooting, the problem was identified to be the LT1807 OP-AMP on the Main PCB, which was not amplifying the signal correctly. This OP-AMP was desoldered and replaced by a new one. The other board was only missing one 500mA diode which was then soldered onto the board. Each board was coupled with a SiPM PCB.

Afterwards, power was supplied to the Arduino Nanos from a laptop computer via USB to USB Mini cables, which powered the whole board. Finally, 4-pin OLED Headers were attached to the Main PCBs to offer the opportunity for the data to be displayed on a screen. It was observed that they were operational, successfully measuring a muon rate of ~0.5 muons per second, which was the expected value.

4.1.1. Assembling New Boards

After receiving the new components which were ordered in the beginning of the project, there were enough parts to build two new cosmic watches. Thus, the soldering process was started for two new boards.

First, the smaller components, namely the resistors, inductors, capacitors and diodes were soldered on the PCBs using a soldering iron and soldering tin. Although it was a simple process, it took an hour due to the large number of components that had to be soldered. Following that, the LT1807 OP-AMP and the LT3461 3MHz DC/DC Converter were inserted on the board. Since they possess eight and six pins respectively, they had to be soldered very carefully such that all the pins were connected to their individual inputs on the Main PCBs. The same procedure was repeated for the sixteen pinned CMOS Logic Hex Non-Inverting Buffer, the ten pinned SD Card socket and the three pinned 3.3V regulator, carefully soldering them onto the SD Card PCBs. Since there were no new SD Card Sockets, the ones used by the previous groups were reutilized by removing them from older non-functioning boards.

Later, the 2x4 header and the 6-pin header, which are the mounts for the SD Card PCB and the SiPM PCB respectively, were soldered onto the Main PCBs. Afterward, the 0.02A 15V Tactile Switch, the 3.5mm audio connection jack, the TMP36 Temperature Sensor, the Arduino Nano, the 5mm LED Light, the 50Ω BNC jack and the SD Card PCB were soldered onto the Main PCBs. Similar to the SD Card Sockets, the BNC jacks were also desoldered from older boards, since no new ones were available.

The next process was building the part that would detect the muons, which includes the SiPM PCB and the scintillator.

4.1.2. Scintillator-SiPM Complex

To do this, the resistors, capacitors, 6-pin plug and the SiPM were soldered onto the SiPM PCB. Two of the four scintillators were yielded from the previous groups, whereas the rest needed to be prepared anew.
Since the SiPM can only detect photons reaching its surface area, the optical transparency of the scintillator needed to be maximized to ensure that the photons were counted as accurately as possible. Due to the impurity of the surfaces, heat polishing was applied using a hot air gun, increasing the transparency by carefully melting the structure and letting it re-solidify, leaving behind a see-through material. Additionally, by wiping the sides with isopropyl alcohol, the total number of photons capable of hitting the SiPM was increased. Reflective aluminum foil was then wrapped around the scintillator and fixed using black wire tape, leaving a small 2 x 2 cm window for the photomultiplier. After applying optical gel to the SiPM and placing it on top of the window, several layers of black tape helped shield the conformation off of ambient light, reducing the signal's noise as well as keeping the SiPM in place as we could not screw it onto the scintillator. (Axani, 2019)
As for the other two scintillators, they only needed to be retaped to ensure a reliable shielding.

4.1.3. Finalizing & Troubleshooting

After finishing the SiPM PCB and connecting it to the Main PCB, the circuit was powered by connecting the Arduino Nano to a laptop computer through a USB to USB Mini cable. This was done so that the boards could be troubleshooted, in case there were any faulty components. During the troubleshooting stage, a rigol multimeter and a handheld multimeter were used to check the voltage differences throughout the circuit, while an oscilloscope, together with a rigol waveform generator were used to simulate and observe the signals as well as to check whether they were amplified correctly.

Finally, when it was verified that all the parts were all functioning as they were expected to, the cosmic watches were placed inside pre-made cases. These casings are made of two metal halves covering the top, bottom and the sides of the watch, while two plastic parts were used to cover the front and the back of the detectors. Each of the plastic parts had four small holes at the corners so that they could be screwed to the metal casing. The plastic parts also had other openings, made for the components that still had to be accessible after putting the casing on. However, some of these openings did not match the components they were made for: the SD Card socket was lower than where its opening on the plastic cover was and the opening for the 3.5mm audio connecting jack was too narrow to connect a cable to the jack. These openings were modified by using a drill, so that they would align with their respective components. The casings were then completed, resulting in four finished and ready to be used cosmic watches.

