Astron 98 Final Project: Muon Detection

Overview

My project will be on detecting muons, specifically using data from the muon detectors that are detailed in the resources in references. My project will be a redesign of one of the projects outlined in the "Example measurements" part of the paper. There is a linear correspondence between the rate at which the detector catches muons and atmospheric pressure where the detector is located, due to the fact that a cosmic muon requires more energy and has a higher likelihood of decaying when trying to get to a high pressure location. There is a negative linear correlation between detection rate and atmospheric pressure, given by the equation,

$$\frac{\Delta I}{\bar{I}} = \beta \Delta P,$$

where I represents the cosmic ray muon intensity, ΔI represents the difference in intensity from the average, and ΔP represents the pressure difference between the average and current pressure (mbar). B, the barometric coefficient, therefore represents the percent change in muon intensity from the average, per unit change in pressure. Intensity/flux is calculated in the number of muons that flow through a given material per minute per centimeter squared, and plotting the percentage difference of flux from the average against the pressure difference gives us a linear correlation, where B is in units of (% / mbar). B should be negative, as higher pressures increase the likelihood of muons decaying into an electron before reaching the surface.

Generate Test Data

There was no real way to generate random test data as there was some correlation between pressure and these measurements and it wasn't easy to generate it randomly without also connecting it to some sort of random pressure distribution.

There were two datasets used, one was the muon detection and the other was the pressure distribution over that same time interval.

The muon dataset looks like this:

	Date	Layer12	Layer13	Layer23
0	2022-06-24 03:00:00+00:00	19564	10121	20360
1	2022-06-24 04:00:00+00:00	19499	10149	20460
2	2022-06-24 05:00:00+00:00	19230	9870	20169
3	2022-06-24 06:00:00+00:00	19763	10296	20388
4	2022-06-24 07:00:00+00:00	19555	10161	20375

where each row contains the amount of muon instances that occurred that hour for each layer (explained in next section) and the date and time which it occurred.

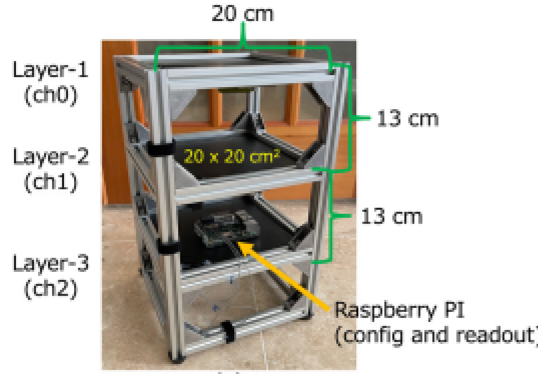
The pressure dataset looks like this:

	station	time	mslp
0	CQT	6/24/2022 3:47	1010.6
1	CQT	6/24/2022 4:47	1010.9
2	CQT	6/24/2022 5:47	1010.9
3	CQT	6/24/2022 6:47	1011.3
4	CQT	6/24/2022 7:47	1011.3

Where each row contains the date, hour, and pressure of the region. Note that the pressure measurements themselves are also normalized, as they measure the mean sea-level pressure over the time period, not the pressure at the actual location of the weather station. This may have a minor impact on our data, but because we only care about pressure deviations this shouldn't matter too much. Muon detectors were located at the Mount Wilson Observatory in California and pressure data was taken from a weather station in downtown Los Angeles.

Data Quality and Reduction

No data filtering was necessary because the detector was already running a program called coincidence mode, which only saves the muon instance when 2 of the 3 detectors trigger within a small time frame, ensuring that most of the recorded instances are muons and not some external noise that happens to trigger one of the detectors. This is why there are 3 measurements for the muon detectors, one for instances that triggered layers 1 and 2 (Layer 12), layers 1 and 3 (Layer13), etc. Note that each of these measurements should be considered to be separate data, as the distance between the layers affects how often they trigger. This is why Layer13 has significantly lower counts per hour, as the distance between layers 1 and 3 on the detector are greater than the distance between either layers 1 and 2 or layers 2 and 3. For reference, here is an image of the physical detector that was used:

