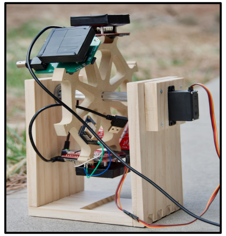
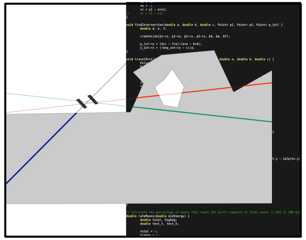
Nondestructive Analysis of Geological Sites Through Muon Transmission Imaging

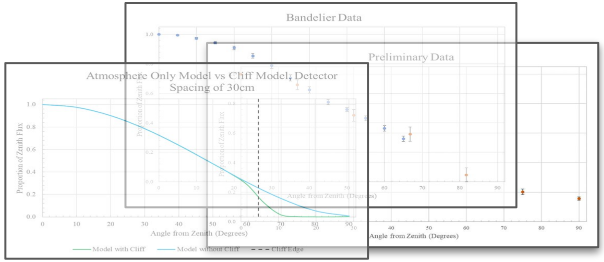
Built Muon Flux Detector



Using changes in cosmic ray muon flux to search for density irregularities in geographical structures.

Created Computer Simulation





Performed Experiments & Analysis

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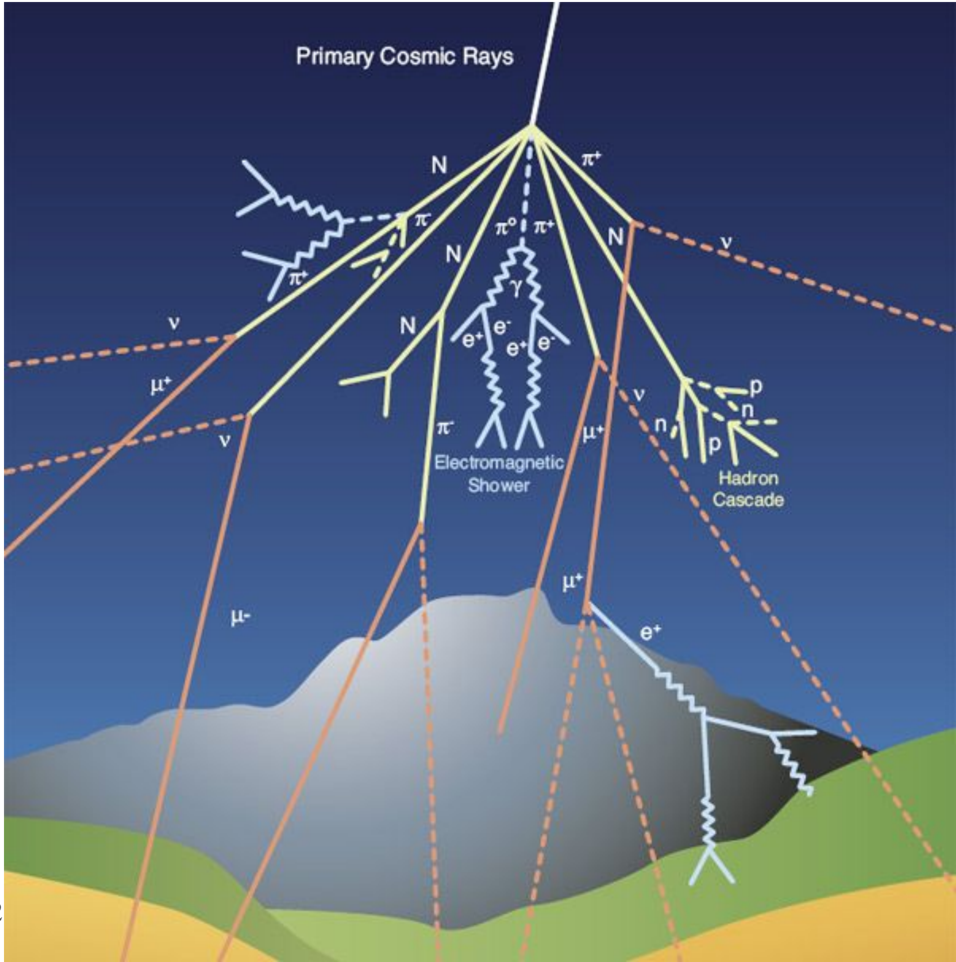
All images created or taken by us unless otherwise noted

Introduction

Source: CERN [1] , https://home.cern/science/physics/cosmic-rays-particles-outer-space



Cosmic rays:

- High energy nucleons are produced by cosmic events (like supernovae).
- Cosmic ray nuclei collide with nuclei of atoms in the upper atmosphere, producing a shower of mostly pions.

