Cosmic Ray Muon Detector Array Program

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Abstract

When a single cosmic ray proton hits earth's atmosphere millions of subatomic particles such as charged muons are created; when these particles pass through 2 or more detectors in a very short time (~100 ns) this is known as a coincidence. The average number of muon coincidences per m^2 of the detector, per minute, per steradian, is measured and is known as cosmic ray flux. To calculate the flux over time a computer program was created in Python and measurements are shown versus atmospheric pressure and solar flare activity. A mathematical calculation is used to reconstruct the cosmic ray collision point in the atmosphere by simulating 5 detector hits at different schools. Noise rates are estimated and compared to expected cosmic ray shower rates. Small Raspberry Pi single board processing computers have been added to our detectors replacing large personal computers for control and data acquisition. DropBox has been implemented as the data transfer service. Reflectivity tests of different detector wrapping materials have been conducted.

Cosmic ray collision point reconstruction

To determine the position and time vector (x_0,y_0,z_0,t_0) of the collision point, we need 4 linearly independent equations where each is obtained using a different detector. To linearize these equations we use a 5th detector:

$$(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 = (ct_i - ct_0)^2 \qquad i=1,2,3,4,5$$

Using one each equation from each detector 2,3,4,5 to subtract equation 1, for example:

$$xi^2 - x1^2 - 2(xi - x1)x0 + yi^2 - y1^2 - 2(yi - y1)y0 + zi^2 - z0^2 - 2(zi - z1)z0 = (cti)^2 - (ct1)^2 - 2(cti - ct1)ct0$$

Rewrite it as the linear equation about (x0,y0,z0,t0)

$$2(xi - x1)x0 + 2(yi - y1)y0 + 2(zi - z1)z0 - 2(cti - ct1)ct0 = xi^2 - x1^2 + yi^2 - y1^2 + zi^2 - z1^2 - (cti)^2 + (ct1)^2$$

We get the matrix equation:

