# Construction of a Muon Detector and testing the suitability for detecting Cosmic Ray Muons at Sea Level

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**ABSTRACT**

Cosmic rays collide with the atomic nuclei of molecules in the upper atmosphere to produce muons, which are known to be the most energetic charged particles found at sea level. For the purpose of studying the muon flux at sea level, a portable, low-cost, durable, and low power-consumed muon counter was built. The portability and the low power consumption of the instrument allows researchers to install multiple muon detectors as an array.

When the susceptibility of a single detector to background radiation was tested, it appeared that gamma rays might interfere with the detector's muon counts. However, when two detectors were stacked and run in the coincident measurement mode, the effect of the background radiation was reduced significantly and thereby improved the signal-to-noise ratio of the instrument. The instrument's minimum operating time for adequate data acquisition was estimated. It was discovered that a time window of 25 ms is appropriate when measuring the muon count rate. The instrument measures an average of 11.2 ± 0.2 counts per hour.

## 1. INTRODUCTION

The detection and analysis of cosmic ray-generated muons is one of the vital experiments carried out in the field of high energy and astroparticle physics. In these experiments conducted worldwide, highly sophisticated detectors with considerably large window areas that allow the researchers to collect large amounts of data are used. Some of the major issues with these very complex structures are the high costs of construction and maintenance, the lack of mobility owing to bulky components, and the high power consumption. Regular photomultiplier tubes typically require 1000 V to 2000 V to accelerate electrons within the chain of dynodes, and hence detectors that use them require somewhat complicated electronics to operate.

However, significantly accurate yet less complex muon detectors, particularly for small-scale experiments, can be built with the use of modern electronics such as silicon photomultipliers (SiPM) in the place of traditional photomultiplier tubes (PM tubes). This study is focused on constructing a portable, low power-consumed, durable, and low-cost muon counter to study the muon flux at sea level.

## 2. METHODOLOGY

As the scintillator, a 5 cm × 5 cm × 1.2 cm size plastic scintillator was chosen and its edge surfaces were smoothed out. It was then wrapped in a reflective aluminum foil to increase internal reflections and guide more photons towards the SiPM.

### 2.1 Construction of a microcontroller-based portable data acquisition system to record data and upload it to a cloud server

The data acquisition system was based on the ESP-32 microcontroller, which comprises a dual-core 32-bit CPU running at 240 MHz and built-in Wi-Fi capabilities to connect to a server. The final code and schematic diagram can be accessed via the GitHub link: https://github.com/ypmj/Muon-Detector.

When the microcontroller detects a pulse, the event is saved to an SD card along with the event id, date/time stamp, and pulse amplitude. The unit also has a display that shows the detector's count rate and other useful information. A real-time clock (RTC) with a one-second accuracy is used to keep track of the date and time. If more precise time information is required, an optional GPS receiver can be connected to the system. It could also be used to record latitude, longitude, and altitude details. The block diagram of the data acquisition system is illustrated in Figure 1.

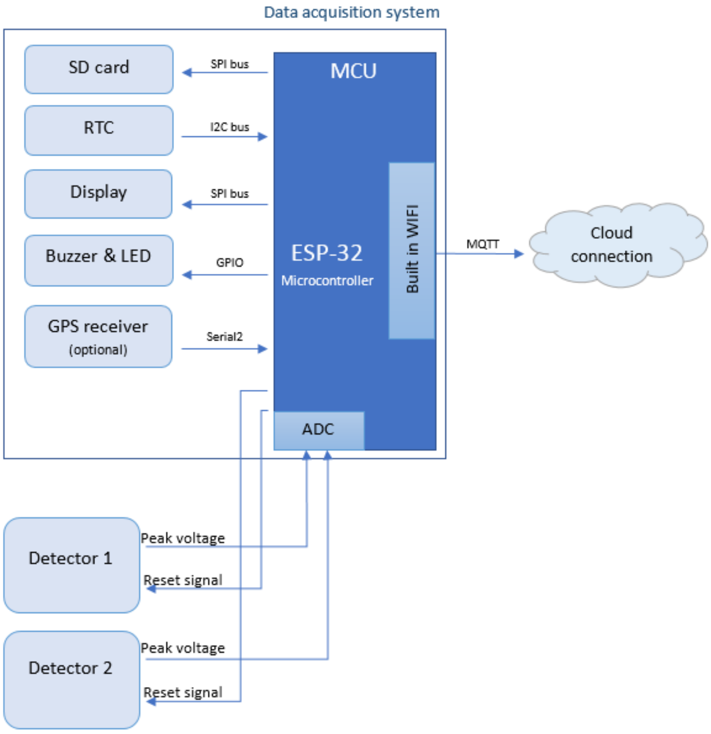



Figure 1: Data acquisition is illustrated in a block diagram. The first and second cores of the MCU handle data sampling and writing to the SD card, respectively, to ensure real-time data collection.

