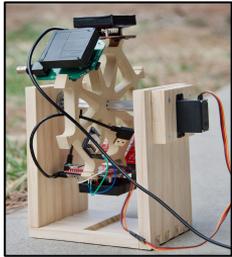
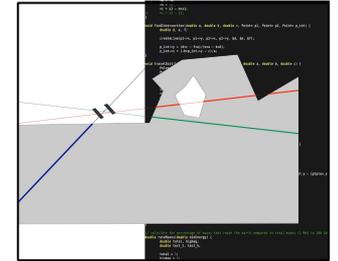


Nondestructive Analysis of Geological Sites Through Muon Transmission Imaging

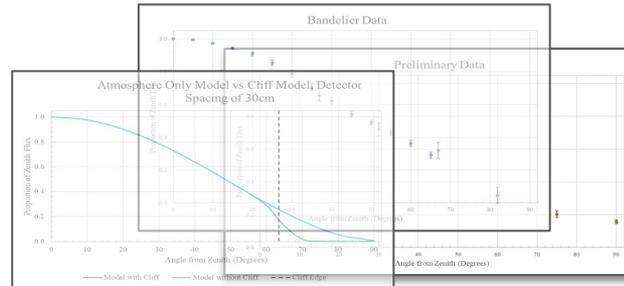
Built Muon Flux Detector



Created Computer Simulation



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



Performed Experiments & Analysis

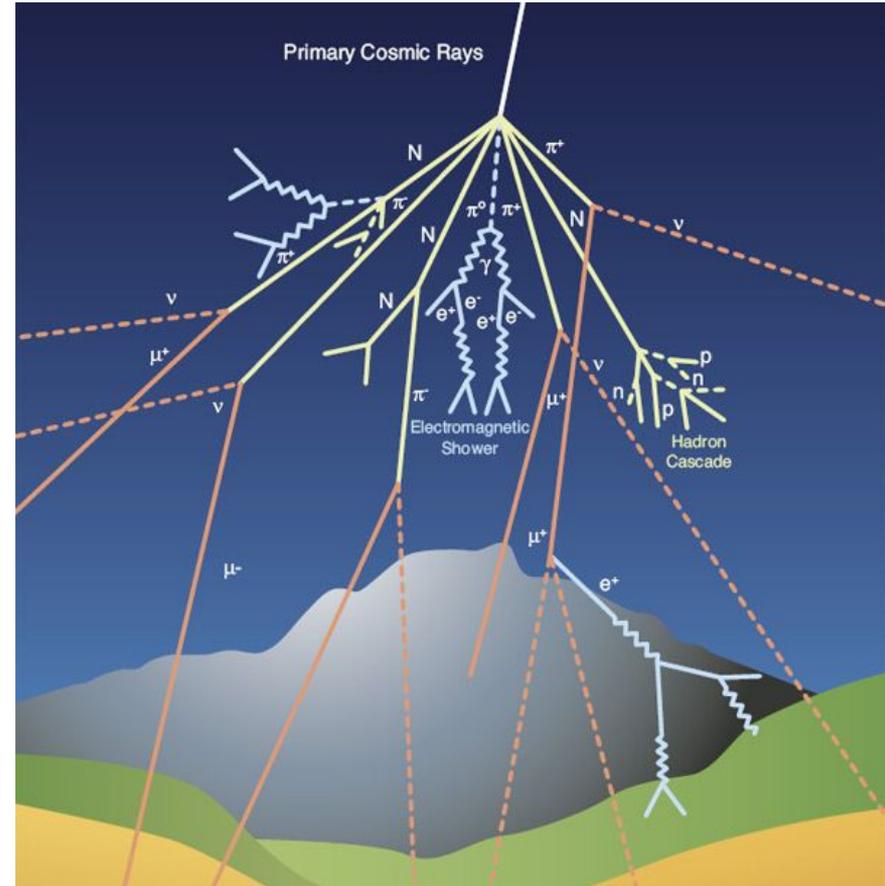
Introduction

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).



Cosmic Ray Shower: <https://home.cern/science/physics/cosmic-rays-particles-outer-space>

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.



Morishima, Kunihiro, et al. "Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons." *Nature* 552.7685 (2017): 386-390.