Muon:

- Muons are heavy particles produced from the decay of cosmic ray pions.
- Very steady flux.
- Assume that all muons we see are minimum ionizing particles (MIPs).[2]

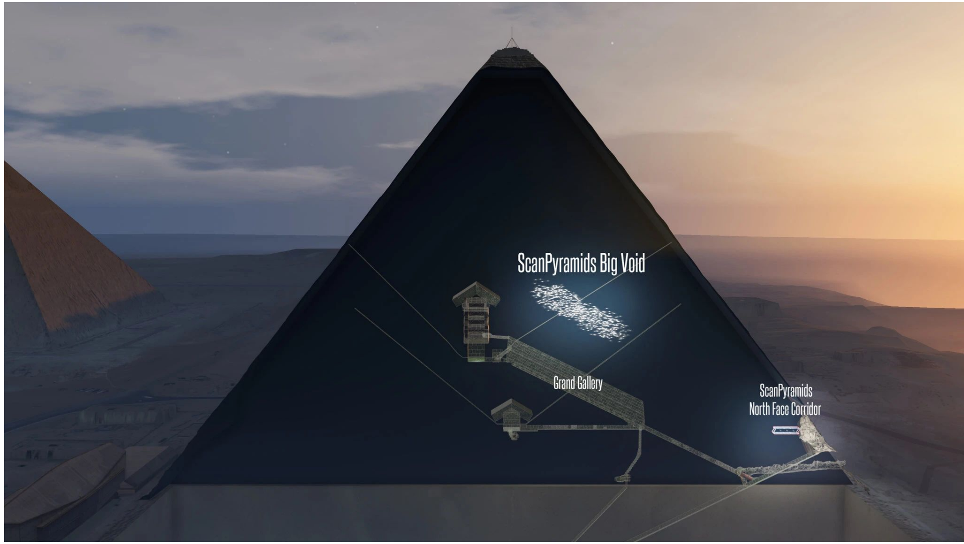
[2] Groom, Donald E., and S. R. Klein. "Passage of particles through matter." The European Physical Journal C-Particles and Fields 15.1-4 (2000): 163-173.

Muography

- Method of using cosmic ray muons to generate a density map of a structure.
- Works similar to an x-ray, but on a much larger scale and much slower.
- Look at small slices of an object and detect muons through that slice for long periods of time.
- Based on the count of muons, one can determine the density of the slice that was being observed.
- Compare the expected count to the actual count to search for density anomalies which might imply a void.

Unlike other forms of archaeology, muography leaves the subject of interest completely untouched.

[3] Morishima, Kunihiro, et al. "Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons." Nature552.7685 (2017): 386-390.



The ScanPyramids project used muography to find a large void in Khufu's pyramid.

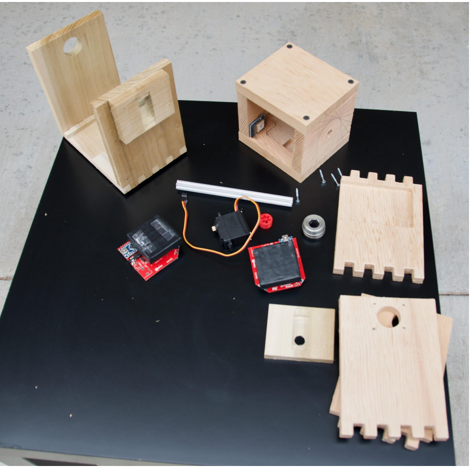
Bandelier National Monument

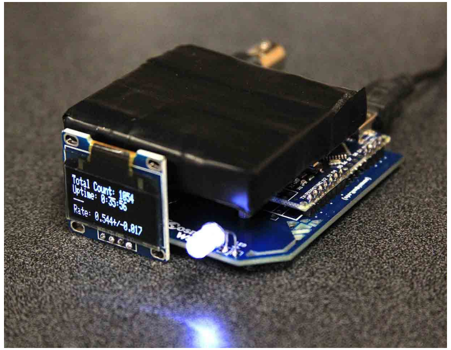
- Historical site of Ancestral Puebloan civilization.
- Cliffs at Bandelier National Monument formed after massive volcano eruptions
- Mostly composed of a type of tuff called ignimbrite.
- Ignimbrite has an average density of 1.57 g/cm^3.[4]

Prime target for study due to the vast amount of caves on its cliffside.

[4] Moon, Vicki G. "Geotechnical Characteristics of Ignimbrite: A Soft Pyroclastic Rock Type." Engineering Geology, Elsevier, 22 Feb. 2003, www.sciencedirect.com/science/article/abs/pii/001379529390068N.

Muon Detectors

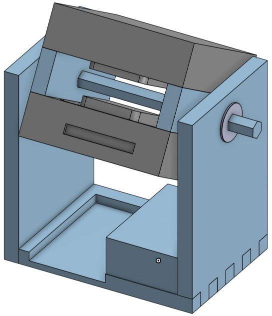


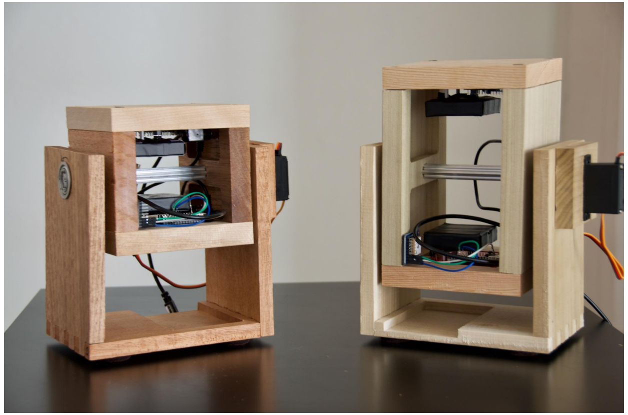


- CosmicWatch muon detectors[5] - used in other projects.
- Use two in coincidence mode to filter out noise.
- Needed to change our setup so we could leave them outside for long periods of time.

What we added:

- CADed a rotating detector enclosure and stand.
- Run all code from Arduino rather than Raspberry Pi to save power.
- Added GPS module for very precise time measurement.
- Motor automatically changes the angle after a certain amount of time.