The output voltage of the peak detector is continually scanned by the microcontroller ADC that takes about 20 μs to complete one reading. If it detects a voltage greater than the specified threshold value (750 mV by default), the system records an event and sends a reset pulse to the detector.

However, two detectors must be triggered to obtain coincident readings within a specific time interval. This time window is typically the time it takes for the ADC to read voltages. This implies that when one detector registers an event, it waits for around

20 μs before checking to see if the other detector has also registered a pulse. If not, the event is abandoned.

If an event is detected, the pulse amplitude and time stamp information are stored in a ring data buffer on the RAM. This data sampling process is controlled by the microcontroller's first core (core0). It takes roughly around 25 μs for writing to the SD card and this is handled by the microcontroller's second core (core1). This is done to reduce the workload on core0, ensuring that the CPU core is available for data acquisition and real-time readings.The microcontroller's second core (core1) updates the display in addition to saving data on the SD card. It also submits the acquired data to a server in real-time via the MQTT protocol. If there is no network connection, it will continue to store data on the SD card as usual. When the network connection is restored, it begins uploading data from the most recently uploaded point.

### 2.2 Construction of the required electronic circuitry for the detectors

An electronic circuit that amplifies the voltage and stretches the pulse was constructed to address the problem of low voltage and narrow width of the original signal. The first circuit was based on a design by Axani [1], and it was later changed to conduct fast sampling by introducing a mechanism to reset the pulse after the microcontroller had read it. A block diagram of the pulse detection circuit is shown in Figure 2.

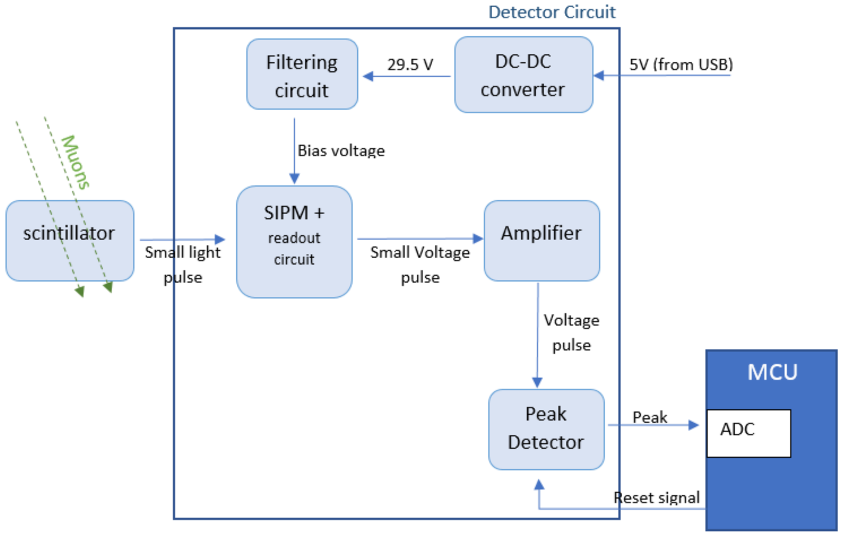
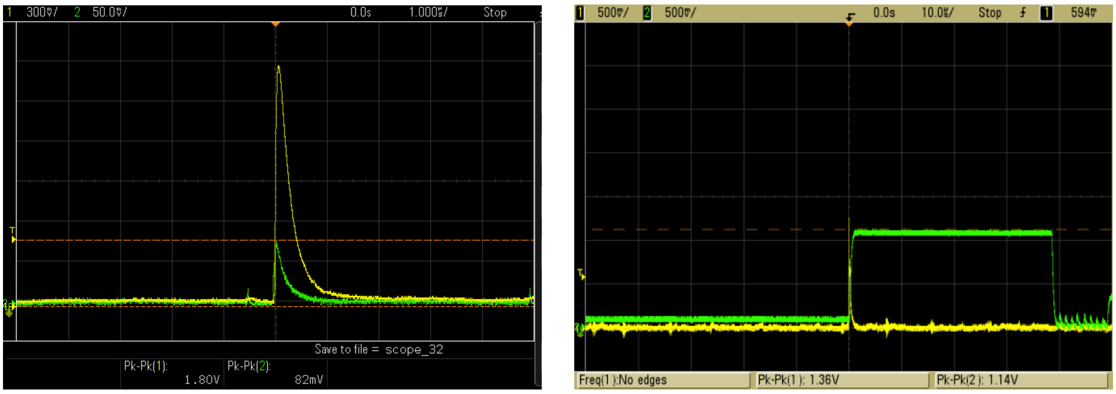



