Investigation of Cosmic Muons Using Domestic Flights

Vedang Lad, Bryan Sperry*
MIT Department of Physics

(Dated: January 27, 2022)

We stack two CosmicWatch detectors across four domestic flights to measure the coincidence rates of cosmic muons between the detectors. We utilize the CosmicWatch incidence rate to determine the altitude of the plane. To do this, we find the function that relates altitude and coincidence rate and compare it to open-source flight data. The scintillator and a silicon photo-multiplier (SiPM) inside the CosmicWatch record the energy of cosmic muons at various altitudes. For a function of the form Rate[Hz] $= \alpha e^{\beta*(Alt(t-\gamma))} + \delta$ we find values of $\alpha = 0.33 \pm 0.04$, $\beta = 0.26 \pm 0.03$, $\gamma = 322 \pm 41$, $\delta = -0.25 \pm 0.03$.

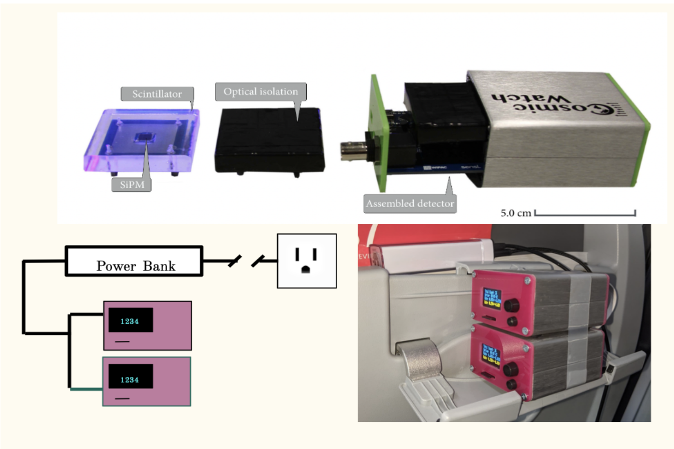

FIG. 1. Pictured at the top, we see the components of the CosmicWatch. When in optical isolation, the released photon in the scintillator is recorded by the SiPM. Pictured on the bottom is the experimental set up on the plane. A back-up power-bank works when the plane outlet fails.

I. INTRODUCTION

Earth's atmosphere is constantly under attack from a flux of particles known as cosmic rays. Relativistic cosmic rays strike a nucleus in the upper atmosphere where the cosmic-ray decays into many particles as seen by 2. We measure the muon by stacking two CosmicWatch detectors as seen in 1.

We place detectors behind seats in the same position across four domestic American Airlines flights. The four flights are divided evenly over two separate days. We extract public flight data from flightaware.com and determine an exponential function that represents the coincidence rate of cosmic particles. We then utilize this exponential function of flight data to see how well the function describes the collected CosmicWatch data. We lastly use the SiPM to see how the altitude of the energy of recorded particles changes with the maximum altitude of the flight.

* vedlad@mit.edu; http://web.mit.edu/8.13/

II. THEORETICAL REMARKS

II.1. Origins of Cosmic Particles

Comic particles are accelerated from inside and out of our solar system by large cosmic events such as supernovas and pulsars. The maximum energy of cosmic particles is limited due to interactions with the cosmic microwave background (CMB). This is known as the Greisen–Zatsepin–Kuzmin (GZK) limit [1]. Once cosmic rays enter the atmosphere they begin to decay into the various particles we see in 2. 74% of these particles are ionized hydrogen, 18% from helium nuclei and the remaining 8% are from trace amounts of heavier elements [1]. Cosmic muons are known to have an inverse relationship with pressure as described by the equation

$$\frac{\Delta I}{I} = \beta \Delta P \tag{1}$$

Where I represents cosmic-ray muon intensity, ΔP is the measured atmospheric pressure compared to the average pressure, and β is the barometric coefficient. This inverse relationship between intensity and pressure is why we expect a higher altitude to correspond to more cosmic muons since atmospheric pressure decreases with altitude.

II.2. CosmicWatch Physics

Physicists have designed many different types of detectors to measure cosmic particles, most notably IceCube and the Super-Kamiokande for neutrinos [1]. For our muons, we utilize CosmicWatch, produced by MIT postdoc Spencer Axani [1].

