DIGIPEN INSTITUTE OF TECHNOLOGY

COMPUTER ENGINEERING 1ST YEAR PROJECT

High-Altitude Muon Detection Balloon

Team: The Cow that Jumped Over the Muon
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Abstract

Muon detection has become a hot topic in the scientific, academic, and industrial fields in recent years. Technologies involving muons detection include: monitoring underground magma flows of the volcano Mount Etna, imaging the interior of the Pyramids of Giza, and inspecting the damaged Fukushima nuclear power plant. The purpose of this project is to collect data on muon flux as it relates to altitude. A high-altitude balloon will be launched with the muon-detection sensor, primarily utilizing a plastic scintillator and a silicon photomultiplier (SiPM), in order to detect muons at varying altitudes in the troposphere and stratosphere. On board the payload, a micro-controller will collect the data and will send it to a transmitter, which in turn will relay the data to a ground station. This data will be valuable to scientists and engineers studying cosmic radiation. For example, this data could be used for researching how to minimize radiation to commercial pilots and aircrews.

1 Introduction

1.1 History

Cecil Powell, 1950 Nobel Prize Laureate in Physics and the man who discovered pions, began his Nobel Lecture with, "Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary cosmic radiation." Cosmic rays are high-energy particles, primarily protons, that rain down upon Earth. These cosmic rays collide with particles in the atmosphere, where these cosmic rays turn into numerous lighter particles such as pions and kaons. In turn, pions rapidly decay into muons [1].

1.2 Mission Statement and Hypothesis

In this project, we designed a muon detector for use in the upper atmosphere (troposphere and stratosphere). Our goal is to find a relation between altitude and muon flux. Theoretically, a muon should pass through the sensor every 2 [sec] when reading at sea-level [2]. However, we do not expect to receive such accurate readings, due to the ambient radiation at the surface of the Earth. Once the sensor leaves the ground, we expect readings to become more representative of muon flux, so as the sensor increases in altitude, the muon flux will increase. At a certain altitude the flux will decrease, because the less dense atmosphere will result in less collisions between the atmosphere and the cosmic rays.

1.3 Inspiration and Related Work

A previous project known as Cosmic Watch, lead by MIT graduate Spencer Axani, was developed with the intent of making a low-cost muon detection system, using a plastic scintillator and silicon photomultiplier (SiPM) [2]. We used similar components for the sensor module, but reconstructed the rest of the system with other components. the Cosmic Watch system has been tested to up to 12 [km] above sea level [2]. We plan to test our system up to 30-35 [km] above sea level.

2 Scientific Background

2.1 Muons

A muon is a negatively-charged particle and has approximately 200 times the mass of an electron [3]. Like an electron, the muon is a fundamental particle classified as a lepton (particles that do not undergo strong interactions). Muons are unstable and decay in approximately 2 microseconds [3].

2.2 Scintillator

When charged particles interact with a scintillating material, the electrons of the atoms in the scintillator are excited to a higher energy state. Afterwards, the electrons fall back to their lower energy state, resulting in an emission of an electron. [1] These photons are emitted around the “emission maximum” wavelength, which is determined by the type of scintillating material. A few dozen photons are emitted by the scintillator per muon.

2.3 Silicon Photomultiplier (SiPM)

The silicon photomultiplier is an electrical network of avalanche photodiodes (APD). When photons interact with a photo-diode, photoelectrons are emitted (thanks to the photoelectric effect), resulting in a minuscule current. These photoelectrons collide with other electrons, creating an avalanche. This results in a measurable current and voltage spike, as seen in Figure 2. [1] A simplified diagram of the sensor is shown in Figure 1.

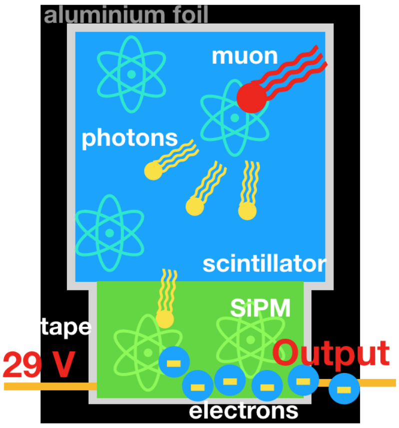

Figure 1: Muon detection process.