$$\mathrm{A.Transpose}[x0, y0, z0, ct0] = r$$

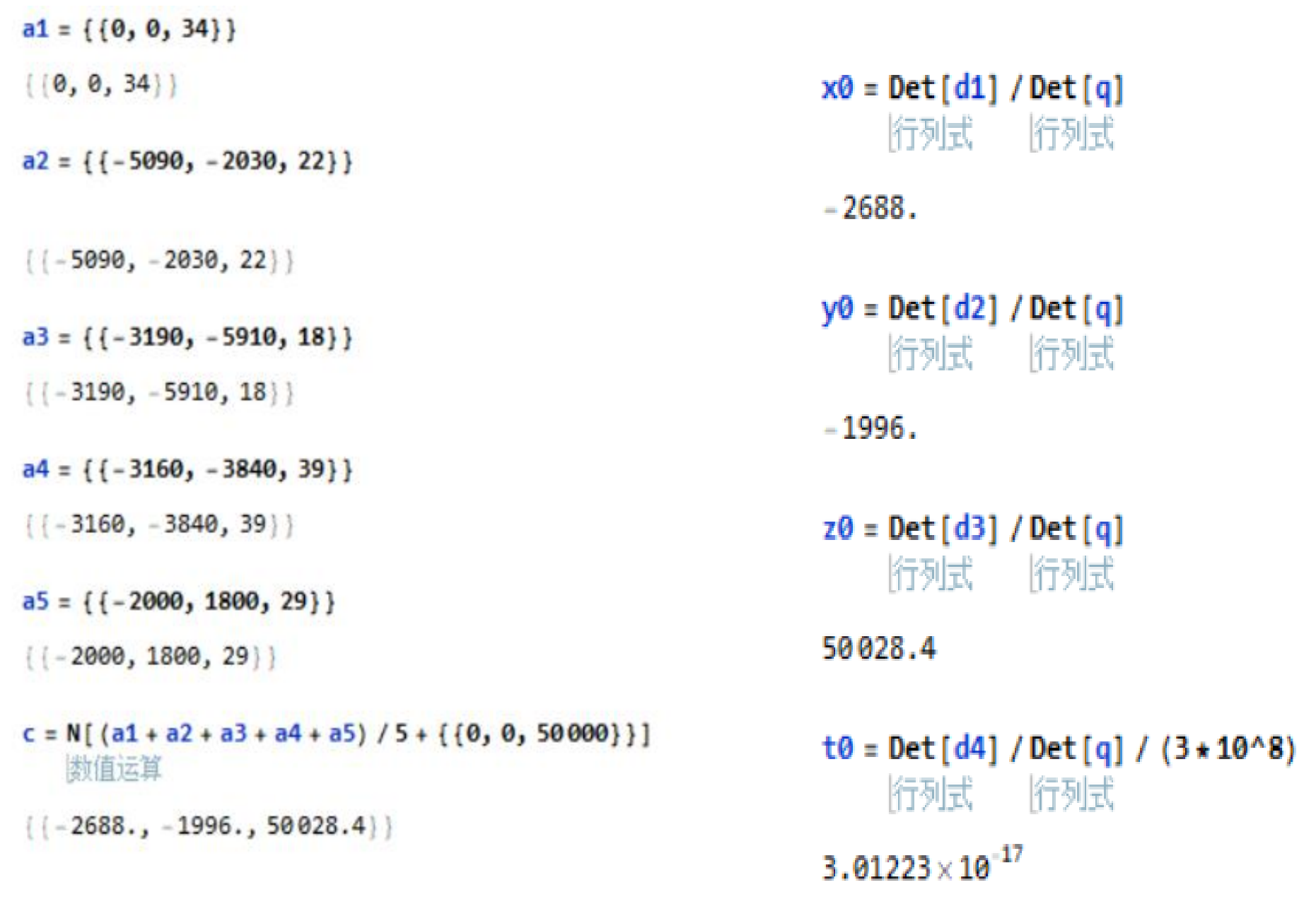
So,

$$x0 = \frac{\det(A1)}{\det(A)}, y0 = \frac{\det(A2)}{\det(A)}, z0 = \frac{\det(A3)}{\det(A)}, ct0 = \frac{\det(A4)}{\det(A)}$$

Where r replaces the ith column of matrix A producing Ai.

Where Ai is the matrix
Here is an example using locations of 5 detectors:
Location (in meters):
1, QCC (0, 0, 34)
2, Queens College (-5090,-2030,22)
3, York College (-3190,-5910,18)
4, St. John's College (-3160,-3840,39)
5, Bayside H.S (-2000,1800, 29)
Result: Collision point happens 50 km above a point central to the detector array.

Mathematica was used to simulate cosmic ray collision points in earth's atmosphere:



```
a1 = {{0, 0, 34}}
{{0, 0, 34}}
a2 = {{-5090, -2030, 22}}
{{-5090, -2030, 22}}
a3 = {{-3190, -5910, 18}}
{{-3190, -5910, 18}}
a4 = {{-3160, -3840, 39}}
{{-3160, -3840, 39}}
a5 = {{-2000, 1800, 29}}
{{-2000, 1800, 29}}
c = N[(a1 + a2 + a3 + a4 + a5) / 5 + {{0, 0, 50000}}]
      数值运算
{{-2688., -1996., 50028.4}}

x0 = Det[d1] / Det[q]
     行列式    行列式
-2688.
y0 = Det[d2] / Det[q]
     行列式    行列式
-1996.
z0 = Det[d3] / Det[q]
     行列式    行列式
50028.4
t0 = Det[d4] / Det[q] / (3*10^8)
     行列式    行列式
3.01223×10^-17
```

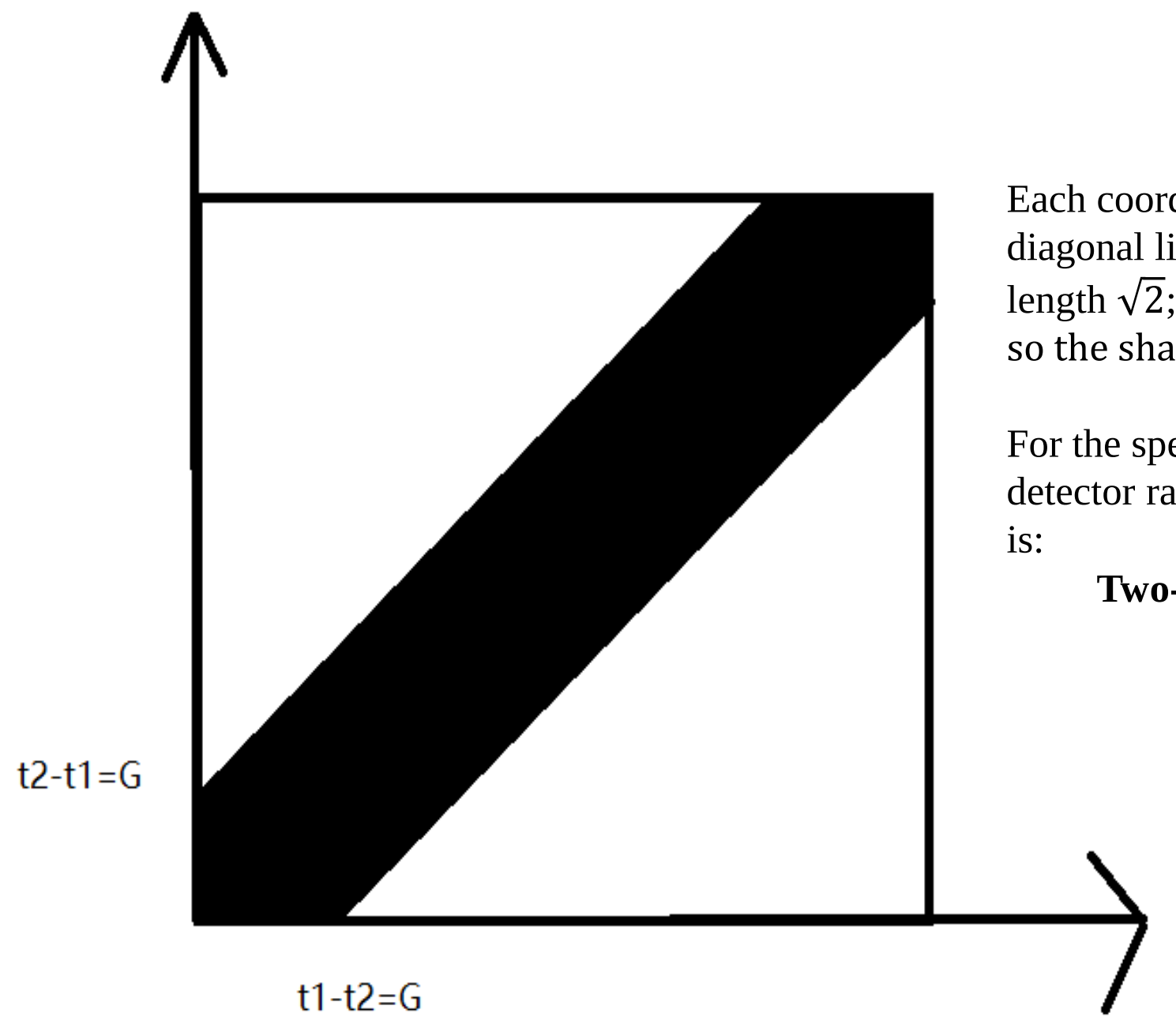
Distinguishing real signals from noise: false coincidences

