High Resolution Muon Tomography using a Portable Prototype Muon Telescope

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Background

Muon tomography is a technique that utilizes muon scattering to create images of large objects of interest such as volcanoes, buildings, or ancient archeological structures.

Muons are subatomic particles created in the Earth's upper atmosphere by cosmic rays colliding with atomic nuclei of molecules in the air. These rays are forms of high energy radiation from outside our solar system consisting of mostly high energy protons. The charged pions created decay into muons and muon neutrinos. These charged pions most often decay into muons and muon neutrinos.

The muons have a mass of 105.67 MeV/c^2 and a charge of -1e; this property makes them weakly interacting elementary particles that readily pass through objects, losing some of their energy in the process. Muon tomography exploits this fact to infer the differences in density of three-dimensional structures as shown in Fig B.

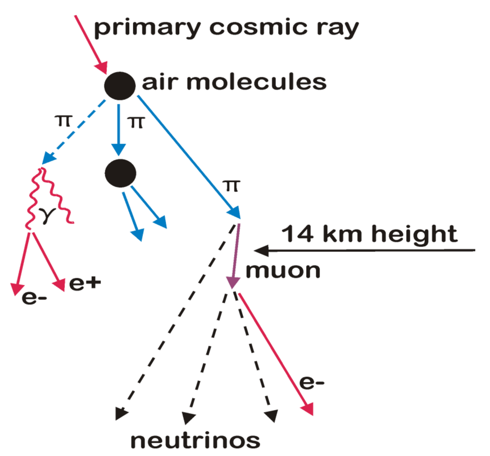

Fig A: Creation of Muon from cosmic ray shower

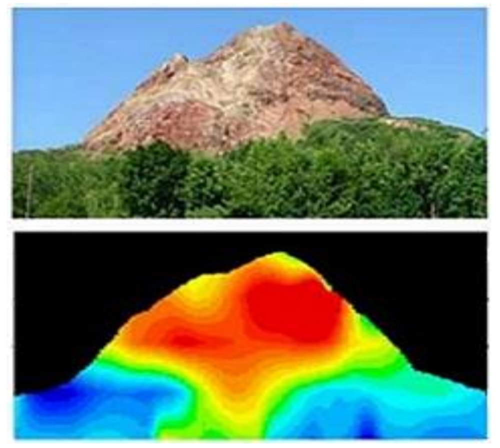
Fig B: Sample Muon Tomography Image

The Prototype Detector

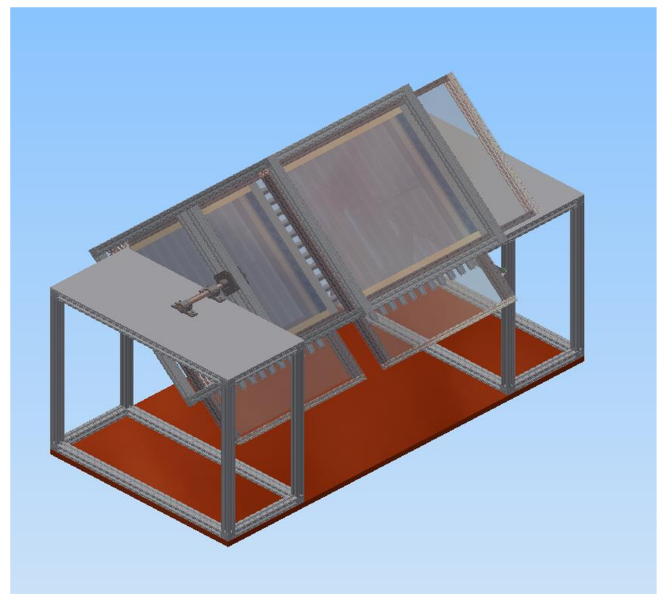
Fig C: CAD model of our detector


Fig D: Our Prototype Detector

Our prototype muon detector is a device comprised of scintillator bars, silicon photomultipliers (SiPMs), Winston cone light collectors, PCBs and a network of Arduinos. The detector consists of two layers with each layer containing two trays set in an x and y coordinate space. This entire set up is made mobile by being mounted on a cart that spans an area of approximately 90 cm by 180 cm and can be rotated 90 degrees to the vertical.

The two trays on each layer have the scintillator bars arranged perpendicular to one another which enables us to define a "hit" in a layer. The straight line between two layers connecting the "hits" is assumed to be the muon track in event reconstruction.