4.2. The Experiment

The aim of the experiment was to measure the relative absorption of the C building at PHS. This was achieved by placing two, almost identical, muon detection set-ups. Two Cosmic Watches were placed on the rooftop of the building, connected in coincidence mode and

powered by a Hiluckey HI-S025 Solar Charger. A 2GB SD card was inserted into the Slave Watch, unto which the detected data could be saved.
A second pair of Cosmic Watches was placed on floor -1. These were also connected in coincidence mode and were powered by a personal laptop. Both of the Cosmic Watches setup underground were also given SD cards.
A phone stopwatch was started immediately when the first two Cosmic Watches initiated the data collection on the rooftop, and stopped as the second setup began documenting. This was made so as to keep a record of the time period in which only the rooftop setup was producing measurements, with the intent of neglecting them during data comparisons.
Due to rooftop availability arrangements, the pair of watches underground were stopped and recovered shortly before the rooftop set up, after roughly 103 minutes of runtime.

5. Results & Analysis

The first step in the data analysis was to remove unnecessary data from the rooftop Slave memory. It was noted that the second set up, at the bottom floor of the building, started running 27 minutes after the one on the rooftop. This meant disregarding the first 483 measurements made by the first pair of detectors. The second set up's entries were monitored real-time via the Arduino IDE Serial Monitor. This made it easy to time the termination of measurements to be immediately after a last entry. This way, the time signature at that last entry can be considered the overall runtime of the device and, consequently, of the experiment. The runtime of the experiment, then, was determined as 6219 seconds, or 103.65 minutes. Since the rooftop pair was also recovered later, all measurements recorded by that pair after this value were equally disregarded.

Drawing upon the data from the US Department of Energy, a muon hits the surface of the Earth at a rate of about 1 muon per minute per square centimeter (Office of Science, n.d.). To calculate the expected rate of detection for the Desktop Cosmic Watch Detector, the following equation is used:

$$A \times R = R_s$$

Where A is the surface area of the scintillator, R is the rate at which muons hit the surface of the earth, and R_s is the rate at which muons come into contact with the scintillator. The width and the length of the scintillators are both 5 cm resulting in 25 cm^2 of surface area. In theory, the device should detect muons at a rate of 0.416 per second.

Throughout the course of the entire 103 minute experiment, the slave detector on the roof of the PHS building recorded 1861 measurements while the one below recorded only 1004 measurements. The roof detector has an average count rate of 0.2996 muons per second with SiPM average peak voltage of 77.0 mV, while the one below ground yields an average count rate of 0.1613 muons per second with SiPM average peak voltage of 71.1 mV. To calculate the relative absorbance between the two pairs of the detectors:

$$\frac{R_R - R_B}{R_R} \times 100\% = \alpha \qquad [1]$$

Where R_R is the muon detection rate on the roof, R_B is the detection rate at the bottom floor, and α is the percentage of muons undetected by the detector located on the bottom floor. Additionally, counts for each four minute interval across the total runtime were plotted in Figure 6.