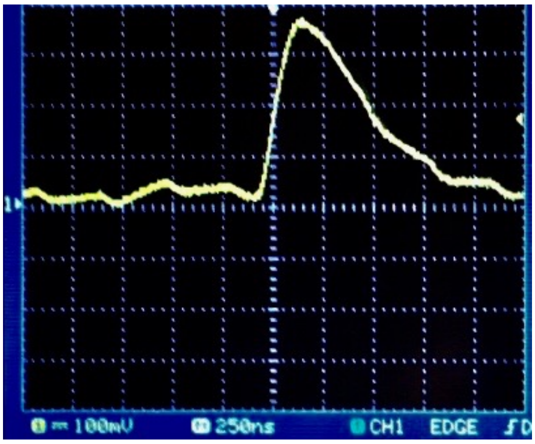

Figure 2: Voltage spike.

3 Methods, Techniques, and Design

A block diagram of the system is shown in Figure 3.

3.1 Battery, Regulator, and DC-DC Booster

We are required to power our system from a 9V Energizer LA522 lithium battery for at least 3.5 hours. the LA522 contains approximately $8\text{V} \cdot 25\text{mA} \cdot 30\text{hr} = 6\text{Whr}$. After calculating the assumed total power consumption of our device's circuit we found that a single 9 V Energizer LA522 lithium battery will perform for a approximately for at least 4.8 hours.

A 5V regulator is utilized to supply the correct voltage to the operational amplifier (used in the amplifier circuit), PIC 12F1572 micro-controller, and DC-DC booster. Its voltage is then filtered to clean up voltage spikes that could damage sensitive components.

A DC-DC booster is used to supply 29V to reverse bias the SiPM. Since the SiPM is sensitive to voltage spikes, the voltage after the DC-DC booster will be filtered to flatten the voltage and prevent damage to the SiPM.

3.2 Sensor, Amplifier, and Filters

The SiPM is attached to the block of scintillator. Because we only want to detect energetic charged particles like muons, we wrap the sensor in aluminum foil. This blocks other lower-energy charged particles from interacting with the scintillator, while still letting muons enter. Afterwards, the sensor is wrapped in black electrical tape. This ensures that the only photons entering the SiPM are from the scintillator during muon interaction.

To ensure maximal signal from the SiPM, the emission maximum of the scintillator has to somewhat match the sensitive wavelengths of the SiPM. We managed to find a scintillator with an emission maximum of 380 nm [4], and a SiPM with peak sensitivity of 420 nm [5]. This certainly isn't ideal, however with a decent amplification after the SiPM, we were able to detect a readable voltage spike.

When the sensor detects a muon, a voltage spike on the order of 10 mV is produced by the SiPM. This signal will be amplified to an order of 100 mV [2]. During amplification, a DC filter will remove high frequency noise and minimize extraneous voltage spikes. The PIC is able to be measure these larger and cleaner signals.

3.3 PIC Micro-Controller and Transmitter

The amplified signal is detected by a comparator in the analog-to-digital converter on the PIC. The signal is measured against a threshold value supplied by the DAC. If the comparator returns that the spike was above the threshold, then the program concludes that a muon was detected, and increments the muon count [6].

The PIC then sends the spike count encoded as a PWM signal to the transmitter. The transmitter then AM modulates the data onto a 433MHz carrier wave. The ground station picks up and demodulates the signal. After the test, the data is analyzed to find the relation between altitude and muon flux. A photo of the completed system is shown in Figure 4.