ScanPyramids: <http://www.scanpyramids.org>

Bandelier National Monument

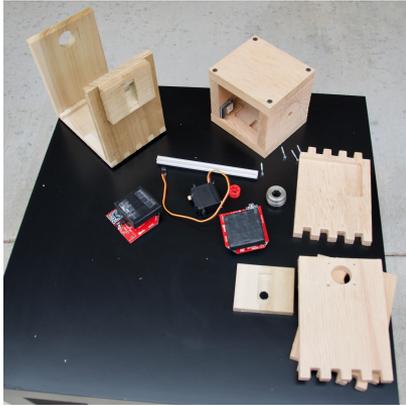


- Cliffs at Bandelier National Monument formed after massive volcano eruptions
- Mostly composed of a type of tuff called ignimbrite.
- Ignimbrite has an average density of 1.57 g/cm^3 .

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

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.

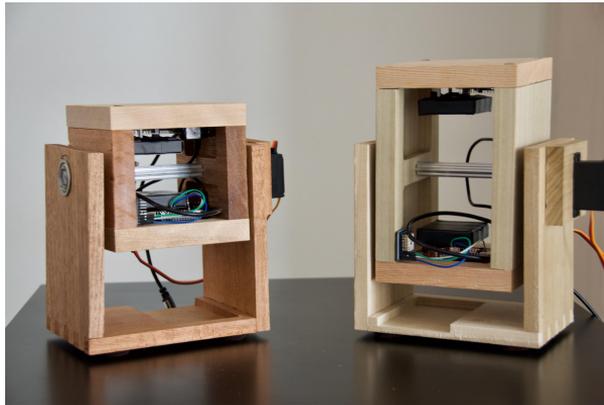
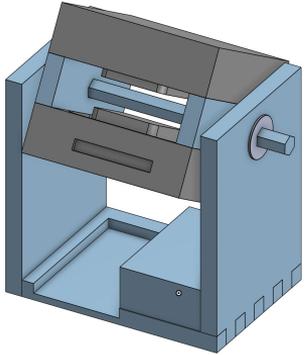
Muon Detectors



- CosmicWatch muon detectors - used before for other projects.
- Used two in coincidence mode to filter out background radiation.
- Needed to build an instrument that can run independently for long periods of time.

What we added:

- Designed in CAD rotating detector enclosure and stand.
- Swerve motor to change the angle of the detectors.
- GPS module for very precise time measurement.
- Major changes to the Arduino code:
 - Use the GPS module to correct Arduino's clock drift.
 - Control for the swerve motor.
 - Automatically change the instrument angle after a certain time



Theory

Energy loss

$$\Delta E = -\frac{dE}{dx} l \rho$$

ΔE is energy loss, $-\frac{dE}{dx}$ is stopping power of MIPs, l is the distance traveled through the material, and ρ is the density of the material

Relative rates of muons

$$rate = \frac{1}{E^e}$$

E is the particle energy and e is Euler's number

Total rate of muons

$$totalrate = \frac{\int_{E_0}^{\infty} \frac{1}{E^e} dE}{\int_{0.01}^{\infty} \frac{1}{E^e} dE} = \left(\frac{E_0}{0.01} \right)^{1-e} GeV$$