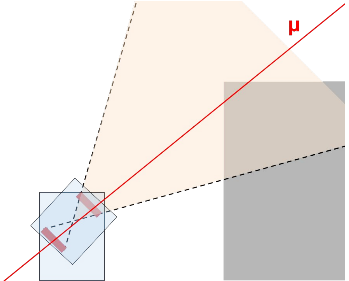
[5] Axani, Spencer, and Katarzyna Frankiewicz. CosmicWatch. http://www.cosmicwatch.lns.mit.edu/

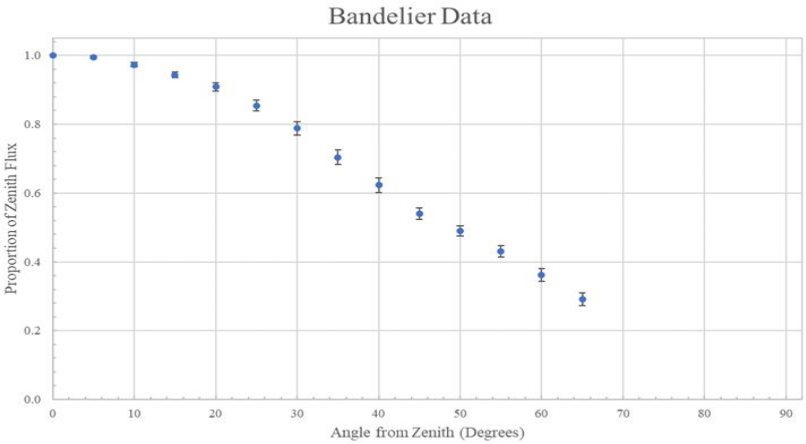
Experiment

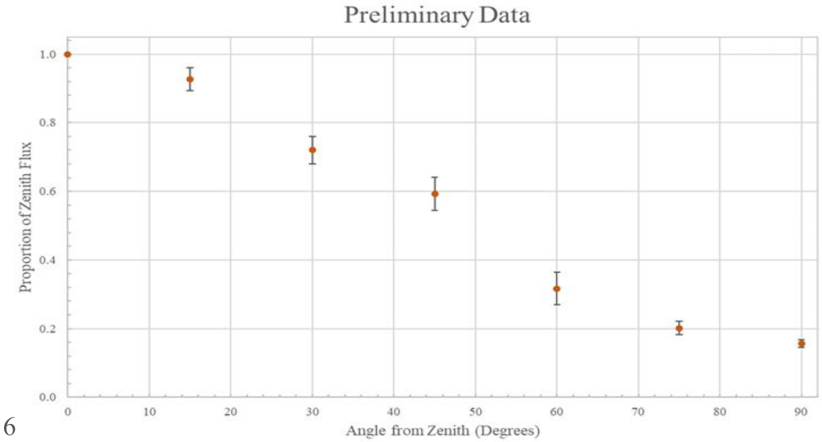
We collect data for a period of 48 hours starting at zero degrees to the zenith. We then repeat, increasing the angle of the apparatus by 5 degree increments. This phase of experimentation stopped at 65 degrees.

As we change the angle, we can observe the muon flux through different slices of the cliff.

The upper graph shows data collected at Bandelier National Monument, while the lower graph shows preliminary data of just open sky.





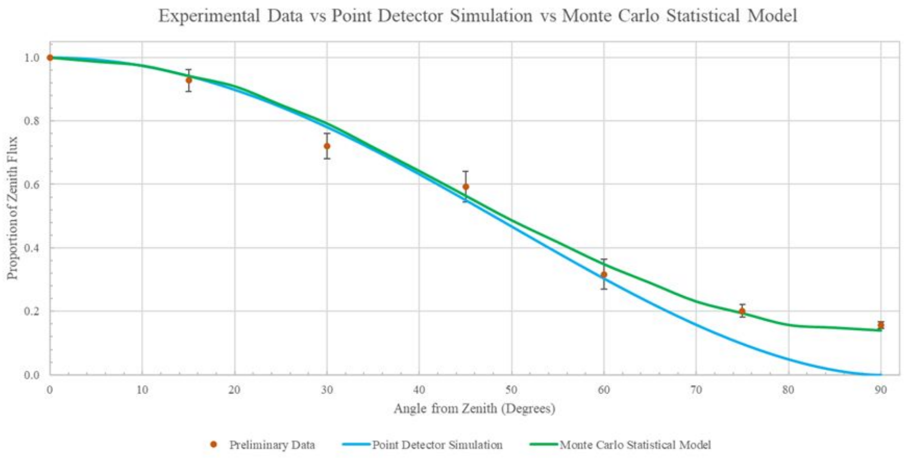


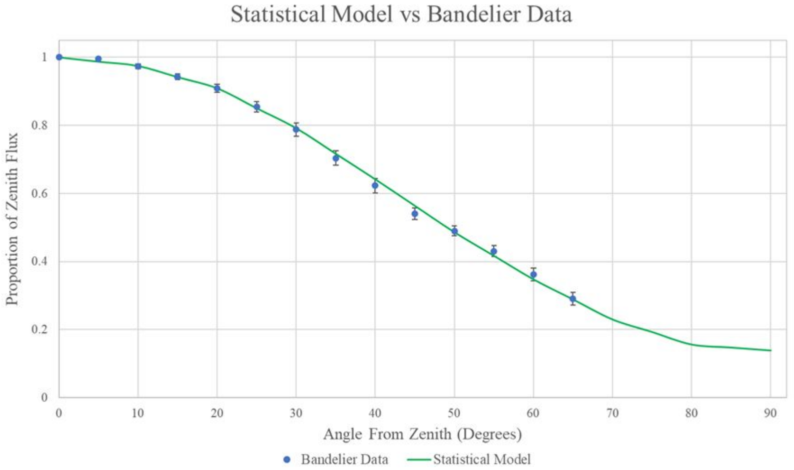
Statistical Model

- Muon rates change as a function of angle, so we need to account for these changes.