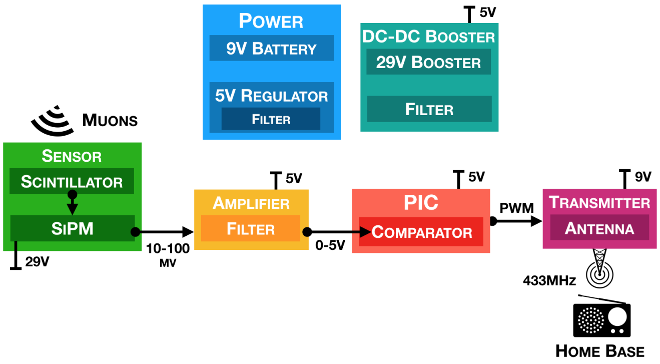

Figure 3: Sensor Block diagram.

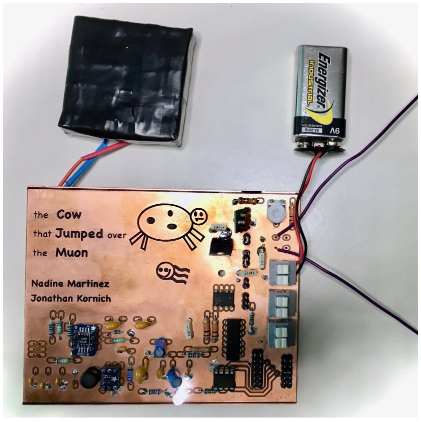

Figure 4: Our muon-detecting payload.

4 Testing and Design Verification

4.1 Battery, Regulator, and DC-DC Booster

The implementation of our power circuitry went fairly smooth. We began by testing that we were getting a steady 5V output from the regulator and the 9V battery. Afterwards, we implemented the booster circuit to ensure the required 29.5 V was coming from the output.

4.2 Sensor, Amplifier, and Filters

When testing the amplifier module by itself (not connecting to the sensor or PIC), its gain was approximately 40. However, when we connected the sensor to the input, the gain went down to 20 (as intended by the Cosmic Watch circuit design). The sensor was the last hardware module we implemented. The SiPM, being a QFN package, was extremely difficult to solder on to a breakout board. When we began the test with all the circuit modules (except the PIC) on the breadboard, there was a lot of high-frequency voltage spikes. These were caused by the parasitic capacitance of the breadboard. This noise was non-existent on our final PCB circuit.

4.3 PIC Micro-Controller and Transmitter

The PWM of the PIC was programmed first, so it could be used for debugging the following software modules. Afterwards, the transmitter was hooked up to the PWM so we could listen to the output instead of probing the PWM with an oscilloscope. Then, the ADC was programmed, and tested by varying the PWM depending on the voltage at the ADC pin. While the sensor was still incomplete, a synthetic voltage-spike generator was used to emulate the output from the SiPM. Unfortunately, the ADC turned out to be not fast enough to catch the 500ns-wide voltage spikes. So, the comparator in the PIC was used instead, as it was fast enough to catch many of the spikes. To vary the threshold for the comparator, the DAC was utilized to programmatically adjust the voltage level. Once the PCB circuit was populated, we adjusted the DAC value until the PIC detected as many spikes as possible, without it falsely detecting any noise.

5 Discussion

5.1 Pre-Flight: Ambient Radiation, Americium

The test done in a building at sea level is shown in Figure 5. Since the increment was 1 [Hz] per count and the rate was 0.19 [Hz/sec], a spike was detected every 5.3 [sec]. When verifying with the oscilloscope, we noticed that many spikes are not counted; usually 1 out of 3 were detected. This means that a particle was detected roughly every 2 [sec]. This agrees with Cosmic Watch's estimate during their experiments done indoors at sea level.