E_0 is the minimum energy required to reach the detector and e is Euler's number

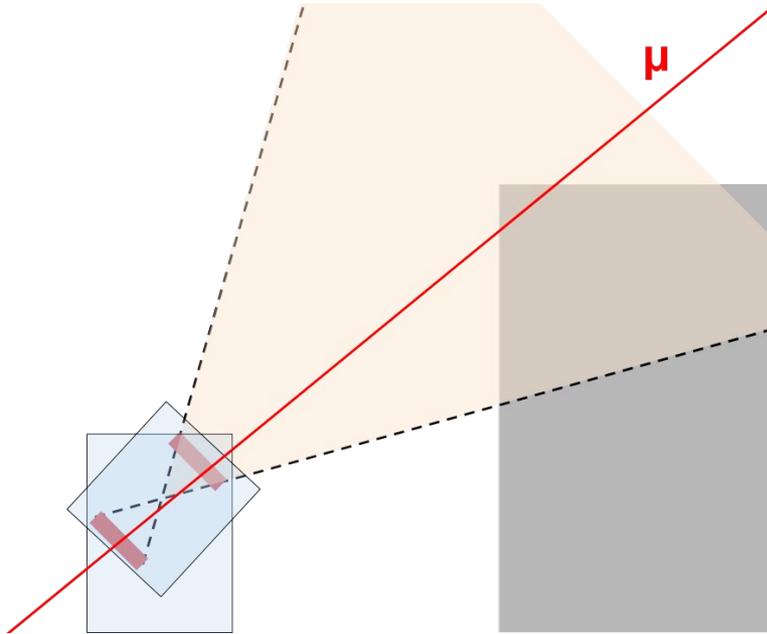
Range of angles seen by the detector

$$range = \theta \pm \arctan \frac{l}{d}$$

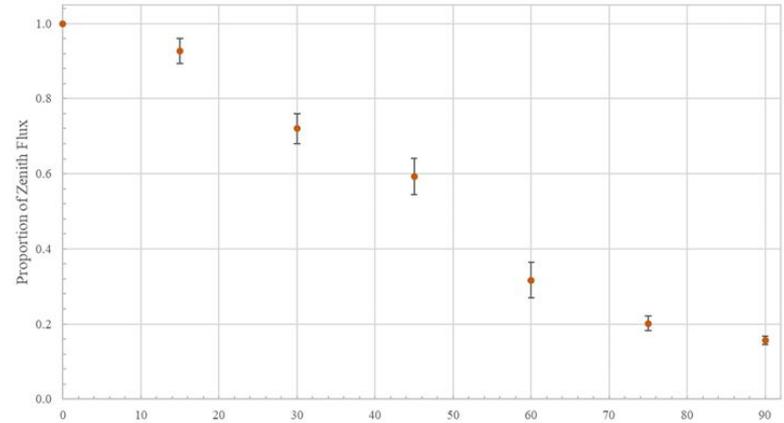
θ is the angle of the instrument, l is the length of the sensor, and d is the distance between the detectors

Experiment

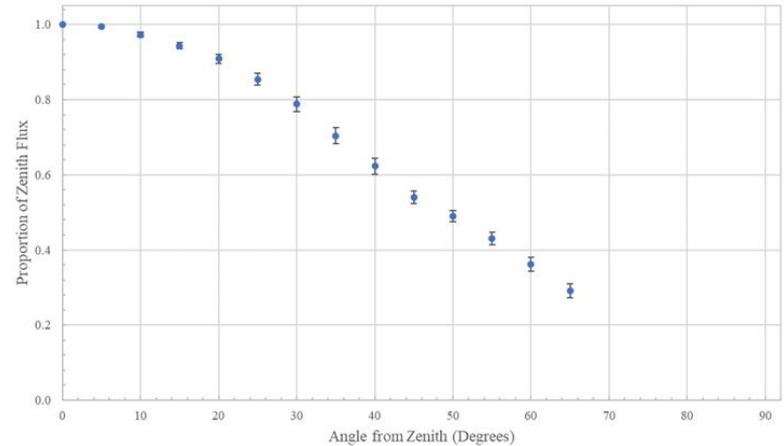
The preliminary data was collected about 2 months ago. The data was collected with the detectors pointed at open sky, and counts were taken over 24 hours at 15 degree increments. Counts for the Bandelier data were taken over 48 hours at 5 degree increments.