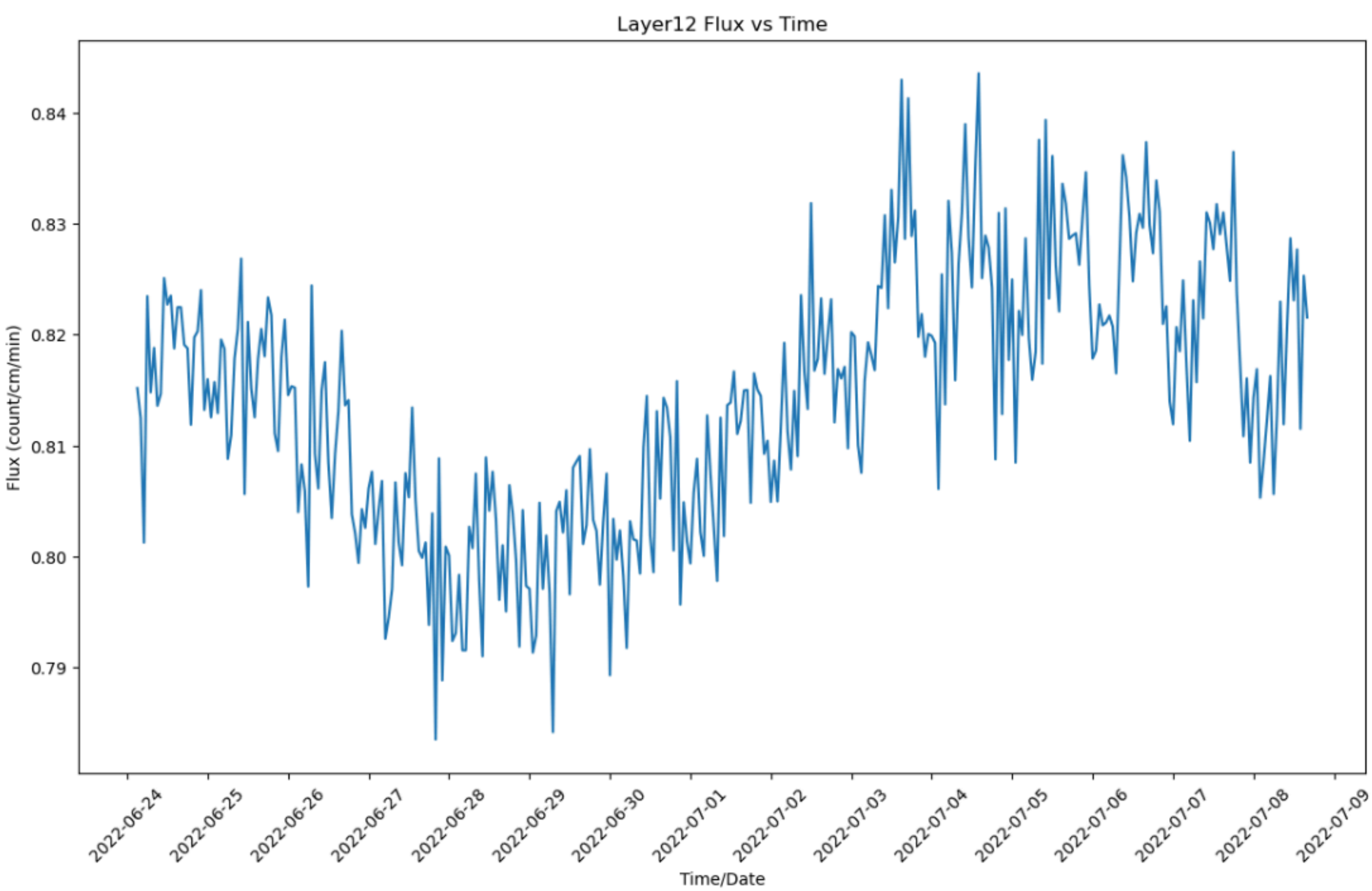


(a)