As seen in 1, we see three main components. The scintillator when struck by a muon, releases a photon due to excitation. The energy of this photon is recorded by independent cells on the SiPM. This is housed in an optical isolation chamber alongside Arduino boards which handle the storage of data and power control. The use of two detectors removes background radiation and recorded muons must strike both detectors within 3 μs to be registered as a muon. The detector records the tem-

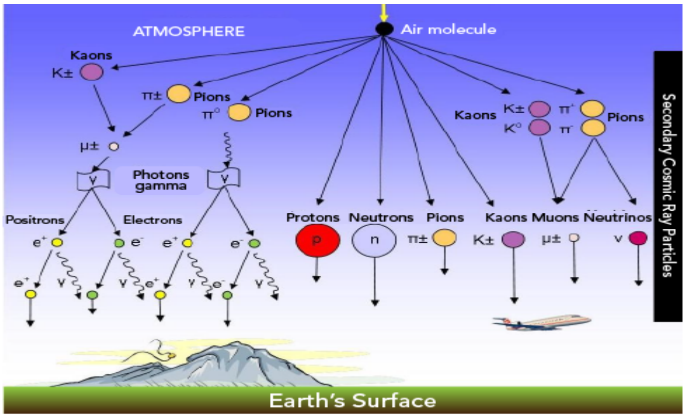

FIG. 2. When the cosmic ray first strikes a nucleus in the upper atmosphere, it will decay it many possible particles. Notice that this occurs above the plane, known as the primary cosmic interaction region. We investigate just the muon for this experiment.

American Airlines Flights

Flight Number, Date and Time	Max Altitude (km)	Duration (secs)
653 11/18 9:45 am	10.97 ±0.88	7250±580
5326 11/18 1:21 pm	7.92±0.63	3438±275
4917 11/21 6:21 am	10.67±0.85	3668±293
2152 11/21 9:00 am	9.46±0.76	3995±319

Flight data is extracted from FlightAware.com

FIG. 4. A table with data taken from flightaware.com shows how all four flights differ from one another. Uncertainties are obtained from the fact that sensors on the plane have up to an 8% uncertainty in measurement.

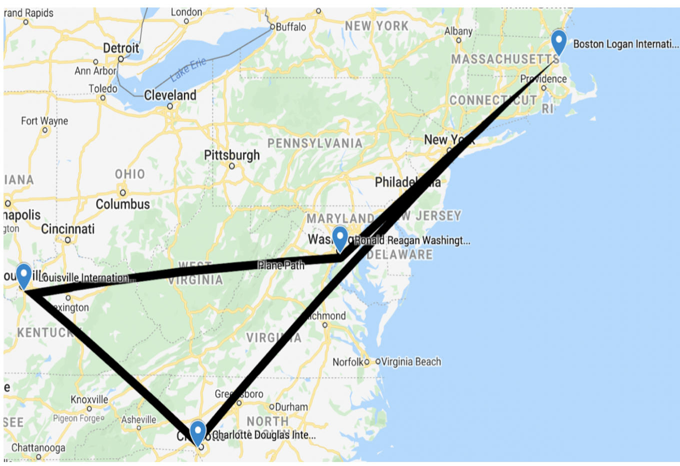

FIG. 3. We see the map of the four flights taken starting and ending back at Logan International Airport in Boston, MA. The first two paths of the flight happen on the same day, while the last two flight happen 3 days later.

perature, pressure, coincident hits, non-coincident hits, all with timestamps.

III. EXPERIMENTAL ARRANGEMENT

The two ComicWatch detectors are placed behind the seat as pictured in 1. This is done across four flights, which are of different duration and altitudes. All data is recorded between plane row 18 and row 22. Flight data taken from flightaware.com can be seen in 4. We start to record before take-off and continue after the plane has landed to best determine the function which describes count rate and altitude. The path taken from all of the planes is different, however, there is a close overlap between the first half of flight 1 and flight 4 as seen in the map 3. While they are on different days, both flights are recorded at around the same time of day. All data collected is uninterrupted.

IV. DATA AND ANALYSIS

IV.1. Flight Altitude and Coincidence Rate

As seen in 6, there is a qualitative relationship between the coincidence rate and the altitude of the aircraft. In the first plot, we present all counts and the coincident count. While all counts seem to be around 4-5 times that of the coincident counts, we attribute this factor due to background radiation present at higher altitudes. This is also supported by the presence of lower energy as seen in 8. This is different from the factor seen at sea level, which is a factor of about 25. This may be a result of more cosmic muons and/or fewer radioactive backgrounds higher in the atmosphere. Without comparison to ground-level data, there is no way to determine which of the two causes a smaller factor. We utilize coincident data for all remaining data analysis.