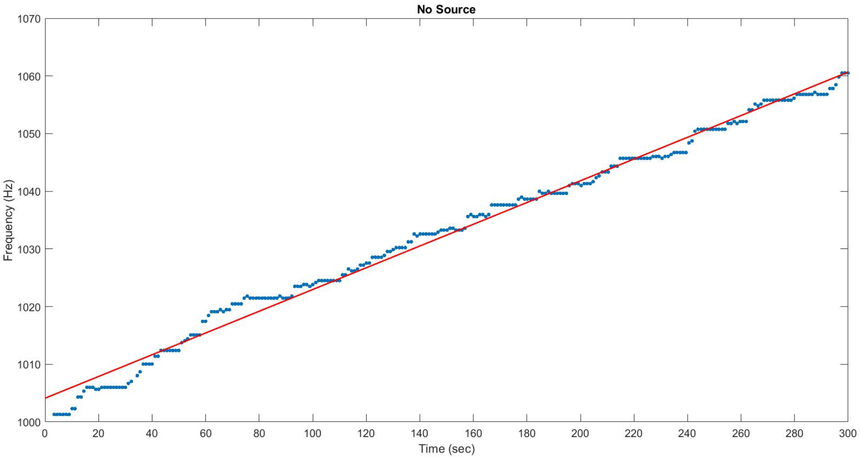

Figure 5: PWM frequency in building.

Prior to the flight, we also tested our payload with a source of Americium (found in smoke detectors) next to the sensor. There were no noticeable differences compared to the plain test.

5.2 Tethered Flight

The test done outside and 30-50 [m] above the ground is shown in Figure 6. Since the increment was 50 [Hz] per count and the rate was 11.6 [Hz/sec], a spike was detected every 4.3 [sec].

The expectation that the detection rate is less slightly above Earth's surface compared to the test in a building seems to be validated with this data.

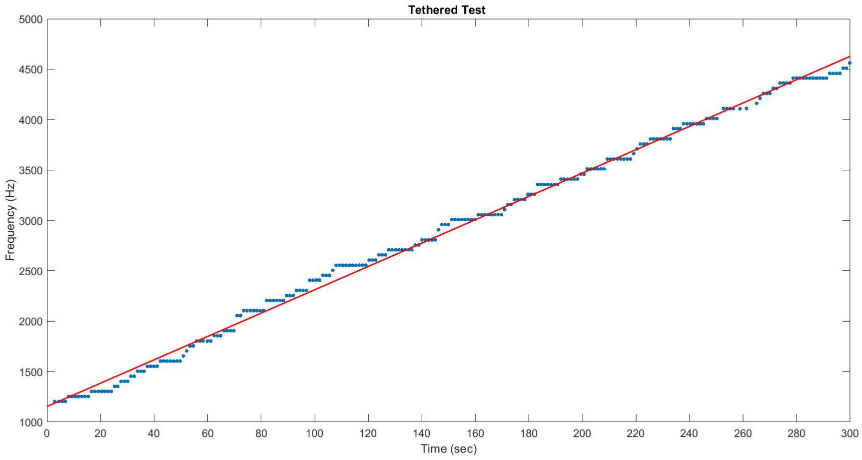

Figure 6: PWM frequency during tethered flight.

5.3 Post-Flight: Uranium

To make sure our payload was properly working, we applied radiation to the sensor. The sensor detects energetic charged particles (not just muons), such as the alpha radiation from Uranium.

The test done in a building at sea level with a 70 [nCi] source of Uranium Dioxide (UO2) is shown in Figure 7. Since the increment was 1 [Hz] per count and the rate was 1.3 [Hz/sec], that meant that 1.3 spikes were detected every second. Similarly, there was a test done with a 140 [nCi] source of UO2, as seen in Figure 8. In that test, 2.6 spikes were detected per second. The increase of the rate of spike detections seems to be proportional to the amount of radioactive substance, which is a reasonable expectation.