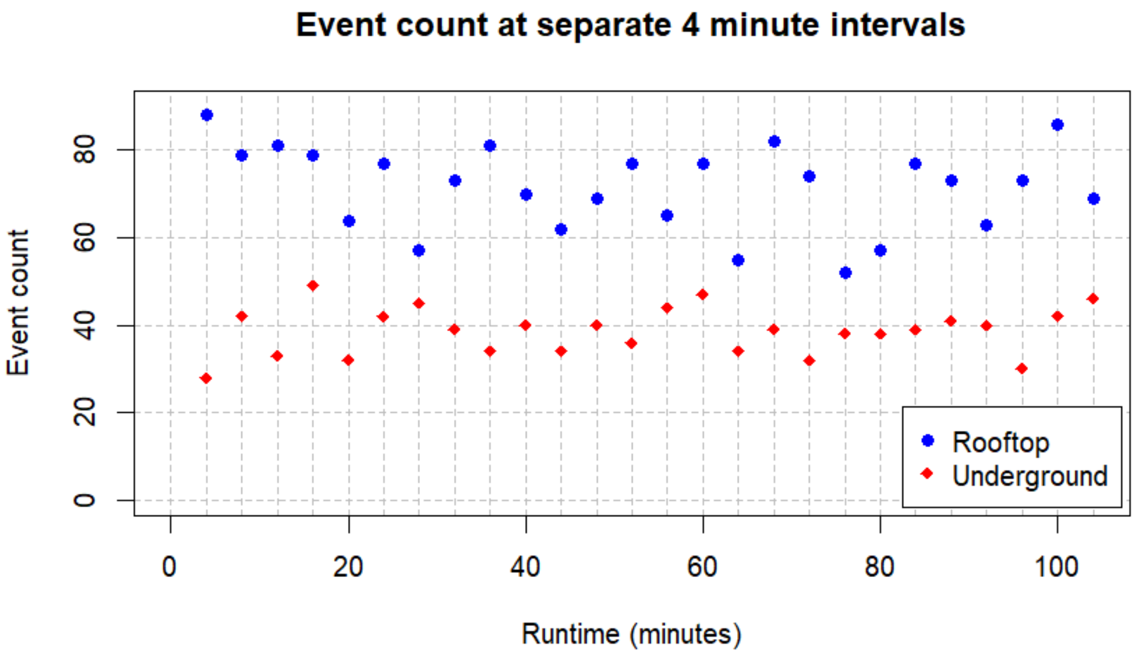

Figure [6]: Data points represent total event counts for the previous four minutes of runtime. Only counts before minute 103.65 were considered for the Rooftop set up event counts.

As it can be observed in the graph above, muon counts recorded on the rooftop were roughly 20 counts higher than those recorded by the underground pair. There were standout peaks at minutes 4 and 100 of the rooftop data, which cannot be seen in the underground one. Only one slight correlation between relative increases and decreases among the two data plots around minutes 56 to 68 could be pointed out. This, however, seems circumstantial. Muon counts show a seemingly random distribution, with no significant correlations between peaks and crests.

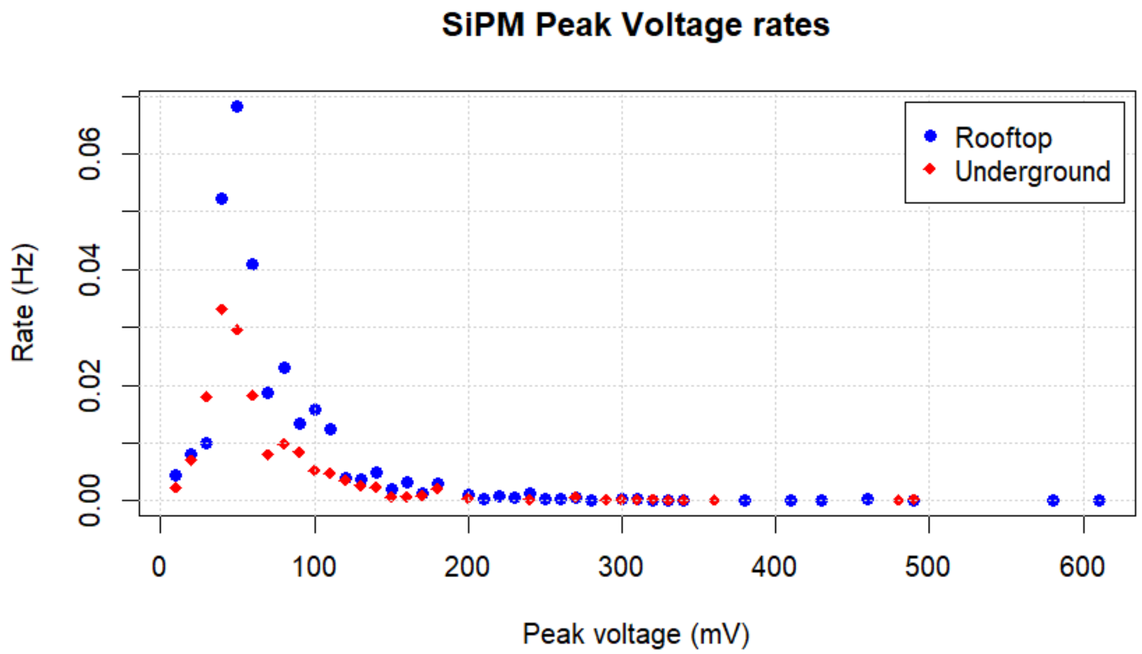

Figure [7]: Distribution of the peak voltages measured by both slave detectors according to how often they happened

Figure 7, once again, displays the substantial difference in detection rates between both setups. It also demonstrates that the rooftop detector captured some higher energy peaks, and has an overall more prevalent presence of high energy readings.