The difference in time of arrival of particles at different detector sites in a cosmic ray shower is important to know; this time difference must be less than the gate time "G" over which detector data files are searched; we take as the gate time the maximum distance between two furthest detectors divided by the light speed.

Lmax is from York College(-3190,-5910,18) to Bayside H.S.(-2000,1800, 29)
Lmax= 7880.4m

$$G = \frac{Lmax}{c} = 2.63 * 10^{-5}s$$

Any pair of particles received at different detectors within the gate time could be from a shower, but noise produces false coincidences; two types of noise are the "background" from small showers producing single-detector cosmic ray muons, and photomultiplier tube (PMT) thermionic emission noise (PMT noise is typically the more frequent). For any two detectors with respective noise rates f1 and f2, the rate of false coincidence for two detectors is the number of possible pairs contained in the shaded area defined by two diagonal lines t2 – t1 = G, and t1 – t2 = G:

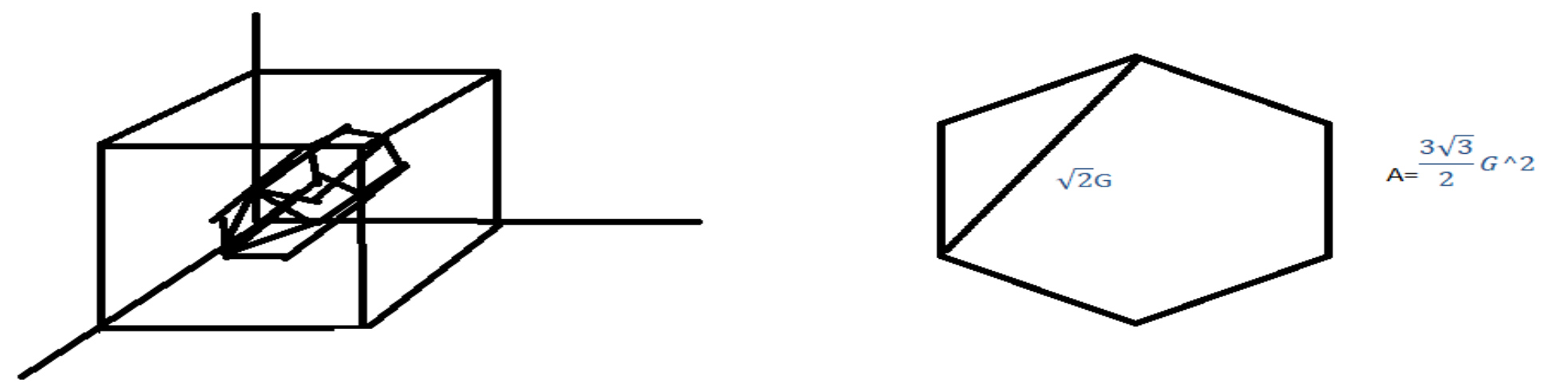


Each coordinate axis goes from 0 sec to 1 sec; the diagonal lines enclosing the shaded area are each of length $\sqrt{2}$; the diagonal area cross section is $\sqrt{2}$G, so the shaded region is approximately of area 2G.