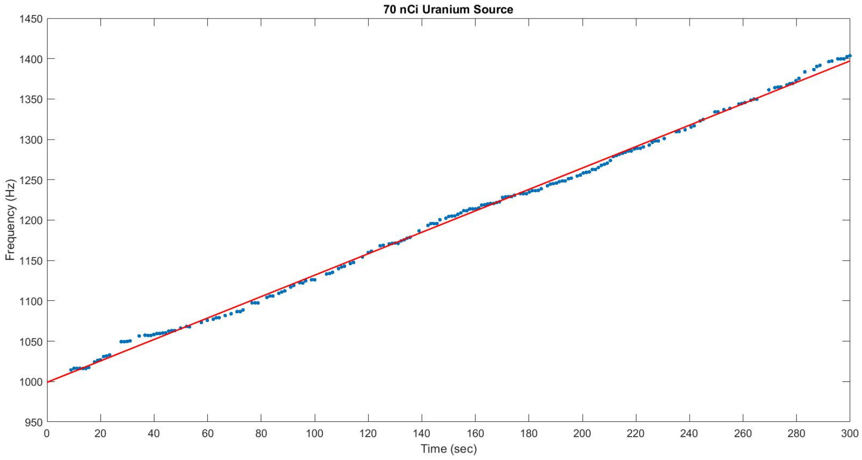

Figure 7: PWM frequency with 70 nCi Uranium source near sensor.

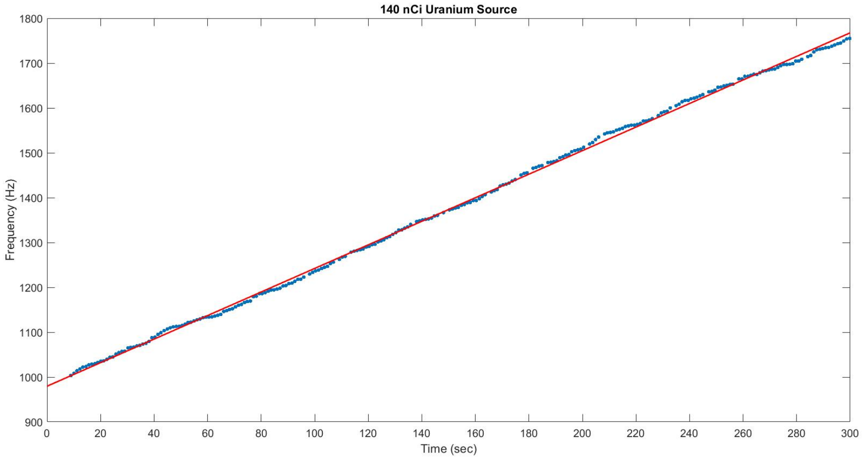

Figure 8: PWM frequency with 140 nCi Uranium source near sensor.

5.4 MATLAB and Aliasing

After reviewing the test flight data we noticed that some of the data points were twice as large as expected. This was due to the aliasing caused by finicky antennas and potentially the close proximity of the transmitter to the receiver. MATLAB was used to collect the data in real time, and to graph the data afterwards. We also utilized it to fix the aliased data, remove the invalid data, and calculate the line of best fit of the graph.

6 Conclusions and Future Work

Though we had a successful tethered launch in which we collected 5 minutes of data, the lack of various altitudes measured resulted in the inability to acquire a definite change of muon flux with respect to altitude. However, we were able to verify that Earth's ambient radiation has a noticeable impact on the sensor readings.

In the future we would like to improve this project by redesigning our PCB into a smaller footprint, reduce its cost, decrease the signal noise, and eliminate aliasing. Another goal this team would like to accomplish is building an entirely new sensor module using a plastic scintillator with an emission maximum closer to the SiPM's peak sensitivity wavelength, and a pre-soldered SiPM in case the current SiPM was damaged during its soldering. Moving forward we can envision this project being upgraded by utilizing multiple sensors in parallel to increase muon detection coincidence measurements. For a more practical application, many clones of this project can be used in creating a global real time radiation detection system.

7 Acknowledgements

The Cow that Jumped Over the Muon would like to thank Professor Jeremy Thomas for supervising us throughout the entire project. Spencer Axani, a creator of Cosmic Watch, for the inspiration of our project as well as assisting us via e-mail. Christopher Theriault, lab manager, for providing us the components we needed for the project and successfully soldering the SiPM on to its PCB board. And Collin MacDicken, fellow freshman and friend, for coming up with the team name and logo.

8 Author Contributions

Nadine Martinez: Constructed schematic, designed and populated PCB.
Jonathan Kornich: Programmed PIC, designed and populated PCB.

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