On each tray there are 11 scintillator bars and 11 SiPMs, which are located at the end of each scintillator bar. We used Winston cones in one of the trays of each layer to improve the light collection efficiency between the scintillators and the SiPM. This light is created when a muon passes through a scintillator bar, and the ionized track creates photons that can be detected by the SiPM. The SiPM converts these photons into electrical signals, which are then amplified, stretched, and digitized. The digitized information is then sent to a computer for recording via a wireless network of Arduinos.

Fig C illustrates the CAD model of our detector, and Fig D shows a picture of our prototype detector in our lab.

Introduction

Our primary objective is to develop a portable muon detector with excellent spatial resolution. The present prototype allows us to study hardware components as well as software reconstruction techniques needed for advanced muon tomography. In 2017, muon tomography was used to find a large cavity inside Khufu's pyramid. Muon tomography has also been used to safely check the damaged nuclear reactor cores in Fukushima which was led by the High Energy Accelerator Research Organization.
Our prototype is now being tested at the Advanced Particle Detector Laboratory. We are in the process of collecting data to create an image of a nearby water tower and its contents at Reese Technology Center.

Data Acquisition System (DAQ)


Fig i: Scintillator bars

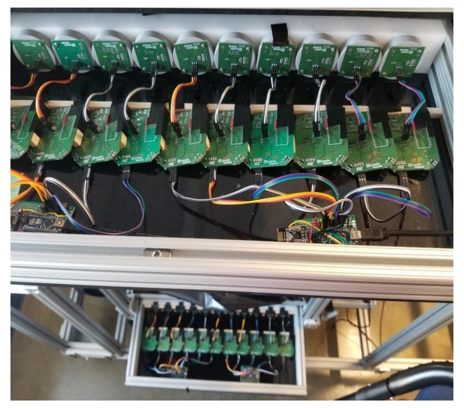
Fig ii: The PCBs and SiPMs

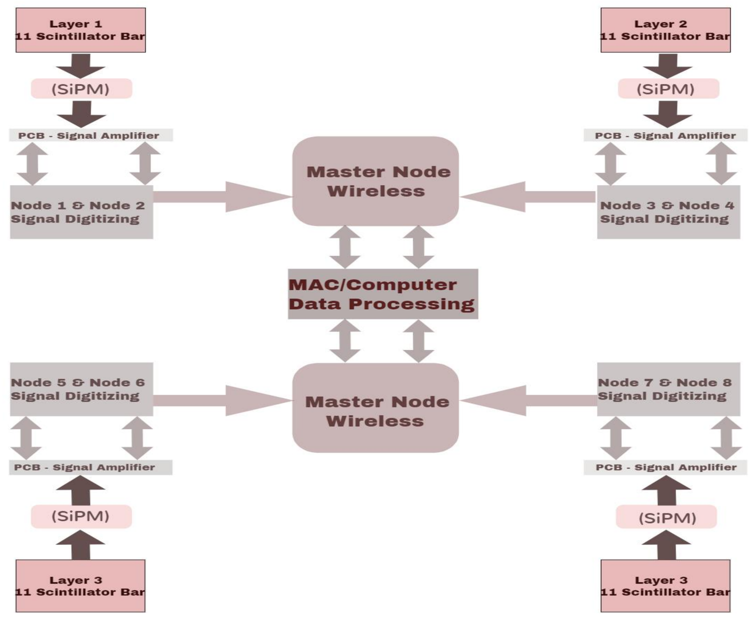

Fig 1 : The communications flowchart

Experiment

We are currently trying to generate images of a water tower nearby our lab using our detector.