For the special case when f1 = f2: $f1*f2=f^2$ and two-detector rate of false coincidences (area of shaded area) is:

Two-detector false coincidence rate = $2Gf^2$

For 3 detectors the rate of false coincidences is: **Rate =** $\frac{3\sqrt{3}}{2}G^2 * \sqrt{3}f^3 = \frac{9}{2}G^2\, f^3$

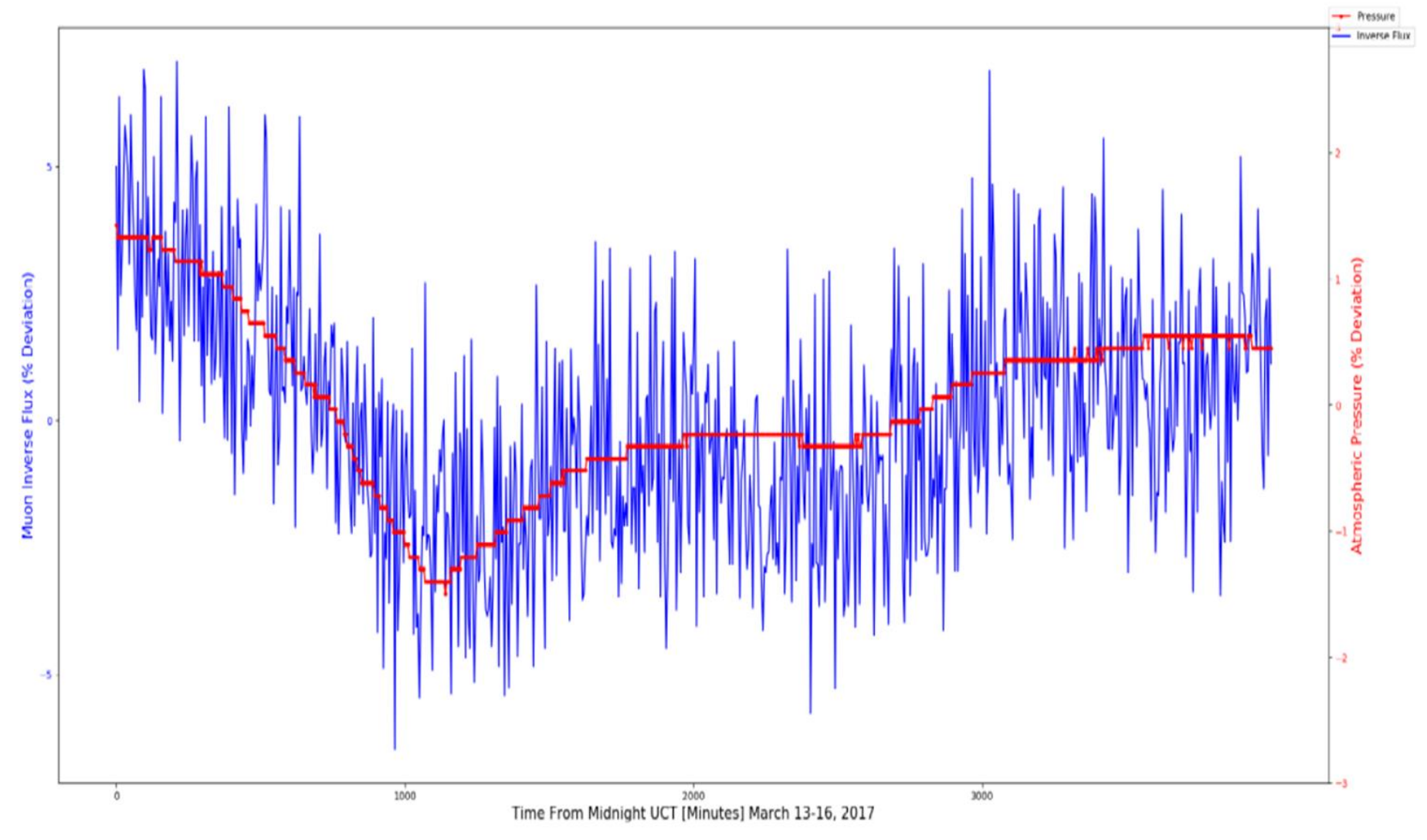


The general coincidence rate formula is:

Rate = $CG^{n-1}f1 * f2 * f3 * \cdots..fn$ (where C is a constant depending on the cross section)