- In our statistical model, we assume that muon flux decreases as a function proportional to $\cos^2\theta$.[6]

- Uses Monte Carlo method to replicate real world conditions where a range of angles can hit the detector.
    - Detectors are 3D, not single points.

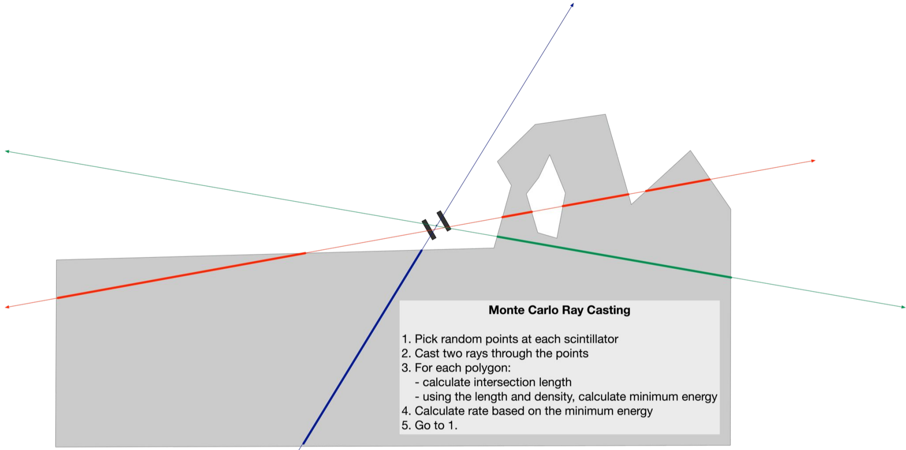


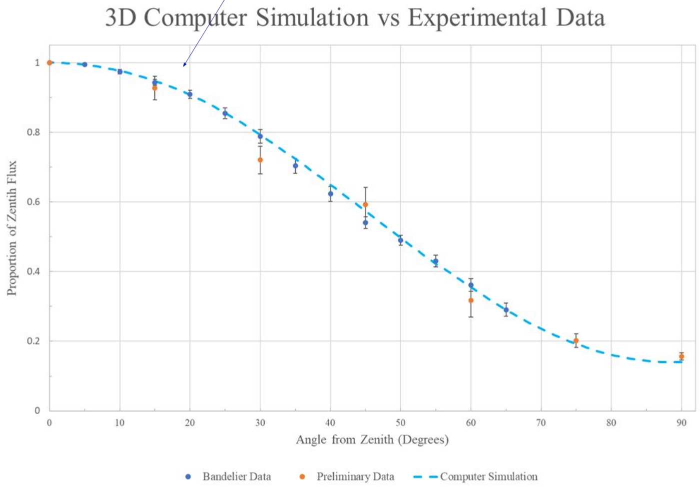


[6] Reyna, D. "A simple parameterization of the cosmic-ray muon momentum spectra at the surface as a function of zenith angle." arXiv preprint hep-ph/0604145 (2006).

Computer simulation

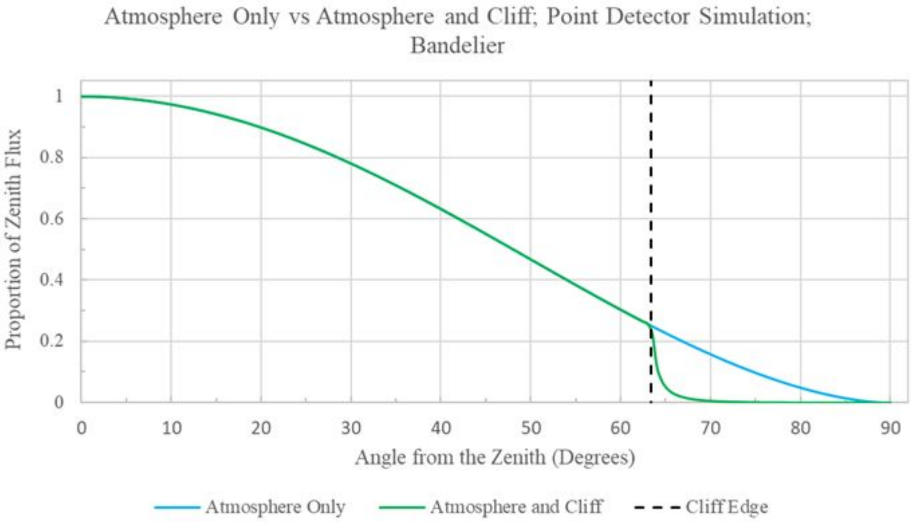
- Calculates the minimum energy for a muon to reach the detector.
- Calculates the number of particles above that minimum energy and divides by the total number of muons, giving us a relative rate.
- Uses Monte Carlo to run the simulation for every possible angle.
- Uses ray casting to determine distance traveled through a polygon
  - Normally used in image rendering
  - Cast a ray and track its movement through different polygons to find distance traveled.
  - Very easy, general solution to calculating energy loss through a cliff.