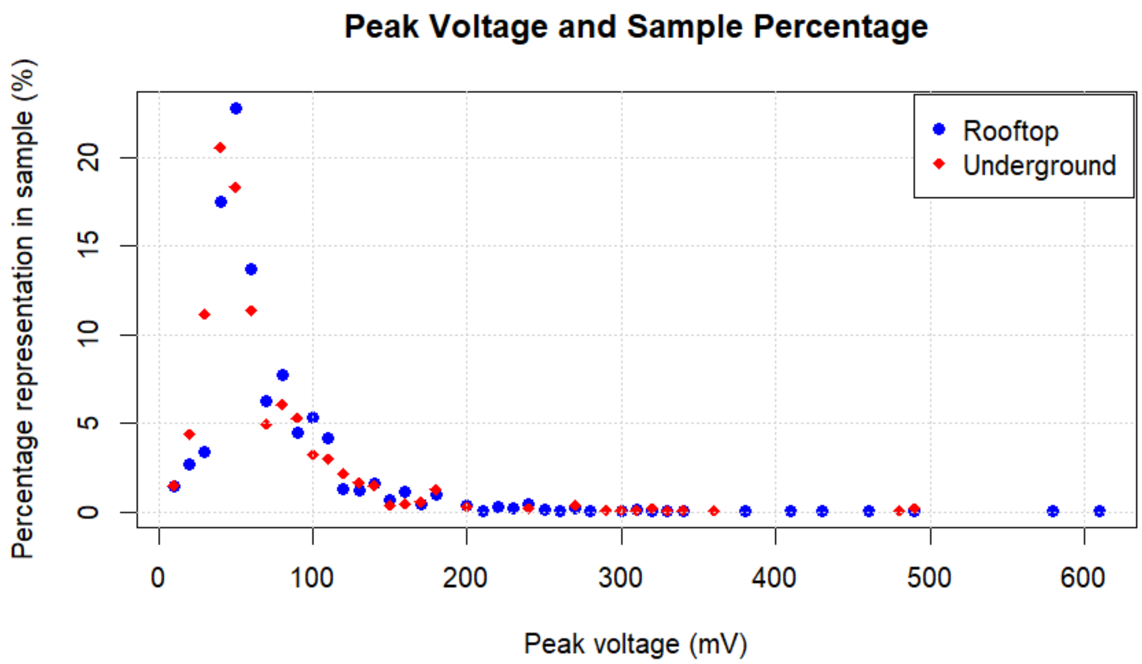

Figure [8]: Percentage of data sample represented by separate peak voltage readings

Figure 8 above shows whether there was a significant difference in the magnitudes of incoming energy signatures measured by either detector. It provides a “percentage presence” of SiPM voltage readings, demonstrating a considerable similarity of peak voltages between those measured on the rooftop and underground. However, it is notable that the most present voltage peaks in the rooftop and underground detectors are 10 mV apart. Points from 10 to 40 mV in underground data reveal a premature rise in percentage presence compared to rooftop data. An earlier rise and peak, and overall lower energy data points (71mV average against 77 mV) implies a slight but broad attenuation of detected muon energy on the lower floor. This could also explain the presence of higher energy muons at the rooftop level which are not present at all underground. This can be indicative of the relative absorbance of the PHS building.
Thus, Equation [1] yields the final value of relative absorption of the building as:

$$\frac{0.2996 - 0.1613}{0.2996} \times 100\% = 46.16\%$$

6. Discussion

In this section we will discuss some of the issues faced while doing this project, either related to building the detector or the experiment itself.

6.1 Scintillators

At the time of applying heat on the new scintillators, it was observed that the plastic did not end up being as transparent as originally intended. As a consequence, the heat polishing could have been applied excessively, thereby damaging the material in the process. This might have affected the accuracy of the detector, since less scintillating material would be functional. This could be an explanation for why the rooftop rate was smaller than expected. .
Due to the lack of materials, the SiPM was not drilled onto the scintillator, and no supports were added in order to help uphold its weight. Although no direct problem was observed from this, it can be argued that the lifetime of the SiPM may be reduced, as the 6-pin connector might deteriorate and bend over time, considering that it has to support all the scintillator’s weight.