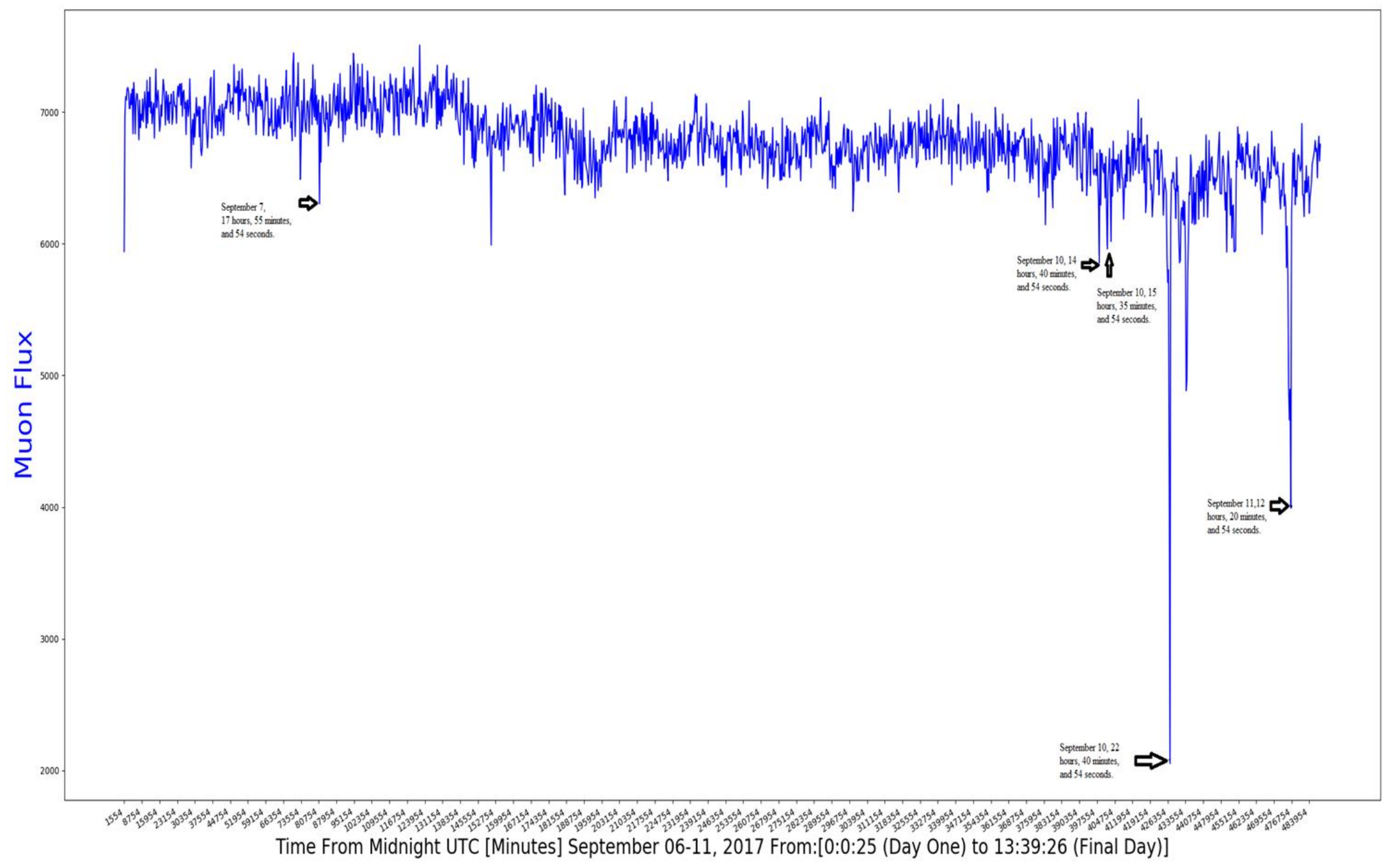
Creating Python code to plot cosmic ray flux data from QuarkNet detectors

When observing muon flux one important measurement is seeing how flux varies with pressure in the atmosphere. For this flux was measured during a big snow storm earlier this year and dramatic drops in pressure coincided with increases in flux. The anti-correlation between the two rates is illustrated by plotting inverse flux, 1/flux on top of pressure; percent deviations from the average for each pressure, and 1/flux, are shown here:

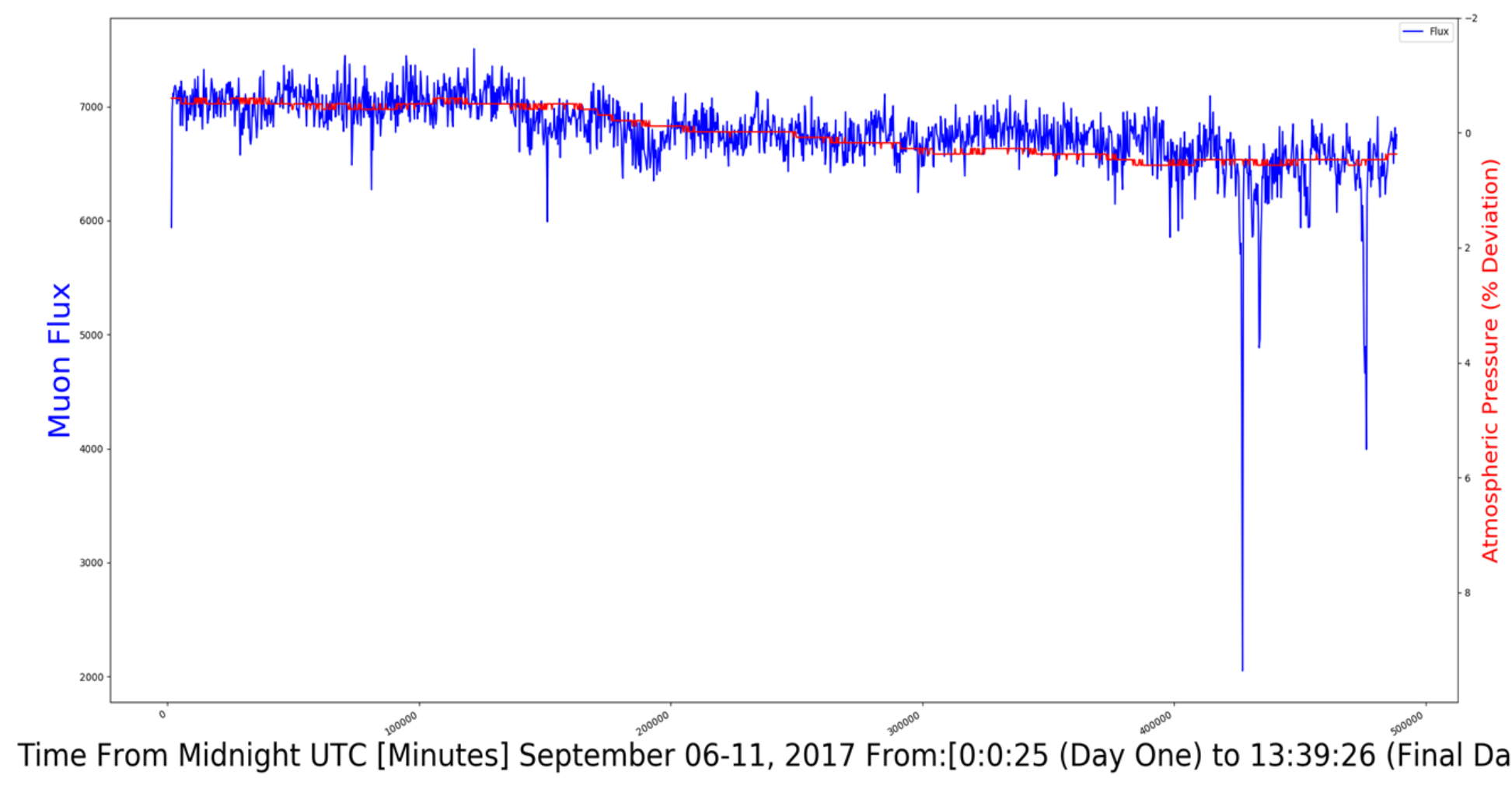


The above graph shows very clearly that a sharp decrease in pressure coincided with a sharp increase in flux. The graph also shows that these changes follow each other very closely: a 6% change in flux (% change below or above the average) correlates with a 2-3% change in pressure. Typically these changes are much smaller as the pressure in the atmosphere normally does not change as drastically, but a good opportunity arose to see during a snow storm.

Another unique opportunity arose this year, to measure muon flux during one of the largest solar flares recorded in the last 11 years. A category X9 solar flare occurred in September. This unique opportunity allowed us to measure whether or not the presence of a solar flare would drastically affect the number of muons passing through our detectors. Interestingly enough, the solar flare did indeed change our values in flux as shown below. The observed dramatic drops in muon flux (large spikes) are not time coincident with the flares, i.e. there are time lags between the two, this is being investigated. The large drops in flux occurred after different solar flares.



Time From Midnight UTC [Minutes] September 06-11, 2017 From:[0:0:25 (Day One) to 13:39:26 (Final Day)]