Preliminary Data



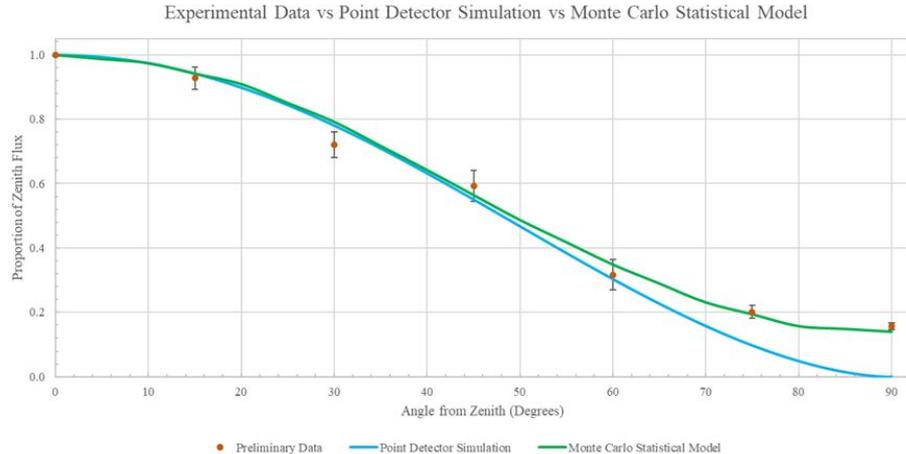
Bandelier Data



Models

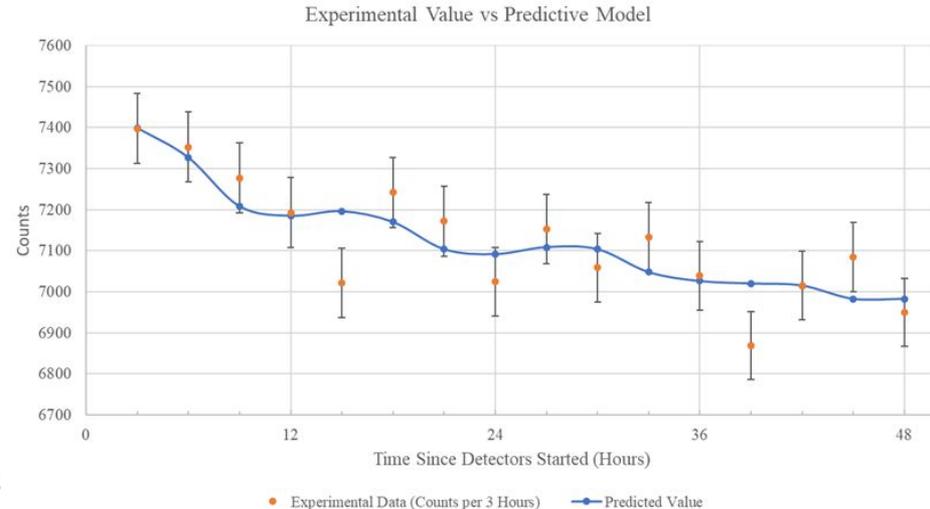
Angle

- 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 $\cos^2\theta$.
- In our computational simulation, we calculate the flux of muons using our energy loss formula.



Air pressure

- Over the course of a day, week, or month, air pressure changes, which may affect muon counts.
- Our model shows that air pressure is generally constant enough to assume that it does not affect our muon counts.



Ray Casting Computer Simulation

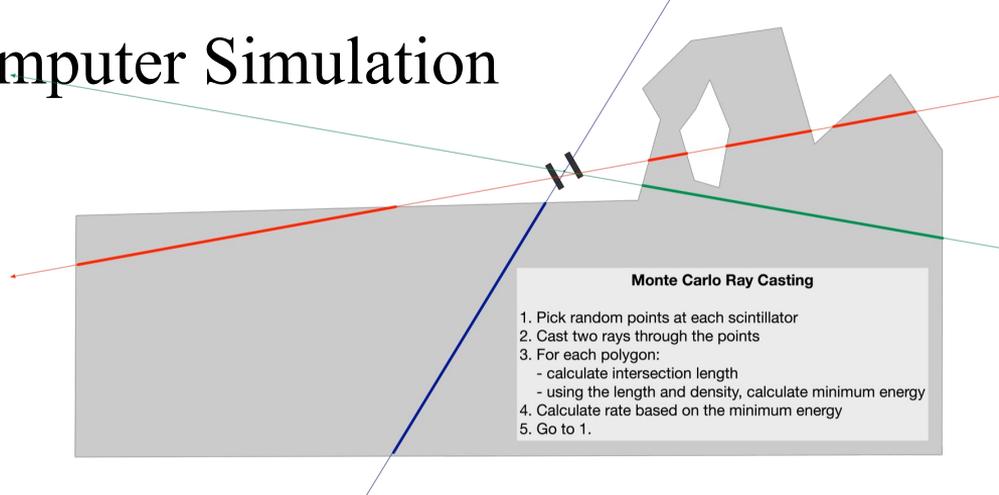
- Ray casting is normally used in image rendering.
- Cast a ray from the camera and track its movement through polygons.

How do we use ray casting?