6.2 SD Cards

At the beginning of the project, four 64GB SDXC SD Cards were ordered. However, it was soon discovered that the Arduino Nano can only read SD Cards that use the FAT16 and FAT32 file systems which the aforementioned SD cards cannot be reformatted into. 16GB and 2GB cards that use either FAT16 or FAT32 were immediately ordered to solve this issue.

The SD Card module requires a 3.3V power supply to function properly. A board inspection with a multimeter suggested that some transistors were mislabeled as 3.3V regulators and that the components soldered onto the 3.3V regulator spots were thus actually transistors. This caused the SD Card module to not receive adequate power, causing it to be dysfunctional.

Due to the lack of available 3.3V voltage regulators, they had to be extracted from spare Arduino Nanos.

Despite the troubleshooting measures so far, only some of the SD Card modules worked. It was found that some components were soldered incorrectly leading to unreliable connections between some parts of the board. Solving this issue finally led to all four of the SD Card modules to be working properly as expected.

6.3 Casings

Several problems were encountered while trying to fit the detectors into their respective boxes. In the old boards this was caused by the components not being properly aligned, while on the new ones the Arduinos were slightly different from the old ones and the 3.5 mm jack male to male cable being too thick. All these problems caused us to modify the holes on the box lids. However, each box was modified differently as each board had different problems.

6.4 Experimental Issues

Part of the limitation of the experiment came from relying on the Arduino Nano's internal clock, which has an accuracy of around 50 ppm. This means that if the experiments were to be conducted over a whole day, there would be a difference of a few seconds in recorded time between the two boards. This can make it impossible to determine whether the peaks occur simultaneously or not.

Also, the experiment has shown a difference of roughly 0.1 muons per second between the expected rate and the observed one for the rooftop detector. This might have been caused by the scintillators not being in perfect condition or them not being precisely on top of each other, which could have led to decreased detection rates. Moreover, the discrepancy could have been partially produced by the inherent deadtime associated with measurement processing and recording data entries. This causes non-trivial downtimes of almost 20ms. Across a lengthy runtime, this value can add up to a few seconds or even minutes in which no detections are made. This necessarily skews the rate from a true value, although it should not make such a significant impact.

7. Conclusion

This project consisted of two parts. While the first one revolved around building the Cosmic Watch muon detectors, the second one involved collecting data with said detectors and analyzing it.
Through the first two weeks of project period and the first part of week 3, the group’s focus was aimed at delivering at least one complete detector as this project had already failed before. Fortunately, all the missing parts had been ordered on time and everything worked out so that half-way through week 2, a fully functional detector saw the light of day. However, while building the other three, some challenges were encountered and required time and common effort to be solved.
In total, four detectors were built, two of them by repairing old boards and the other two from scratch. This process took multiple weeks and hours upon hours of hard work and dedication to analyze the circuit, to learn how to use the various soldering tools, and to efficiently troubleshoot at multiple steps of the process. At the end of week 3, all four detectors were ready and it was time to put them to the test.
An experiment to determine the absorption of building C at PHS was designed in order to put the detectors to use. This was accomplished by placing two detectors in coincidence mode on the rooftop and two detectors in coincidence mode in the underground parking lot and comparing the data afterwards. After some laborious hours sorting out and cleaning the data, some rather accurate and pleasing results were extracted from the data collection. Even though this project could have been improved, both parts were successful. Four detectors were built and the experiment carried out produced some accurate and observable results which allowed for the successful observation of the absorbance of our chosen building.
However, further experiments need to be conducted in order to verify the findings or to observe different properties of cosmic-ray-originated muons, such as the east-west asymmetry.