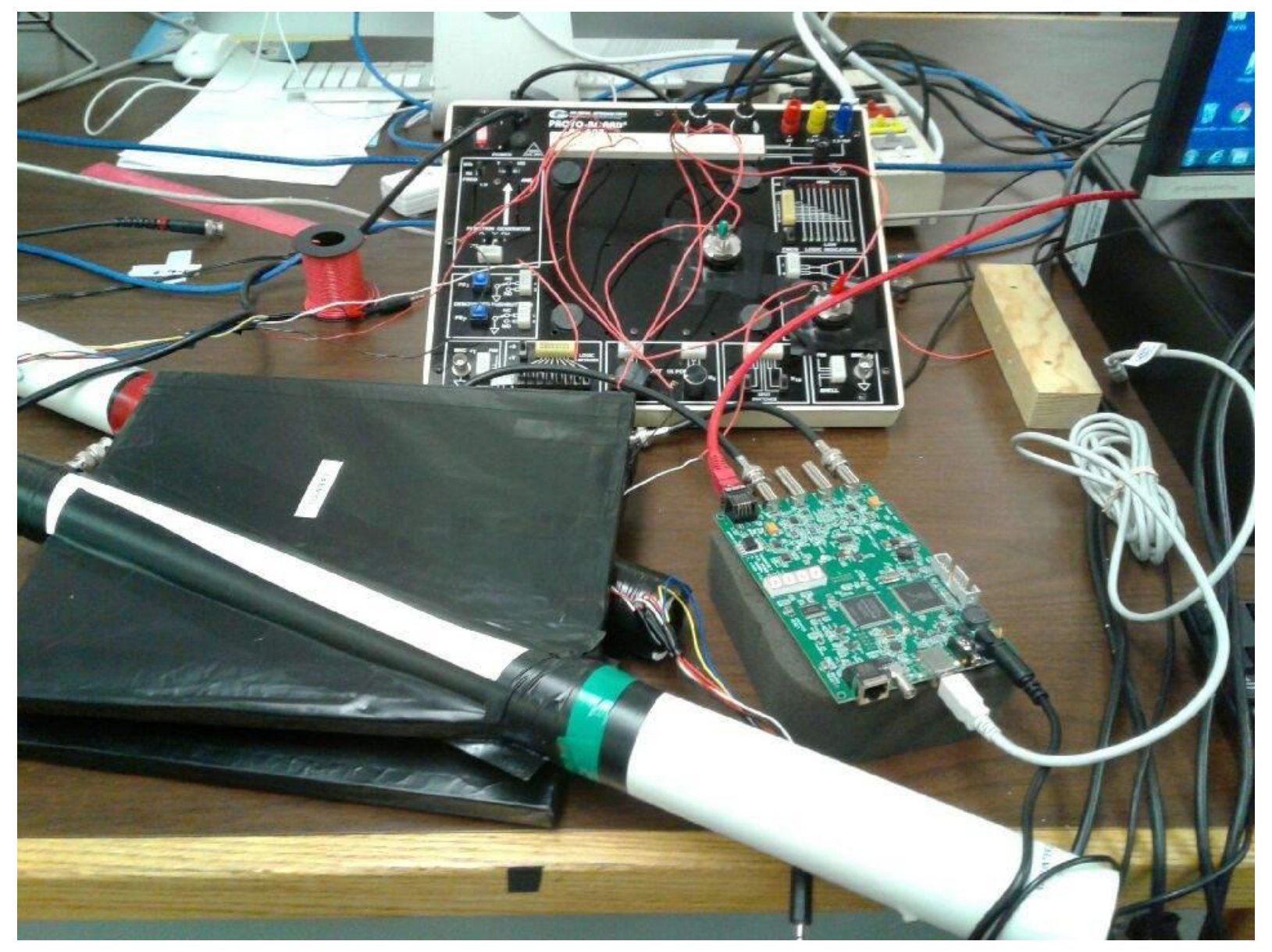


Time From Midnight UTC [Minutes] September 06-11, 2017 From:[0:0:25 (Day One) to 13:39:26 (Final Day)]

In the above plot the changing atmospheric pressure (red curve) is shown inverted so the rising pressure is shown as a drop over time; this correlates with the general decrease in muon flux. The large drops in muon flux (large spikes) happened on several occasions as there was more than one solar flare, and not all on the same day). large changes in flux for intervals lasting around 10 minutes at a time are observed (the flux is binned in averages over 5 minutes intervals).

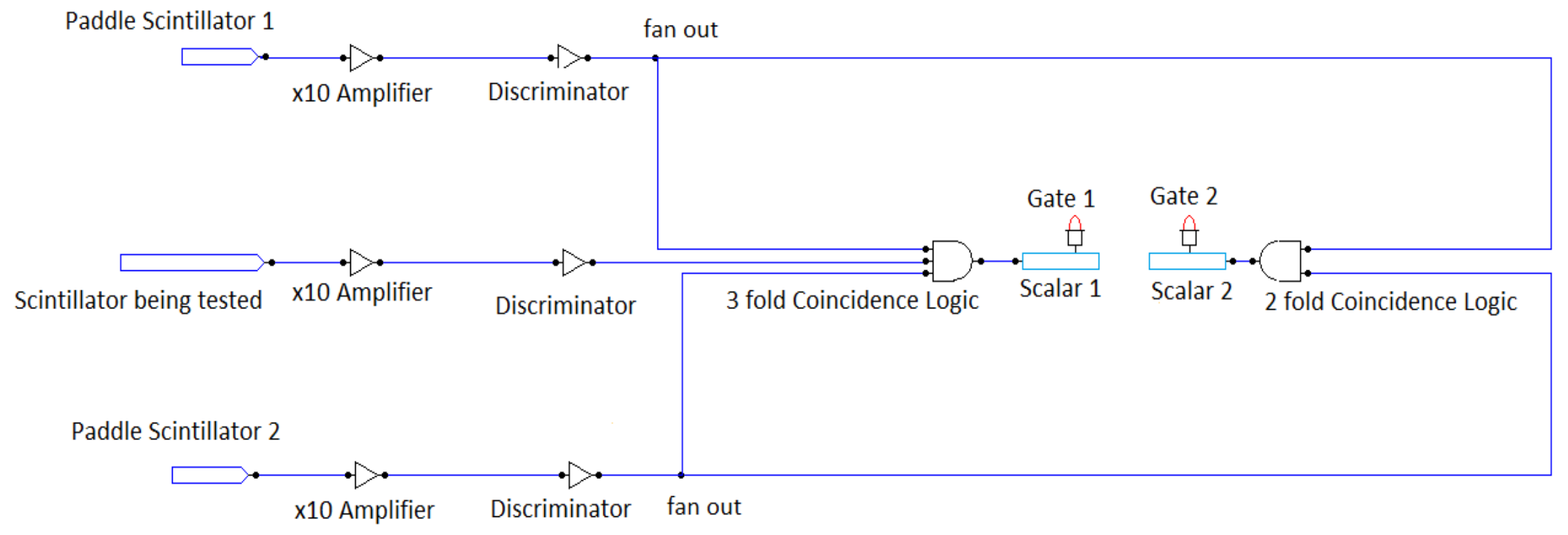
Voltage dividers for power distribution to pmts