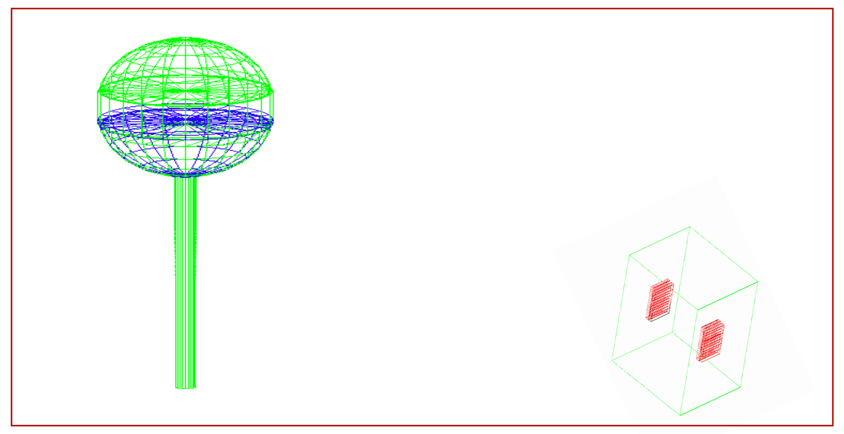
Fig E: The World Geometry in GEANT 4


Fig F: The water tower

Data Analysis

The digitized data received from the 8 nodes is converted into a text file which contains information about the particle ID, spatial location, ADC count and timing of each signal reported by the master Arduino. Using these data, we can infer several observables about the muons hitting our detector, such as the angle of hit (Fig 1.2), the trajectory of the muons through the detector and their projection (Fig 1.3), the energy deposit to the scintillator (Fig 1.1) and so on.

The muon analysis program identifies the muons by requiring a muon to pass through both the layers within a given time threshold. A particle interacting with a scintillator is considered to be a "hit", and our program distinguishes a true muon hit from a stray hit using such cluster analysis. Once we have our "true muon" hit cluster, the muon tracks are reconstructed to create useable data of our muon hits. The muon tracks and their associated energy are used to create the 2D tomography image of the object of interest.

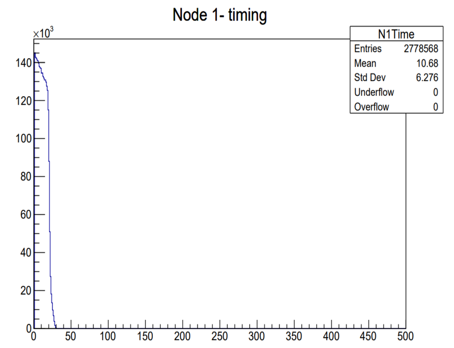

Fig 1.4 : Timing distribution of muon hits.

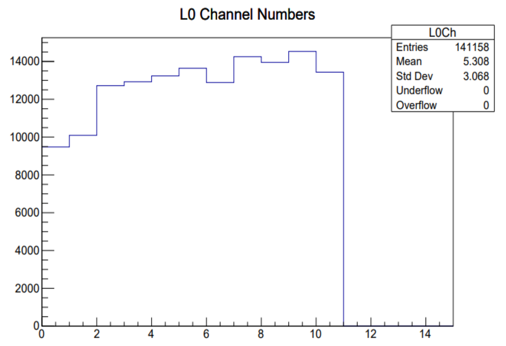

Fig 1.2 : The angle distribution of muon hits.

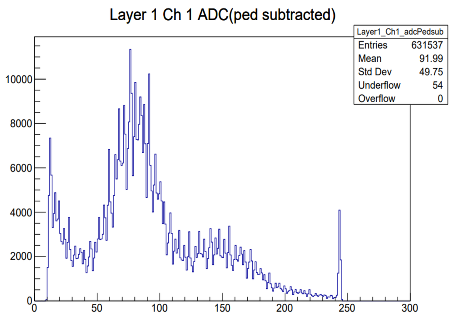

Fig 1.1 : ADC distribution of muon hits for a channel.

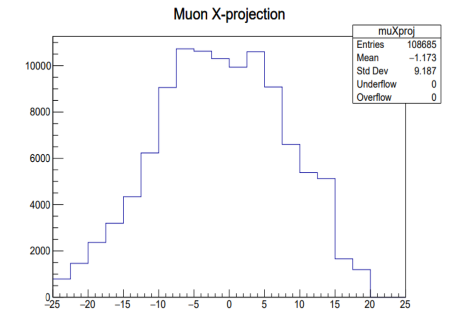

Fig 1.3 : Muon trajectory projection onto the plane of the water tank.