Figure 2: A block diagram of the pulse detection circuit.

When a muon passes through the scintillator, it emits a small light pulse that is then guided to the SiPM. This causes the photodiode to breakdown, allowing a small current to flow in the reverse bias direction. A resistor was connected in series with the cathode of the SiPM to determine the reverse current whenever the reverse breakdown occurs.

The generated signal has an amplitude of a few millivolts and a pulse time of around 500 ns. Due to the low voltage and narrow pulse width, a regular ADC in a microcontroller cannot sample this signal. The amplifier boosts the voltage from the SiPM to a usable level (Figure 3 (a)), allowing the peak detector circuit to hold the peak value of the voltage pulse (Figure 3 (b)).

After the ADC reads the voltage, the microcontroller sends a reset signal to the peak detector. This signal resets the peak voltage that had been holding and prepares the circuit for the next pulse.




(a) (b)

Figure 3 (a): The output of the SiPM (Green) and output of the amplifier (Yellow).

(b): The output of the amplifier (yellow) and output of the peak detector (green).

All the op-amps operate with a working voltage of 5 V DC. However, the SiPM requires a biasing voltage around 29 V for a proper function. In order to increase the voltage of 5 V to 29.5 V, a DC-DC boost module was used. A low pass R-C filter was added to the boost converter's output to reduce voltage ripple and noise.

The final detector consists of two of these units, as needed for making coincident measurements. The finished PCB of the detector electronics is shown in Figure 4.


Figure 4: The constructed PCB containing detector electronics (pulse detection circuit).

### 2.3 Making of light-tight enclosures

Making a light-tight enclosure for the device is crucial to eliminate the false triggerings. For this, enclosures for the detectors were constructed using 3D-printed PLA plastic. The SiPM was pressed against the scintillator using four spring-loaded screws, which allowed the pressure to be uniformly distributed when tightened (see Figure 5). To improve the detector efficiency by matching their refractive indices, a small amount of optical gel was placed between the light window of the SiPM and the bottom face of the scintillator plate.