8. Contribution Table

Berna Emre	Troubleshooting Old and New Boards, Fixing Old Boards, Desoldering Parts from Old Boards, Soldering New Boards, Data Collection, SiPM PCB Soldering, SD Card Troubleshooting Paper Contribution: Building the Cosmic Watch, Assembling New Boards, Finalizing & Troubleshooting, Resources, Formatting, Proofreading
Hurairah Abi	Code Tweaking, Data Collection, Casing, SD Card Troubleshooting, Method of Recording Data Directly to Computer, Taking and Editing Pictures, Filtering the Data, Presenting Paper Contribution: Data Acquisition, About the Experiment, SD Card, Proofreading
Melendez Romay Mario	Inventory Keeping, Troubleshooting Old and New Boards, Data Collection, Customizing the Boxes, Code Tweaking, SD Card Troubleshooting, Heat Polishing Paper Contribution: Theoretical Background, Discussion, The Scintillator, The Photomultiplier, Main PCB, Proofreading
Perazo Mathias Enrique	Inventory Keeping, Troubleshooting Old and New Boards, Fixing Old Boards, Desoldering Parts from Old Boards, Soldering New Boards, Data Collection, SD Card Troubleshooting, SiPM PCB Soldering, Filtering Data Paper Contribution: The Experiment, Results and Analysis, Plotting and Graphing, Proofreading
Thiessen Nils	Troubleshooting Old and New Boards, Desoldering Parts from Old boards, Data Collection, Code Tweaking, SD Card Troubleshooting, Presenting, Heat Polishing Paper Contribution: Introduction, Coincidence Mode, Scintillator-SiPM Complex, Structure of the Cosmic Watch, Proofreading
Vezbergaite Indra	Fixing Old Boards, Desoldering Parts from Old Boards, Data Collection, SiPM PCB Soldering, Presenting Paper Contribution: Introduction, Theoretical Background, Structure of the Cosmic Watch, Conclusion, Formatting, Proofreading

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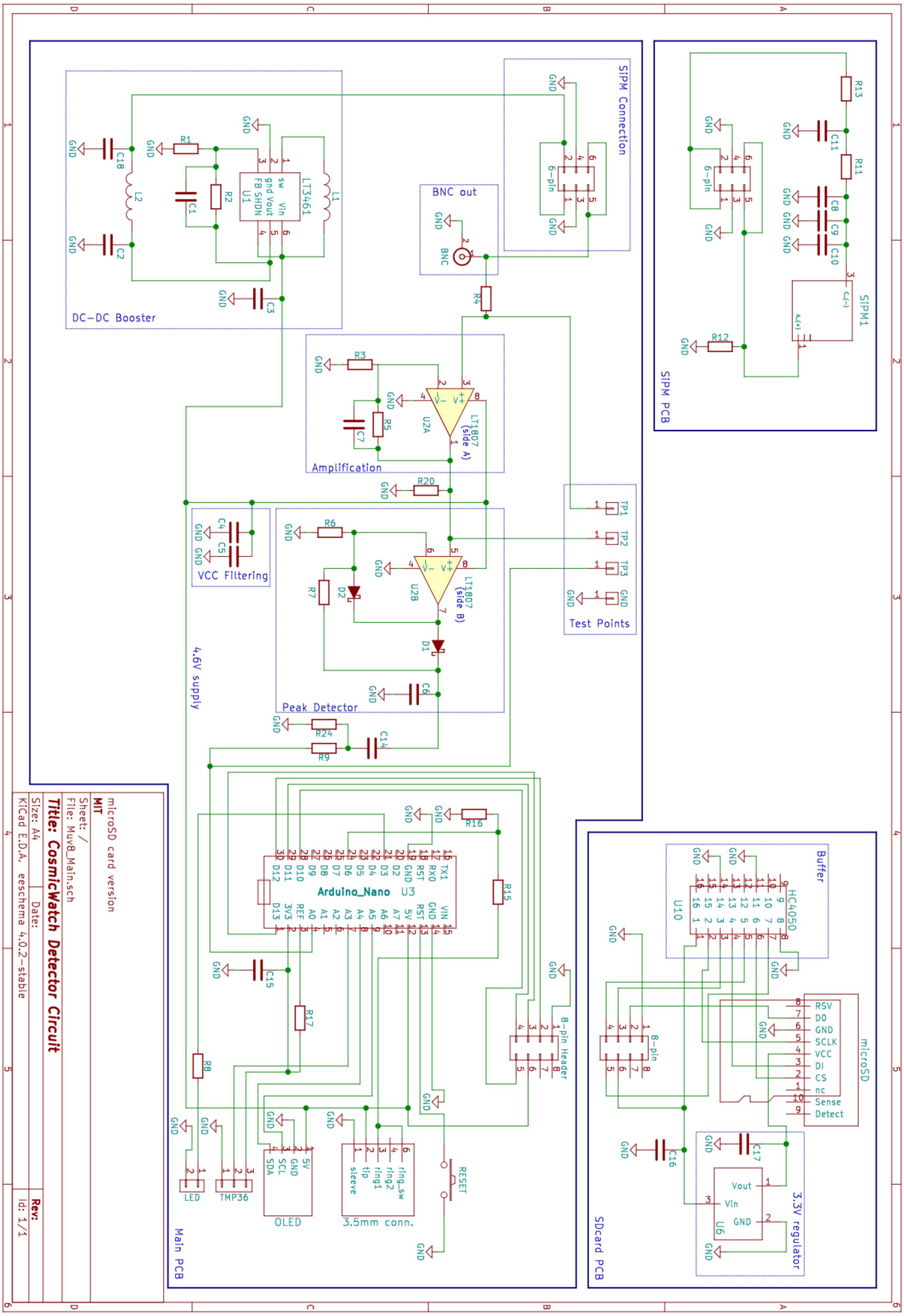
10. APPENDIX