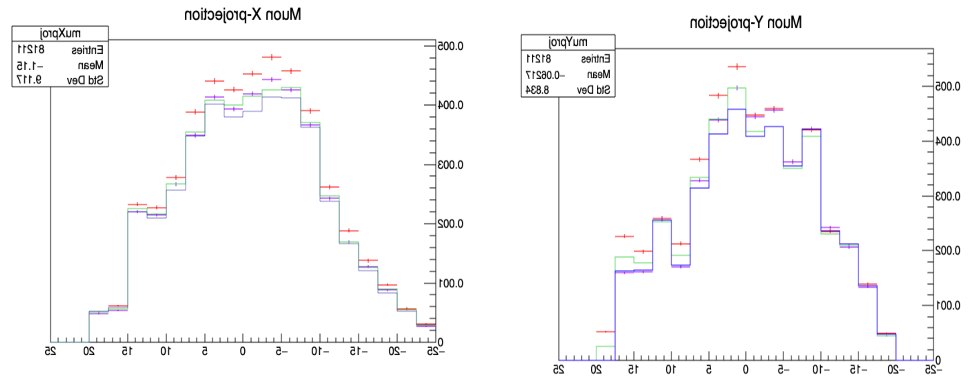
Fig 2.3 : Muon Projection data.

Monte Carlo Simulation

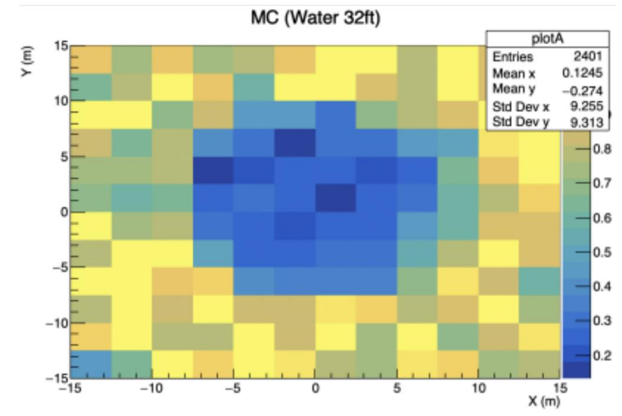

Fig 2.1 : Water tower mage from simulation

The shadowing effect of a water tower was simulated earlier as part of a feasibility study of the muon detector with the water tower at the Reese Research Center. Cosmic muons were generated with Cosmic-Ray Shower library (CRY) and propagated through a simplified water tank using Geant4. Muon tracks were reconstructed from hits in four trays each containing 11 scintillator bars.

Figure 2.1 illustrates a 2D view of the water tank, filled with water. Muon tracks were projected on to a plane near the water tank at ~50 meter away from the detector. The shadowing effect is clearly seen as blue points at the center (0,0). This image represents the muon absorption in the water tank. The change in color represents the decrease of the muon density from yellow to blue being the lowest amount of muons detected.

Experimental Results

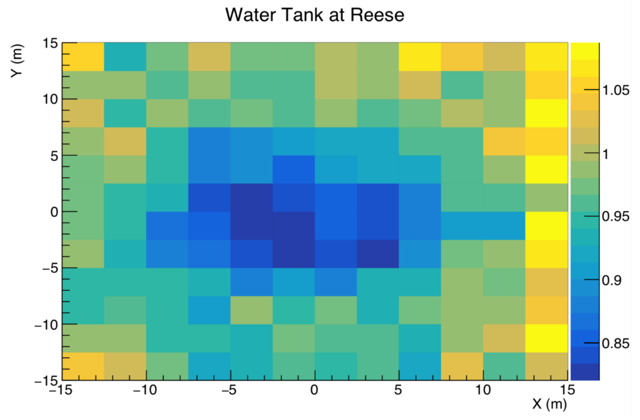

Fig 2.2 : 2D Muon Absorption Image

Figure 2.2 shows the very first result on the shadowing effect of the water tank. Data was taken with the detector pointing at the center of the tank and pointing away from the tank with the same elevation angle. This figure was generated using a weighted mean method of the muon numbers captured over the total exposure time of the muon telescope.

Muon Deficit Figure 2.3 shows the difference of those runs, delta= (tower)-(away). Deficit of muon counts are clearly seen due to absorption or multiple coulomb scattering of low energy muons in the tank. High statistics runs are in progress to make 2D and 3D map of the structure of the water tank and the tower.

Conclusion

We were able to see a shadow image of the water tower from the muon deficit caused by muons getting absorbed by the water tank. This shadow image generated by our detector has a resolution of 50 milliradians and agrees with the results from the Monte Carlo simulation.

The next phase for our project is to further improve the resolution of the detector by implementing faster communication protocols, using higher number of smaller scintillator bars with fiber optics, and deploying greater number of SiPMs. We aim to achieve a resolution of 0.5 milliradians with the next prototype.

Acknowledgement

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- GEANT 4 and ROOT, CERN
- Cosmic-ray Shower Library (CRY), Lawrence Livermore National Laboratory

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