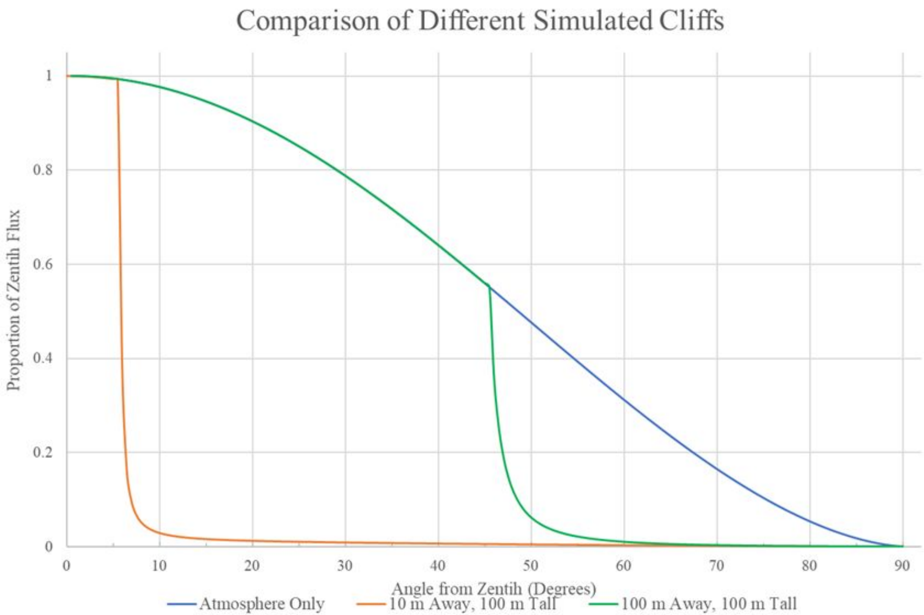




Clearly follows our experimental data at Bandelier.

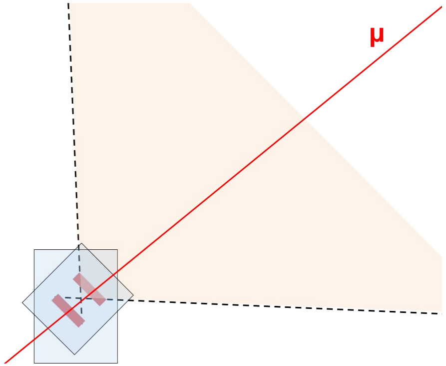
Point Detector Simulation

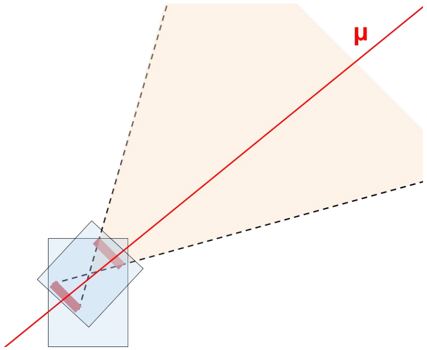


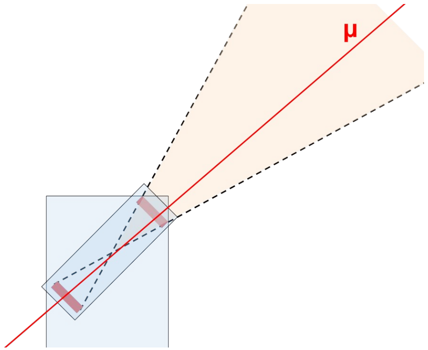


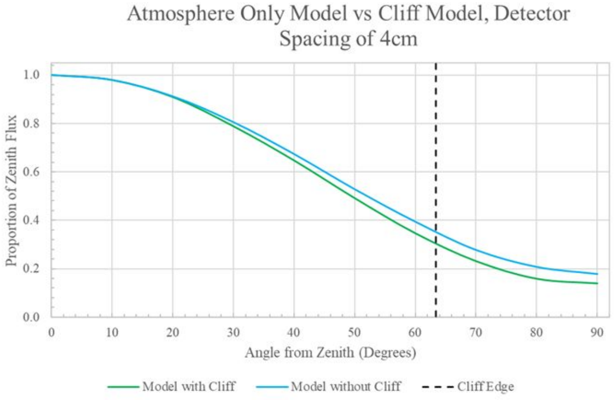
Modeled Effect of Detector Spacing on Cliff Data

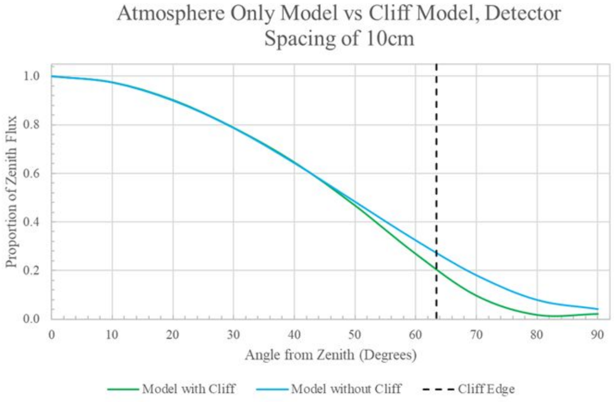
The graphs below demonstrate how different detector spacing affect our data with only atmosphere.