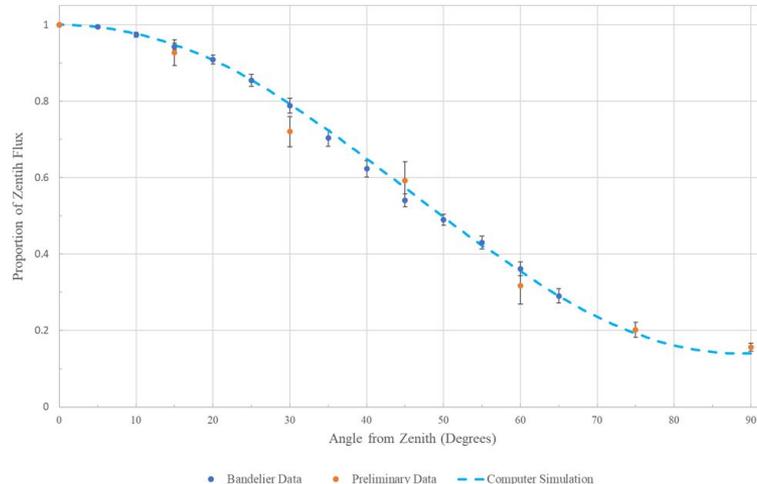
- Find the total distance traveled through a particular polygon.
- Use the energy loss formula for that distance.
- Enables extremely high control over the surroundings of the detector (create any polygons easily).

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 choose random ray passing through both detectors.
- Uses ray casting to determine distance traveled through a polygon and calculate the minimum energy.



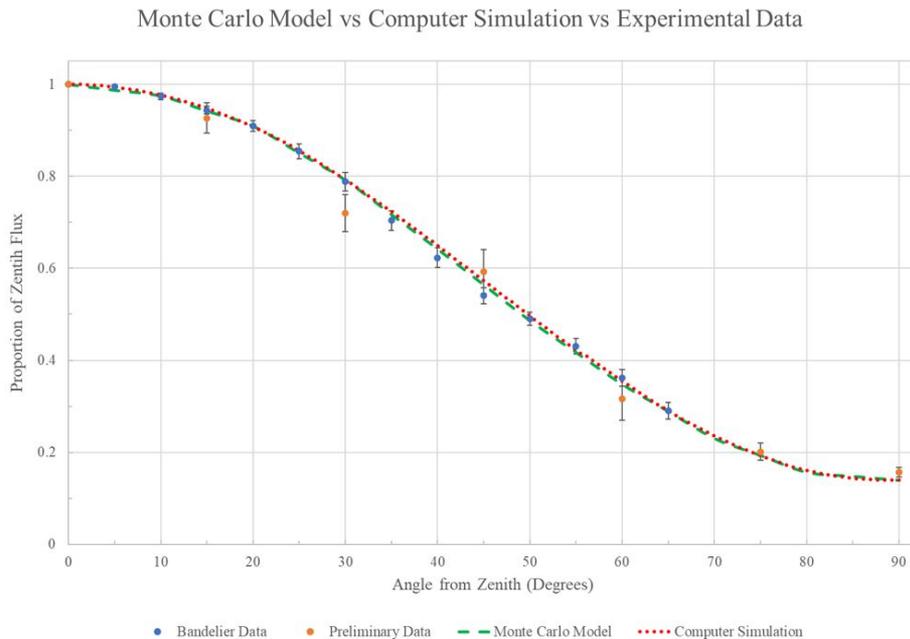
3D Computer Simulation vs Experimental Data



Modeling the Bandelier Data

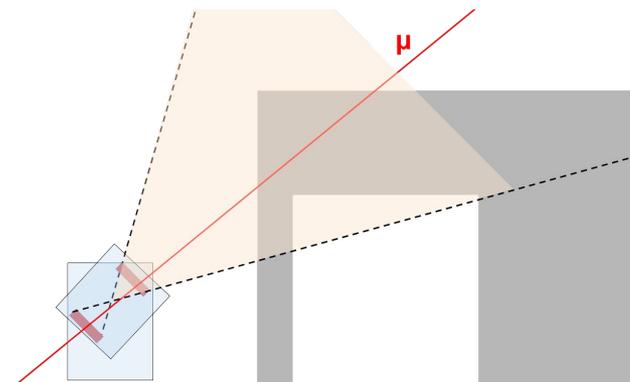
Both the statistical model and the computer simulation use Monte Carlo to take into account the real size of the detectors. Currently, due to the small distance between the detectors, it is difficult to see a significant fall off due to the cliff.

Both of our models accurately follow the experimental data.