PCB populating reference

Component	value	Discription	Link	Comment
R1	10k	RES SMD 10K OHM 1% 1/8W 0805	Digikey Part Number: 311-10.0KCRCT-ND	
R2	226k	RES SMD 226K OHM 1% 1/8W 0805	Digikey Part Number: 311-226KCRCT-ND	
R3	249	RES SMD 249 OHM 1% 1/4W 0805	Digikey Part Number: 311-249CRCT-ND	
R4	1k	RES SMD 1K OHM 1% 1/8W 0805	Digikey Part Number: 311-1.00KCRCT-ND	
R5	10k	RES SMD 10K OHM 1% 1/8W 0805	Digikey Part Number: 311-10.0KCRCT-ND	
R6	100k	RES SMD 100K OHM 1% 1/8W 0805	Digikey Part Number: 311-100KCRCT-ND	
R7	100k	RES SMD 100K OHM 1% 1/8W 0805	Digikey Part Number: 311-100KCRCT-ND	
R8	1k	RES SMD 1K OHM 1% 1/8W 0805	Digikey Part Number: 311-1.00KCRCT-ND	
R9	Short	RES SMD 0 OHM JUMPER 1/8W 0805	Digikey Part Number: 311-0.0ARCT-ND	SHORT
R10	NS			
R11	49.9	RES SMD 49.9 OHM 1% 1/8W 0805	Digikey Part Number: 311-49.9CRCT-ND	
R12	49.9	RES SMD 49.9 OHM 1% 1/8W 0805	Digikey Part Number: 311-49.9CRCT-ND	
R13	49.9	RES SMD 49.9 OHM 1% 1/8W 0805	Digikey Part Number: 311-49.9CRCT-ND	
R14	NS			
R15	1k	RES SMD 1K OHM 1% 1/8W 0805	Digikey Part Number: 311-1.00KCRCT-ND	
R16	10k	RES SMD 10K OHM 1% 1/8W 0805	Digikey Part Number: 311-10.0KCRCT-ND	
R17	Short	RES SMD 0 OHM JUMPER 1/8W 0805	Digikey Part Number: 311-0.0ARCT-ND	Short
R18	NS			
R19	NS			NS
R20	10k	RES SMD 10K OHM 1% 1/8W 0805	Digikey Part Number: 311-10.0KCRCT-ND	
R24	24.9k	RES SMD 24.9K OHM 1% 1/8W 0805	Digikey Part Number: RMCF0805FT24K9CT-ND	
R25	NS			NS
D1	500ma diode	DIODE SCHOTTKY 40V 500MA SOD123	Digikey Part Number: MBR0540CT-ND	**Has direction**
D2	500ma diode	DIODE SCHOTTKY 40V 500MA SOD123	Digikey Part Number: MBR0540CT-ND	**Has direction**
L1	47uH	FIXED IND 47UH 170MA 1.3 OHM SMD	Digikey Part Number: 490-4063-1-ND	
L2	2.5k Ferrite Bead	FERRITE BEAD 2.5 KOHM 0805 1LN	Digikey Part Number: 587-1919-1-ND	
C1	22pF	CAP CER 22PF 50V NP0 0805	Digikey Part Number: 399-1113-1-ND	
C2	0.47uF	CAP CER 0.47UF 50V X7R 0805	Digikey Part Number: 399-8100-1-ND	
C3	1uF	CAP CER 1UF 50V Y5V 0805	Digikey Part Number: 587-1308-1-ND	
C4	10uF	CAP CER 10UF 6.3V X5R 0805	Digikey Part Number: 490-1718-1-ND	
C5	0.1uF	CAP CER 0.1UF 50V X7R 0805	Digikey Part Number: 399-1170-1-ND	
C6	20nF	CAP CER 20nF 50V X7R 0805	Digikey Part Number: 1276-2472-1-ND	
C7	10.0pF	CAP CER 10PF 50V C0G/NP0 0805	Digikey Part Number: 1276-1109-1-ND	