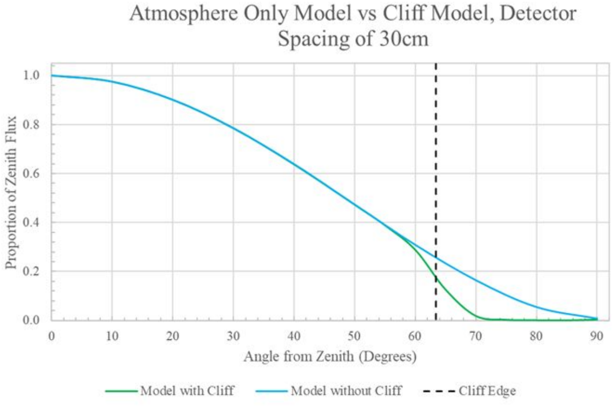






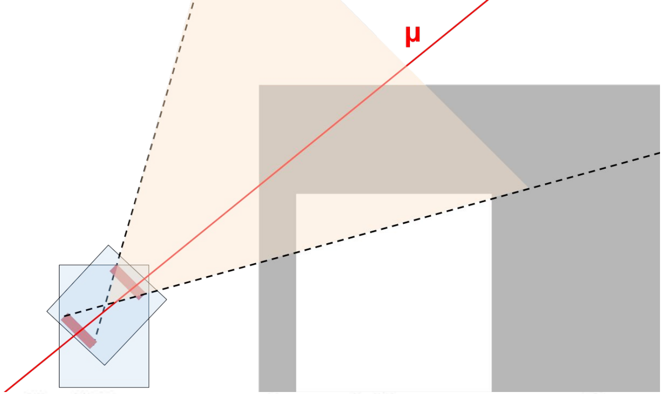


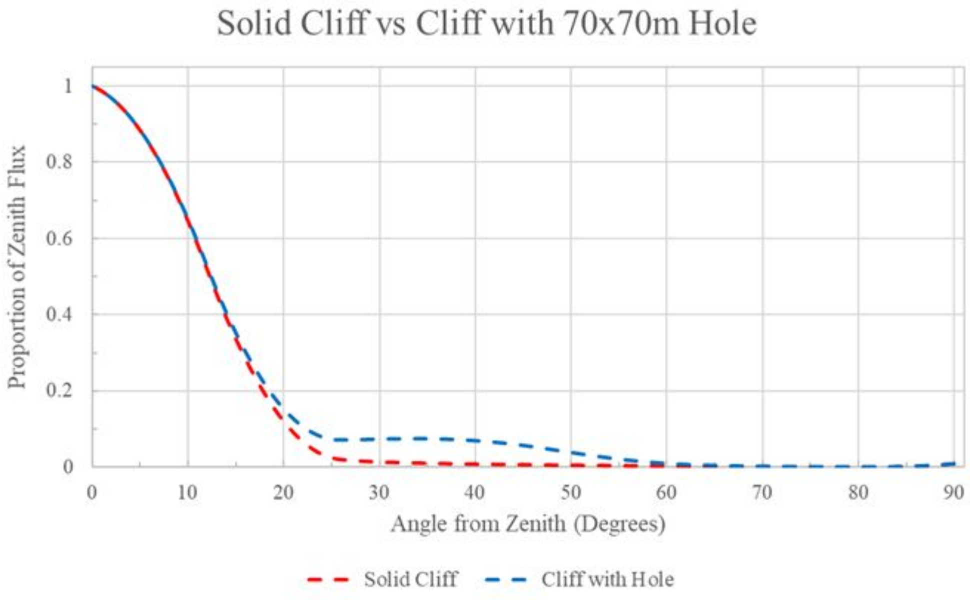


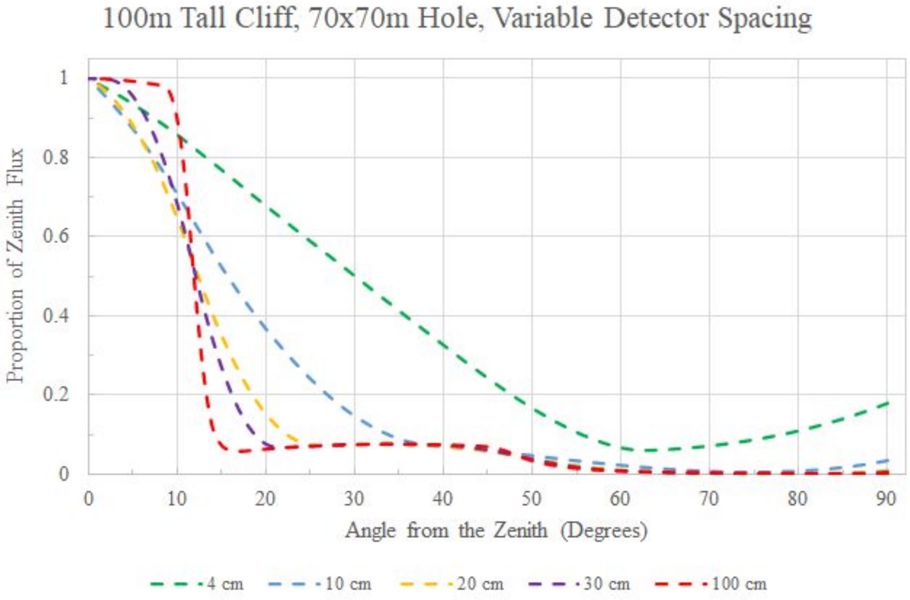


Simulation of a Cliff with a Hole

The detectors are 4 cm in size with 20 cm spacing between them.







Conclusions and Next Steps

Our models clearly follow experimental data and inform us that we need greater spacing between our detectors in order to make muography more feasible.