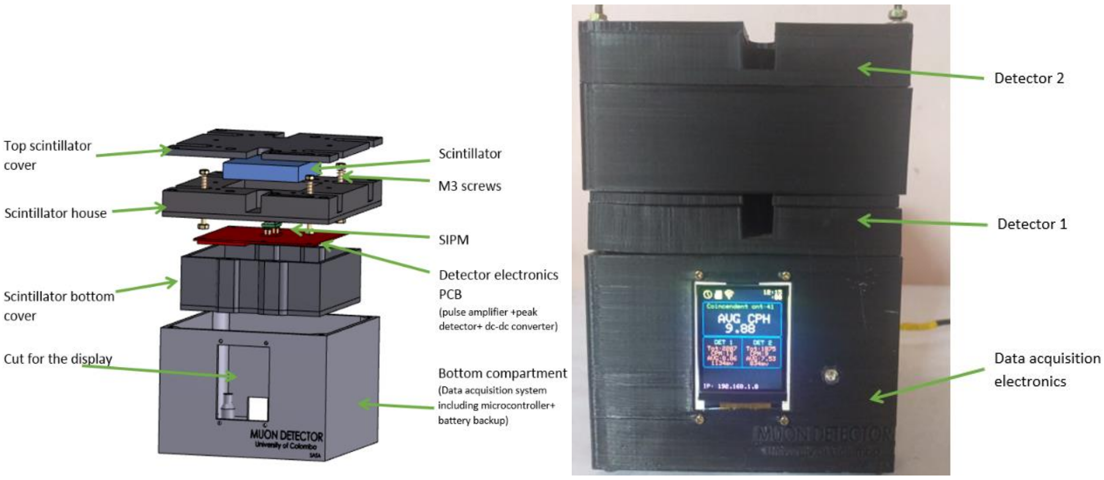



Figure 5 Left: An expanded view of the detector's 3D model. (For simplicity, only one detector is shown.)
Right: The device consists of two detectors (light-tight compartments) stacked on top of each other and one data acquisition system at the bottom.

The scintillator's top cover, housing, and bottom cover make a light-tight compartment for the scintillator. There are two light-tight compartments in a single device for each pair of SiPM and scintillator, and these two detectors have been used to make coincident measurements. Meanwhile, the bottom compartment houses the data acquisition system PCB and battery backup for the system. The final product is fully portable and can be used to measure muon count rates at desired locations.

## 3. RESULTS AND DISCUSSION

### 3.1 Testing the detector sensitivity to alpha, beta, and gamma rays

Background radiation refers to ionizing radiation that originates on the Earth's surface. These radioactive processes are classified into three types of emissions: alpha, beta, and gamma radiation. Compared to cosmic-ray muons, the energy scales of these radiations are relatively low [3]. However, because of their natural abundance on the Earth, they have the potential to interfere with our measurements by triggering the detectors. The sensitivity of the detector to alpha, beta, and gamma rays was tested using the radioactive sources that are listed in Table 1.

Table 1: Sources of radiation used to measure the sensitivity of the detector.

| Source | Radioactivity (μCi) | Generated rays |
|---|---|---|
| Americium-241 | 1 | Alpha |
| Strontium-90 | 5 | Beta |
| Cobalt-60 | 1 | Gamma |

The individual detectors (not in the coincident mode) show no significant change in the count rate for alpha and beta rays. However, when a gamma-ray source is kept at 15 cm and 5 cm distances, the count rate increases approximately by 78% and 180%, respectively, confirming that the gamma rays might trigger the detectors.

Even if gamma rays have enough energy to travel through several scintillator plates, they have a significant probability of undergoing Compton scattering, causing a change in the direction of the ray within the scintillator material. As a result, it is improbable for a gamma-ray to trigger both detectors simultaneously when they are running in the coincident mode, and hence, the detectors are inherently unlikely to be triggered by them.

### 3.2 Coincident measurements

'Coincident measurements' mean the measurements of events that have trigged both detectors within some time window. This time window was introduced to account for the slow ADC sampling time. Coincident measurements can be taken when two detectors are connected to the same data acquisition system.

This mode helps to reduce events due to background radiation and improve the purity of muon measurements. Coincident events are likely to be occurred due to the cosmic ray muons passing through both detectors and not by the background radiation. As background radiation events are highly random, they are unlikely to trigger both detectors at a given small time window.

When taking coincident measurements, detectors are usually set up to stack one detector on top of the other. Thus, the coincident mode only accepts muons coming from a small solid angle, as shown in Figure 6. However, practically, the acceptance angle could be much lower.

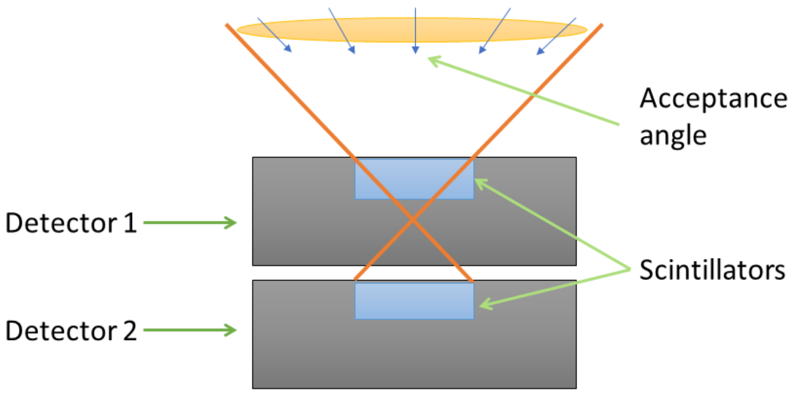



Figure 6: The detector arrangement for taking coincident measurements.