First, we obtain an uncertainty on the counts by utilizing the number of counts and the dead time of the detector. We bin recorded counts at 60 second intervals, taking uncertainty as the square root of the value of the bin where the mean value forms a data point. Note that plots shown in 6 are artificially stitched back to back for presentation. To connect flight altitude and coincidence relate we use the function

$$\text{Rate[Hz]} = \alpha e^{\beta * (\text{Alt}(t-\gamma))} + \delta \tag{2}$$

where $\alpha, \beta, \gamma, \delta$ are fit parameters and Alt represents the flight altitude data. Since exact take-off and landing

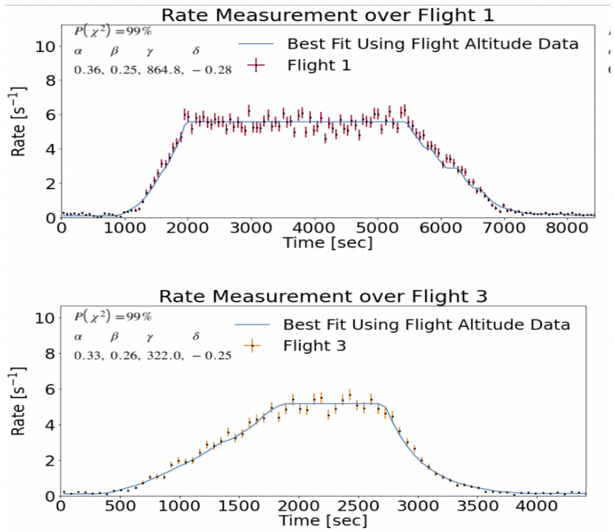

FIG. 5. The fit of only flights 1 and 3 are shown above, where the remaining fits are qualitatively similar. The steady elevation of the plane at high altitudes still results in random fluctuations about the altitude line.

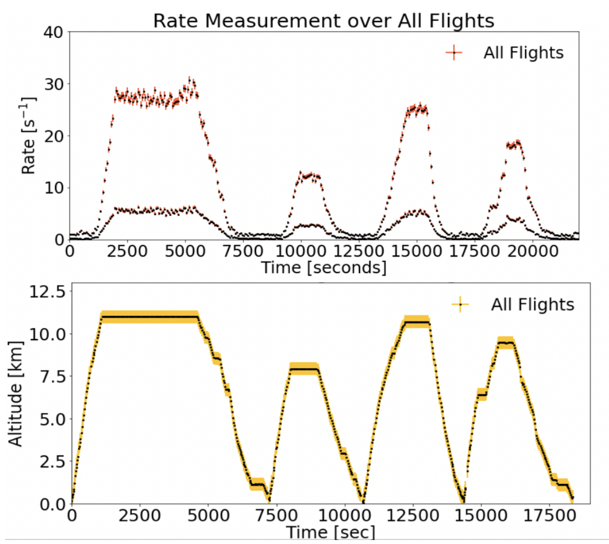

FIG. 6. Top we see the data collected on the CosmicWatch. The larger graph represents all counts while the smaller one only represents coincident counts. This suggests the importance of using two detectors. The flight altitude data is qualitatively similar to the recorded counts. The four flights are artificially stitched together for presentation

times are not recorded, we allow for the γ factor to determine the exact takeoff and landing time. The fit for all four flights results in a P(χ^2)= 99%. The fit parameters are as noted on 5 and are utilized to check how well it represents the collected data.

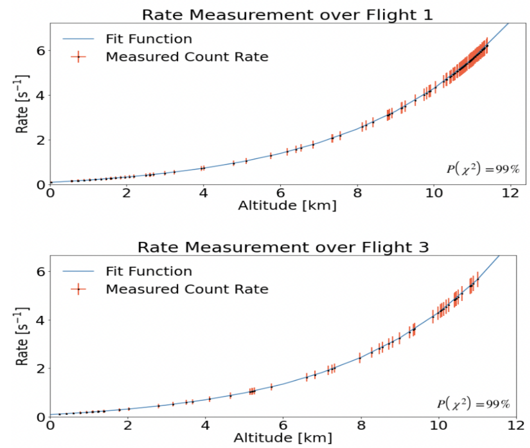

FIG. 7. With a P(χ^2)= 99%, the function represents the data points well seen by the exponential relationship seen as we increase altitude. Note that at higher altitudes, this exponential relationship will not hold due to the Primary Cosmic Ray Interaction Region.

IV.2. Correctness of Function

We determine the correctness of our function by using the fit parameters from equation 2. We set the cosmic data equal to the equation 2 and solve for the altitude. This is seen in 7, where the blue line represents the fit equation and the data points with red error bars represent CosmicWatch data. We propagate error bars in the same way they were done in figure 6, using detector dead-time and binning.