Model Fitting & The Process

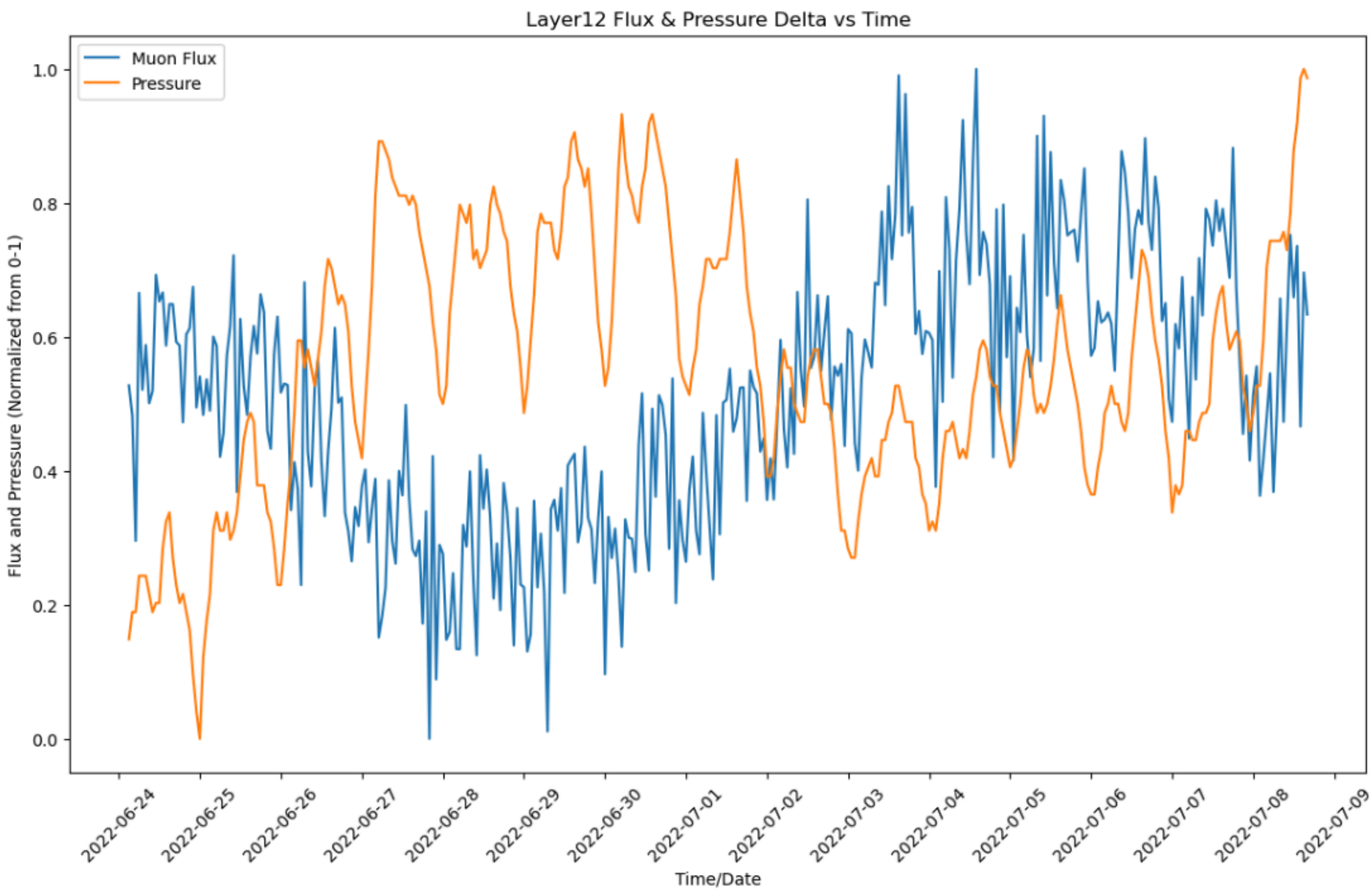
The thing that took the most time out of the entire project was just merging the two datasets together to make sure that I had the right pressure measurement for every muon instance. This required the use of the datetime package to help convert dates into a format pandas can read in a dataframe, and for actual plotting, the matplotlib.dates function to recognize when we crossed into the next day so we can denote those as ticks on the x-axis.

First thing we did was convert the muon counts to flux measurements and compare our flux to the average, which is about 1 muon per cm^2 per minute. We can solve for this by converting to counts per minute and dividing by the surface area of the detector, which is given to us from the physical diagram as 20cm x 20cm, or 400 cm^2. Plotting this on it's own graph:



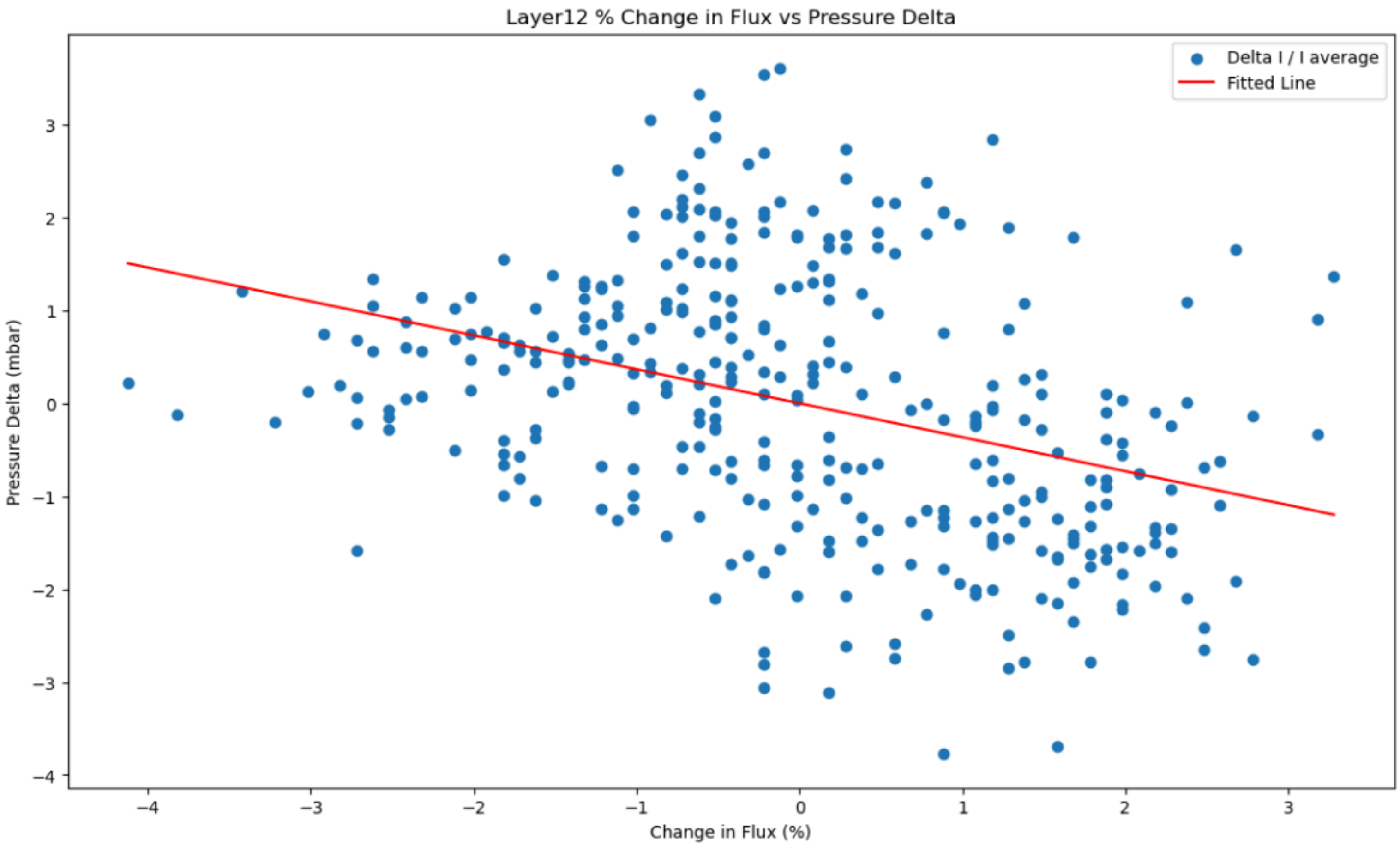
This shows that the flux rate for Layer12 hovered around 0.8. This was the same for Layer23, while Layer13 hovered around 0.45. This makes sense for the same reason as before, increasing distance between the layers reduces the likelihood of a muon triggering both, lowering the count rate and the intensity proportionally.

We can see that there is some sort of trend going on here, and it's much more visible once we plot this and the pressure deviations on the same graph. Computing the pressure delta, first by computing the average pressure and then subtracting it from the mslp column, we get a pressure deviation that ranges between -10 mbar and 10 mbar. Using the MinMaxScaler function to plot the normalized muon flux and pressure delta values so that they are proportional to each other, we get a graph that looks like this:



Now we can see more clearly that there is a negative correlation between this pressure delta and muon flux.

Finally, to quantify this negative correlation by solving for the barometric coefficient, we first compute the percentage difference from the average muon flux at every point. Subtracting the average flux from the flux column to get a flux delta, dividing the flux delta column by the average flux, and multiplying by 100, we get a signed percentage that represents the percentage difference from the average flux, denoted by the %Change column. Plotting this against the pressure delta column and doing a linear regression, we get graphs that look like this:



where the slope of the line is the barometric coefficient, B (% / mbar). Doing this for all 3 layers, we get these results:

	Coefficient	Error
Layer12	-0.365307	0.002515
Layer13	-0.407395	0.002841
Layer23	-0.354104	0.001963

Results

First to note is that the barometric coefficient derived from Layer13 is very similar to the coefficient derived from Layers 12 and 23, even though the count rates for Layer13 were drastically different. This shows that it is somewhat of an applicable constant, however in practice this constant varies based on location. Our barometric coefficients are similar in magnitude to other studies, which range from -0.114%/mbar to -0.18%/mbar (Berkova et al., 2011; De Mendonça et al., 2013; Dmitrieva et al., 2013), but are noticeably larger. This could be due to a variety of factors, first being that the pressure measurements weren't pulled directly from the detectors location, but a weather station nearby. Also, because the detector was at a higher altitude, it experienced much more pressure variations than the ground surface where other studies occurred. There is also evidence that this varies based on season, and in order to account for this we would have to have taken data over an entire year, which we didn't do. Finally, there is a correlation between muon flux and temperature, which was not accounted for, and the detector's location being higher altitude and colder may have affected the experimental barometric coefficient.

References:

- Muon Flux Variations Measured by Low-Cost Portable Cosmic Ray Detectors and Their Correlation With Space Weather Activity
    - Data was taken from this study