Next steps:

- Continue taking data at Bandelier National Monument
  - Redo the experiment with further separation between the detectors.
  - Test our new experimental setup:
    - Further separation between detectors
    - More detectors allows us to cut our data collection time
- Utilize the computer simulation
  - Simulate different environments to understand what our experimental data should look like before experimentation.
  - Further understand the conditions necessary for an experimental setup that finds density anomalies

This setup has a spacing of 20 cm and is currently collecting data at Bandelier.

Acknowledgements

We would like to thank our mentor Dr. Matt Durham for his continuous support and patience with this project. We also thank Spencer Axani and Katarzyna Frankiewicz for their CosmicWatch project, which allowed us to conduct experiments. We also greatly appreciate the National Park Service for allowing us space in Bandelier National Monument to set up our experiment.

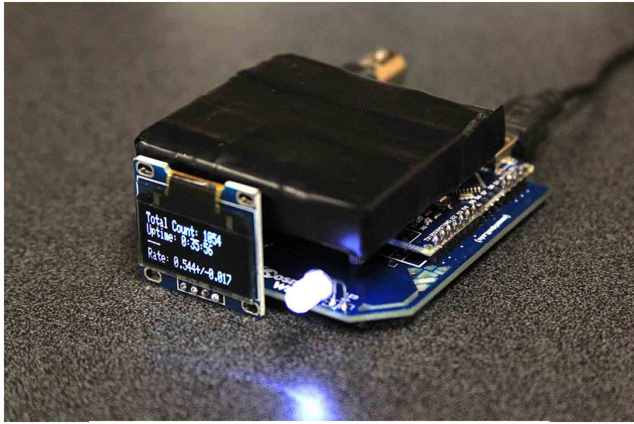
References

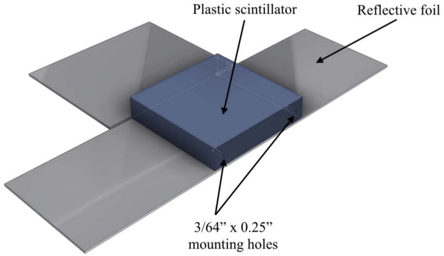
1. Axani, Spencer, and Katarzyna Frankiewicz. CosmicWatch. http://www.cosmicwatch.lns.mit.edu/
2. Groom, Donald E., and S. R. Klein. "Passage of particles through matter." The European Physical Journal C-Particles and Fields 15.1-4 (2000): 163-173.
3. Morishima, Kunihiro, et al. "Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons." Nature552.7685 (2017): 386-390.
4. M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).
5. Reyna, D. "A simple parameterization of the cosmic-ray muon momentum spectra at the surface as a function of zenith angle." arXiv preprint hep-ph/0604145 (2006).
6. Tioukov, Valeri, et al. "First muography of Stromboli volcano." Scientific reports 9.1 (2019): 1-11.
7. Papaioannou, Athanasios. "Cosmic Rays – Messengers from Space." Solar-Terrestrial Sciences, 19 Mar. 2018, blogs.egu.eu/divisions/st/2018/03/19/cosmic-rays-messengers-from-space/.
8. Moon, Vicki G. "Geotechnical Characteristics of Ignimbrite: A Soft Pyroclastic Rock Type." Engineering Geology, Elsevier, 22 Feb. 2003, www.sciencedirect.com/science/article/abs/pii/001379529390068N.
9. Cosmic Ray Shower: https://home.cern/science/physics/cosmic-rays-particles-outer-space
10. Monte Carlo Example: https://commons.wikimedia.org/wiki/File:Pi_30K.gif
11. ScanPyramids: http://www.scanpyramids.org

Backup Slides

Additional Information About CosmicWatch Detectors

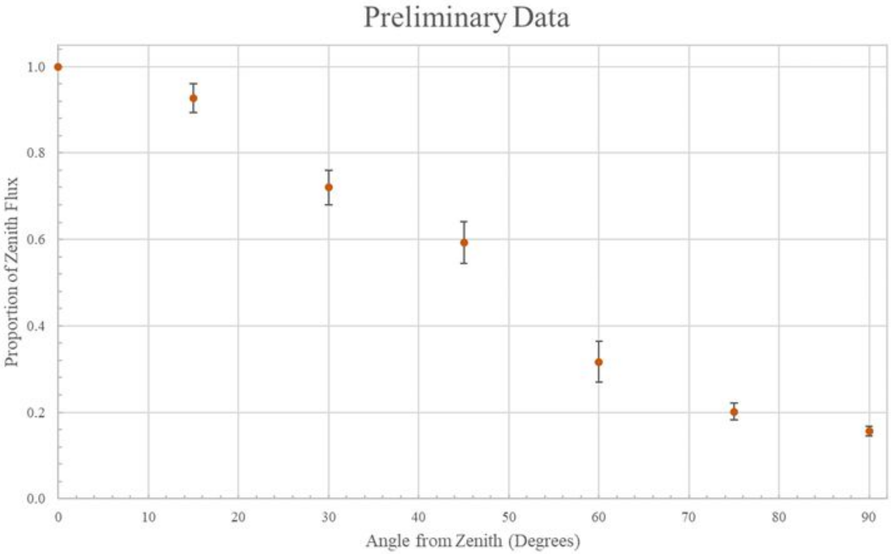
- CosmicWatch project aimed to create a cheap, small, and easily available muon detector.
- Muons deposit 1-3 MeV/cm in the plastic scintillator.
- When scintillators receive this energy, they emit photons.
- These photons are observed by the Silicon Photomultiplier (SiPM).
- When the SiPM detects these photons, it considers it to be a "count."
- In order to ensure that we are seeing muons, we run the detectors in "coincidence mode" - 2 detectors stacked on top of each other.
- A particle has to pass through both detectors within 1 μs to be counted as a "coincidence."