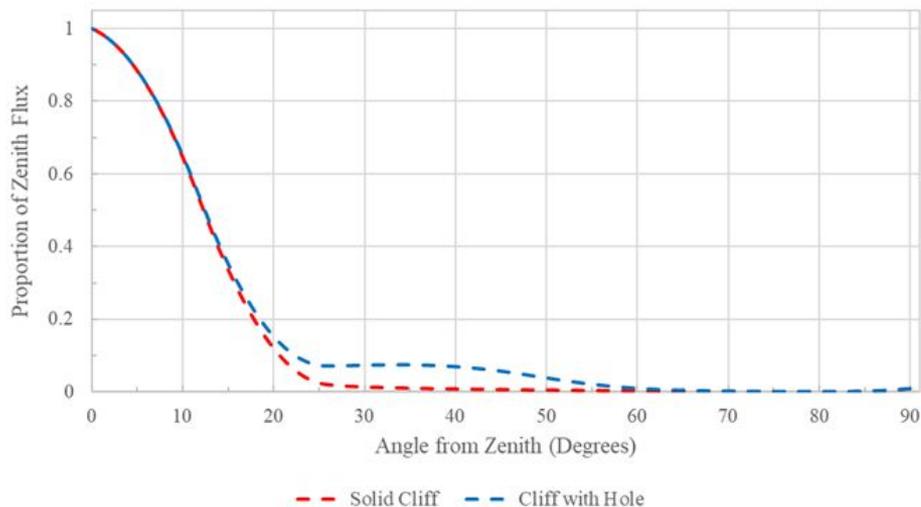


Simulation of a Cliff with a Hole

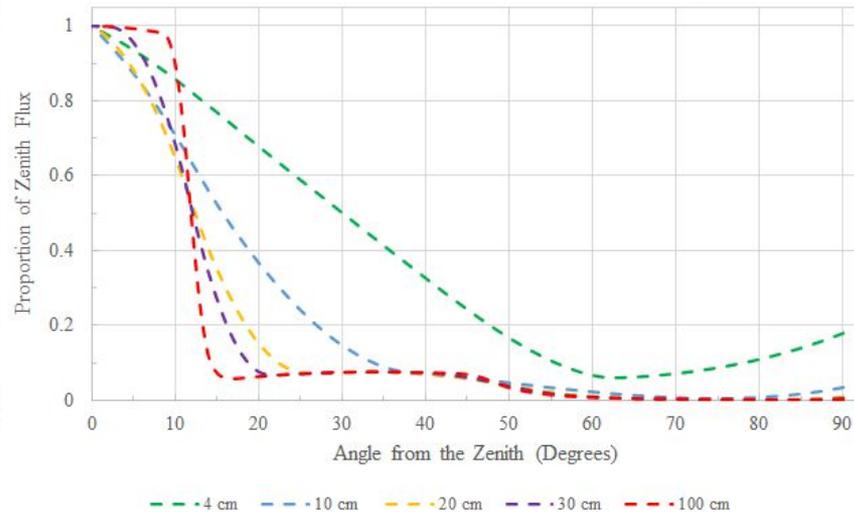
The detectors are 4 cm in size with 20 cm spacing between them.



Solid Cliff vs Cliff with 70x70m Hole



100m Tall Cliff, 70x70m Hole, Variable Detector Spacing



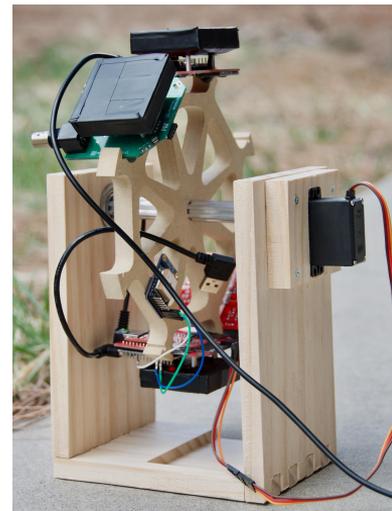
Summary and Conclusion

- Collected data at Bandelier National Monument.
- Created a Monte Carlo statistical model that accurately represented our data from Bandelier.
- Developed a computer simulation uses ray tracing and Monte Carlo that also accurately represented our data from Bandelier.
- Currently taking more data at Bandelier with a new setup that has greater spacing between our detectors.

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

- More angular distribution data
 - Further investigate the effective size of and distance between our detectors.
 - Determine the optimal distance between our detectors.
- 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
- Future steps for the experimental setup
 - Solar power allows us to set up our experiment in more places
 - Better control of temperature
- 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.

We would like to thank our mentor Dr. Matt Durham for his continuous support and patience with this project. We also thank the 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. 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.
2. M. Tanabashi et al. (Particle Data Group), *Phys. Rev. D* 98, 030001 (2018).
3. 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).
4. Tioukov, Valeri, et al. "First muography of Stromboli volcano." *Scientific reports* 9.1 (2019): 1-11.
5. 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/.