It is important to note that the exponential relationship will not exist past 10 km as plotted, due to the Primary Cosmic Ray Interaction Region [1]. This is the region in which the muons first strike a nucleus and begin to decay.

IV.3. Energy Analysis

We use recorded SiPM data from the CosmicWatch to analyze muons from a different perspective. As seen in figure 8, we plot the energy spectrum of counts across all of the flights. There is a large domination background radiation, seen by the first part peak since it peaks before 50 mV [1] The second peak we see higher energies, around 400 mV. Both peaks likely contain background radiation and muons based on known energy values [1], however, there is no definitive way to discern the two from the data. Regardless of the energy, the vertical ordering of the flights remains uniform. This order is identical to the maximum altitude of the flights as seen in 4. Furthermore, the highest energy counts come from flight one which flew at the highest altitude. This is seen by the rightmost orange strip in the graph. Both the ordering of the flights and the energy of the flights sup-

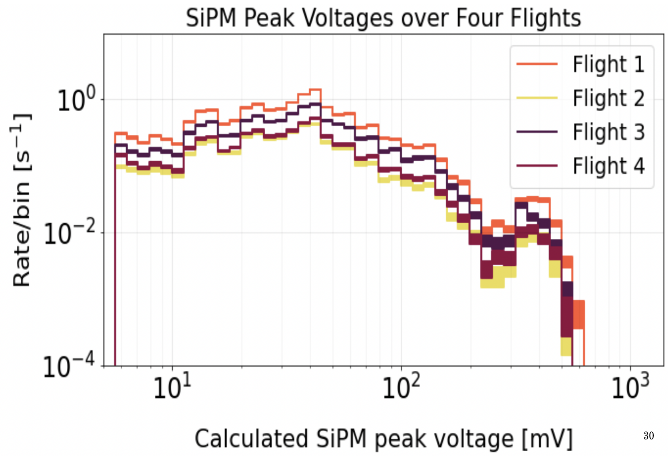

FIG. 8. Shown above are the calculated SiPM peak voltages for all of the data collected. Notice that regardless of the voltage, the order remains identical to the order of maximum altitude across the flights. Also note that the highest flight (1), in orange, also records the greatest voltage.

port the strong correlation between flight altitude and the presence of cosmic muons. Data presented is binned at 60-second intervals for the entire flight.

IV.4. Uncertainties

The two largest uncertainties are likely attributed to the Latitude Effect and atmospheric variations across the flights. The Latitude Effect [1] states that earth's magnetic field behaves like a dipole magnet and therefore is uniform across latitudes.

This is best illustrated by flight 3, which runs horizontally from Louisville, KY to Washington DC as seen in 3. For this reason, we present our third flight as the most reliable fit parameters across all of the flights.

We determine the uncertainty of 5% by measuring deviations of cosmic muon rate when the plane is at constant altitude in 5. The largest variation resulted in a little less than 5% deviation in fit parameters. The second uncertainty arises due to atmospheric variation across all of the flights. Since all flights have different routes, different times, and different altitudes, this introduces various non-random variables. Many of these variables are temperature and pressure.

We determine the uncertainty of 5% by measuring deviations in atmospheric pressure across various points along the flight path. The largest deviation was about 5% along with the points of the flight. In total, we see about a 10% attributed to uncertainty in the measurement.

V. SUMMARY

Characterized by the exponential relationship in 7, the CosmicWatch determines the altitude of the flight with relatively high accuracy. While there are natural deviations in the data due to atmospheric variations we motivate flight 3 as the best fit since it flies at a constant latitude, and therefore a constant magnetic field. Factoring in all uncertainties, including those statistically and systematically propagated we find that Rate[Hz] $= \alpha e^{\beta*(Alt(t-\gamma))} + \delta$ we find values of $\alpha = 0.33 \pm 0.04$, $\beta = 0.26 \pm 0.03$, $\gamma = 322 \pm 41$, $\delta = -0.25 \pm 0.03$. Further experimentation may possibly utilize multiple flights traveling the same horizontal flight path in order to filter out atmospheric effects.

ACKNOWLEDGMENTS

We gratefully acknowledge the help of Andres Reyna, Xiaowei Ou, Professor Paus for generously. We thank the flight attendant on AA flight 2152 who trusted my explanation of the suspicious object behind my seat.

[1] Axani, S. N. (2019). The physics behind the cosmicwatch desktop muon detectors. arXiv preprint arXiv:1908.00146.www/JLExperiments/JLExp51.pdf

[2] P. Bevington and D. Robinson, Data Reduction and Error Analysis for the Physical Sciences (McGraw-Hill, 2003).