The coincident counts were measured continuously over a period of ten days, and an average of 11.2 ± 0.2 counts per hour was calculated. The daily average coincident count rate was calculated to be 11.2 within the error margins over the tested durations. The calculated standard deviation was 0.58.

### 3.3 Variation of the count rate with the distance between the two detectors

The two detectors were arranged in the coincident mode, and the count rate was measured by altering the distance between them. The experimental data are presented in Table 2. Figure 6 shows that the muon acceptance angle decreases as the distance between the two detectors increases. As a result, the coincident count rate should decrease with the increasing distance, and the acquired data confirm this fact.

Table 2: Variation of the count rate with the distance between the two detectors.

| Distance between the two detectors ± 0.1 (cm) | Coincident counts (per hour) | Uncertainty in coincident counts (per hour) |
|---|---|---|
| 1.0 | 35 | ± 2 |
| 5.0 | 10 | ± 1 |
| 10.0 | 2.7 | ± 0.7 |
| 13.5 | 1.2 | ± 0.4 |

For each distance in the configuration, data was collected for 5 hours. The above distances were measured as the distance between the scintillators of the two detectors.

### 3.4 Variation of the count rate with the length of the coincident time window

To measure the effect of various time windows, the two detectors were set up vertically (zenith angle = 0° and the scintillator plate is horizontal), and the coincident time window was altered by using the microcontroller program.

The microcontroller would only register an event as coincident if both detectors were triggered in the given time window. This experiment was conducted to determine if the coincident counts are caused only by a muon passing through the detectors and not by random triggering caused by background radiation.

The count rate was obtained by varying the time window duration (see Figure 7). Data was collected for approximately12 hours for each data point.

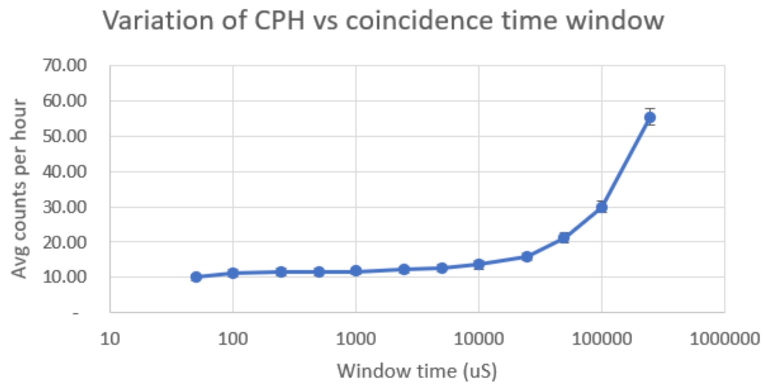



Figure 7: The variation of the coincident count rate with the coincident time window (in log scale).

The coincidence count rate remains nearly constant when the coincident time window is less than 25 ms. Since the time duration is small, it is very unlikely for both detectors to get triggered in the given small-time window by random background radiation. However, when increasing the duration of the coincident time window, the random triggering of the detector by background radiations becomes significant; hence, the count rate increases.

## 4. CONCLUSIONS

The primary goal of this project was to build a portable muon detector device that would serve as the key elements of a large-scale detector array intended to be used in the future for exploring cosmic ray-generated muon events in Sri Lanka. The constructed detector uses the combination of a scintillator and a Silicon Photomultiplier (SiPM) to detect muons.

A data acquisition system was also developed to record the events from the detector in an SD card as well as to upload data to a server in real-time. The setup is portable and can be used with battery power, allowing users to make measurements at desired locations.

The detectors are sensitive to gamma rays but not to alpha and beta rays. So, the gamma-ray component in the background radiation could interfere with the count rate of the detectors. However, the effect caused by the gamma radiation can be significantly diminished with the coincident event measuring setup.

The dependence of the coincident count rate on coincident time windows was studied, and it was found that a time window of less than 25 ms is required to make reliable coincident measurements. Therefore, even with slow microcontrollers (compared to the 240 MHz clock speed used in the present study), it is possible to build detectors that can produce satisfactory results. However, it is observed that the coincident count rate rapidly falls when increasing the distance between the two detectors.

## 5. REFERENCES

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