C8	10 nF	CAP CER 10000PF 50V X7R 0805	Digikey Part Number: 311-1136-1-ND	
C9	10 nF	CAP CER 10000PF 50V X7R 0806	Digikey Part Number: 311-1136-1-ND	
C10	10 nF	CAP CER 10000PF 50V X7R 0807	Digikey Part Number: 311-1136-1-ND	
C11	10 nF	CAP CER 10000PF 50V X7R 0808	Digikey Part Number: 311-1136-1-ND	
C14	Short	RES SMD 0 OHM JUMPER 1/8W 0805	Digikey Part Number: 311-0.0ARCT-ND	SHORT
C15	0.1uF	CAP CER 0.1UF 50V X7R 0805	Digikey Part Number: 399-1170-1-ND	
C16	10uF	CAP CER 10UF 6.3V X5R 0805	Digikey Part Number: 490-1718-1-ND	
C17	0.1uF	CAP CER 0.1UF 50V X7R 0805	Digikey Part Number: 399-1170-1-ND	
C18	1uF	CAP CER 1UF 50V Y5V 0805	Digikey Part Number: 587-1308-1-ND	
U1	LT3461	3MHz Step-Up DC/DC Converters	http://www.linear.com/product/LT3461A	Has direction
U2	LT1807IS8#PBF	325MHz, Dual, Rail-to-Rail Input and Output, Precision Op Amps	http://www.linear.com/product/LT1807	Has direction
U7	NS			NS
U6	3.3V regulator	IC REG LINEAR 3.3V 300MA SOT23-3	Digikey part number: AP2210N-3.3TRG1DICT-ND	Has direction
U8	SD card socket	SMT SMD Cell Phone TF Micro SD Memory Card Slot Holder Sockets	Amazon: uxcell 6 Pcs SMT SMD	
U10	Non-Inverting Buffer	High Speed CMOS Logic Hex Non-Inverting Buffers	Mouser Part Number: 595-CD74HC4050M96,	Has direction
SiPM1	SiPM	SiPM MicroFC-60035-SMT	SENSL	Has direction
Reset	Reset button	SWITCH TACTILE SPST-NO 0.02A 15V	Digikey part number: P12215S-ND	
2x4 SD header	2x3 header +2x1	header for mounting SD card PCB. 2x3 + 1x2	Comes with Arduino	
15x1 header	15x1 header	2x headers for mounting Arduino, should come with Arduino	Comes with Arduino	
Arduino_Nano	Arduino Nano	16 MHz CH340/ATmega328P Arduino Nano		
BNC receptacle	BNC header	CONN BNC JACK R/A 50 OHM PCB	Digikey part number: WM5514-ND	
OLED header	4 pin header	CONN FEMALE 4POS .100" R/A TIN	Digikey part number: S5440-ND	Bottom
LED	LED light	Any color, 5mm	https://www.amazon.com	
6-pin Header	6-pin Header	SOCKET 7 MM SOLDER TAIL DOUBLE	Digikey Part Number: 1212-1229-ND	
3.5 mm jack	3.5mm jack	CONN JACK 4COND 3.5MM SMD R/A	Digikey Part Number: CP-43515RSSJCT-ND	
Temp	TMP36	Temperature Sensors TMP36 Precision Linear Analog Output		
SiPM PCB 6-Pin	6-pin Pins	WM17457-ND	WM17457-ND	

APP. [1]: PCB Populating List



APP. [2]: Diagram of the Cosmic Watch Detector Circuit