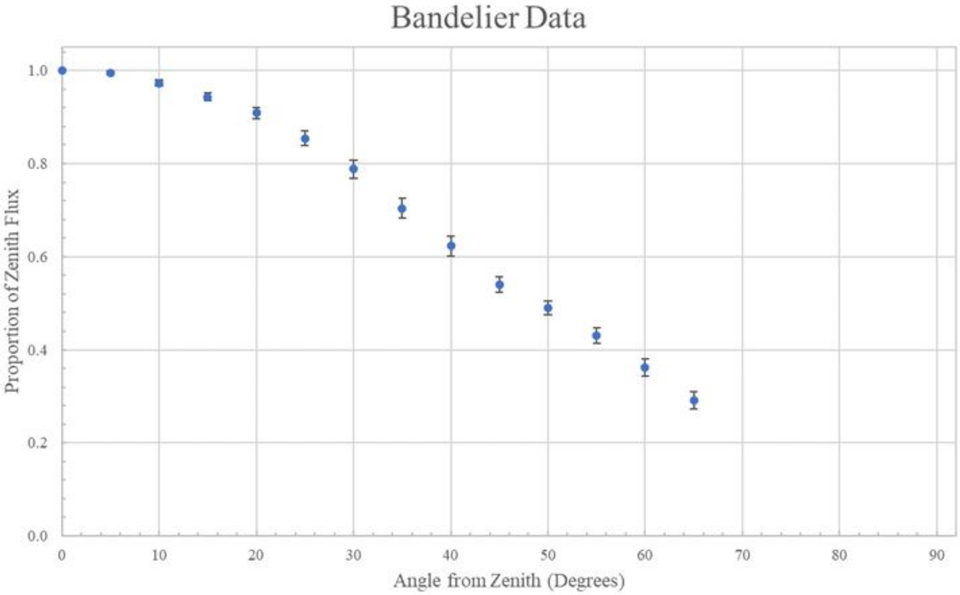


Experimental Data

The preliminary data was collected about 2 months ago. The data was collected with the detectors pointed at open sky, and counts were taken over 24 hours at 15 degree increments.



Counts for the Bandelier data were taken over 48 hours at 5 degree increments.



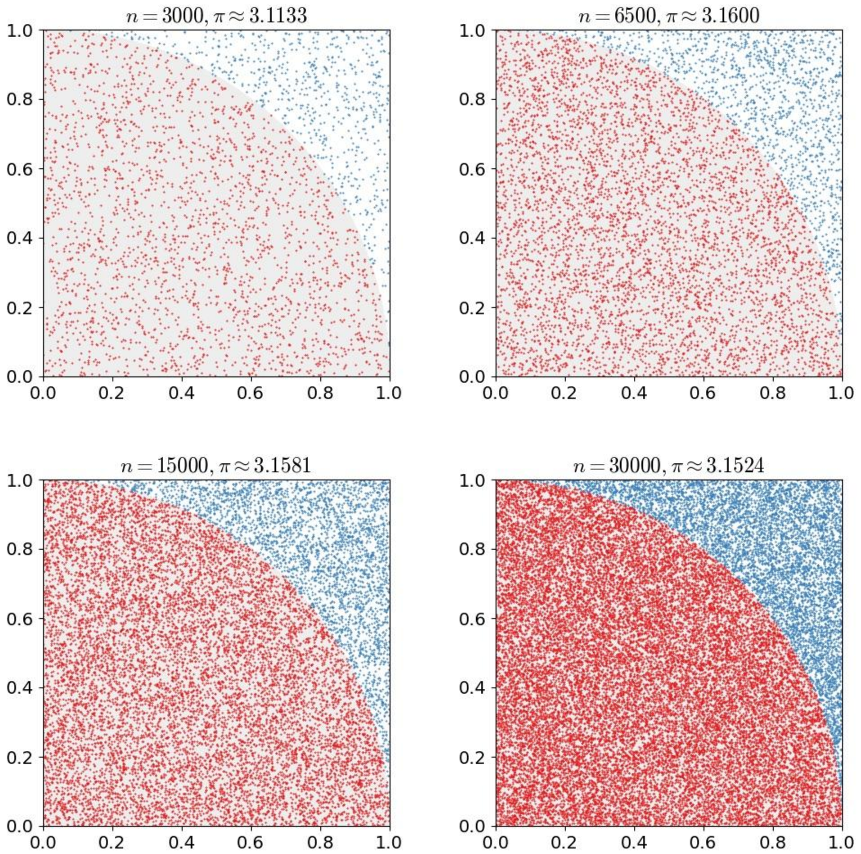
Monte Carlo Method

- Method that repeatedly selects random numbers to solve a certain problem.
- As more and more numbers are selected, the result is more and more accurate.

How do we use Monte Carlo?

- Model the angular spread of the field of view of the detectors.
- Our model randomly selects points on the detectors and calculates the relative muon rate through that particular angle.
- The average rate of all these angles gives the true rate seen by the detector setup.

Example of the Monte Carlo method being used to calculate pi



How Does Increasing Detector Spacing Improve Resolution?

Below is a demonstration of how the field of view of the detector setup becomes more refined as the spacing between the detectors increases. The model uses our current detector dimensions and varies the spacing between the two detectors.