Temporary voltage divider circuits were assembled by using potentiometers and power supplies:



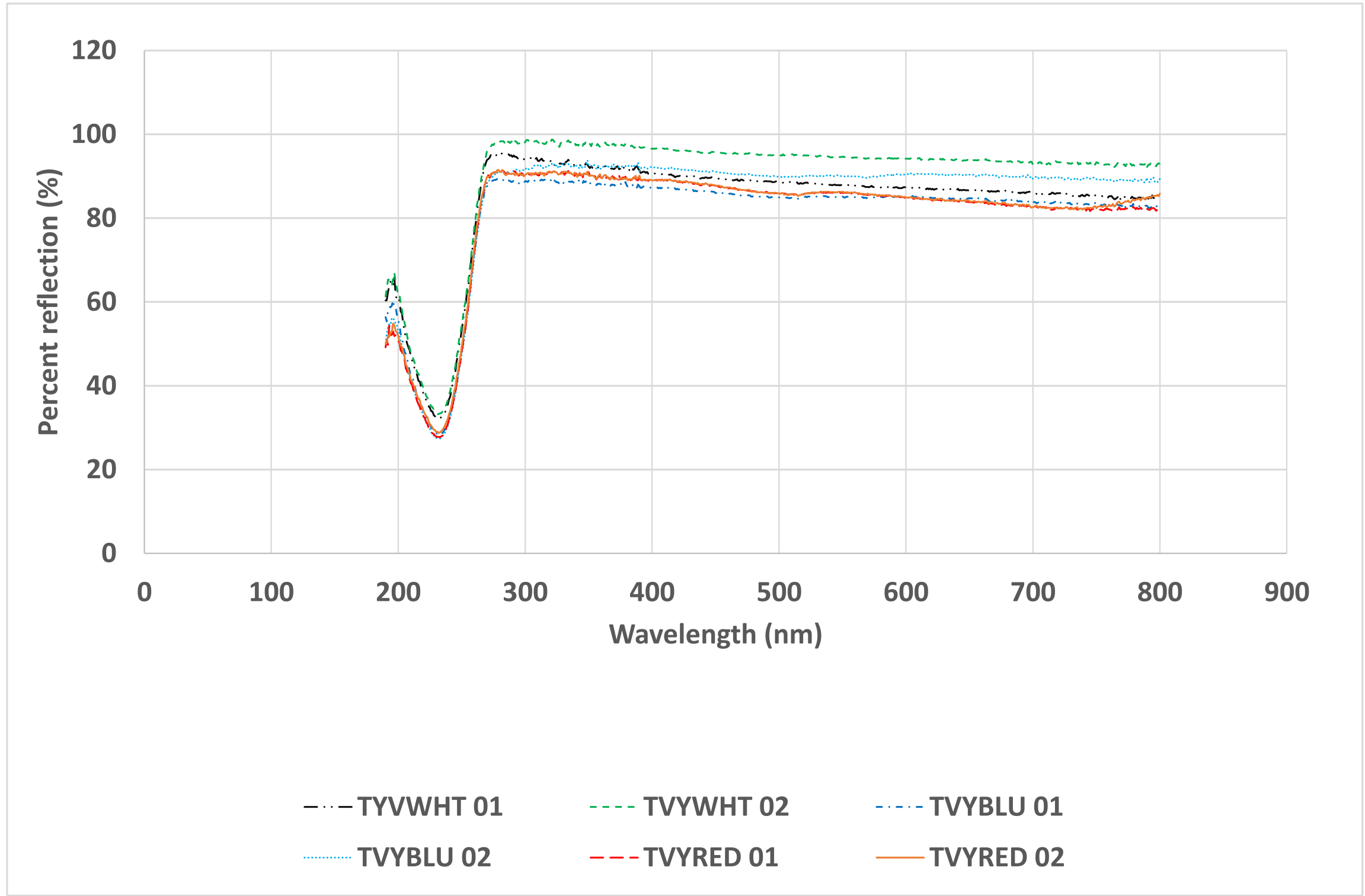
Wiring block diagram for scintillator efficiency measurements done at Brookhaven Lab

Our group at QCC drew circuit block diagrams and made plots for measurements made by other students within our group at BNL; below is a wiring diagram for a muon telescope setup used to measure scintillator efficiency; here two smaller cosmic ray counters sandwich the scintillator under test and the cosmic ray 3-fold/2-fold ratio of coincidences is measured.



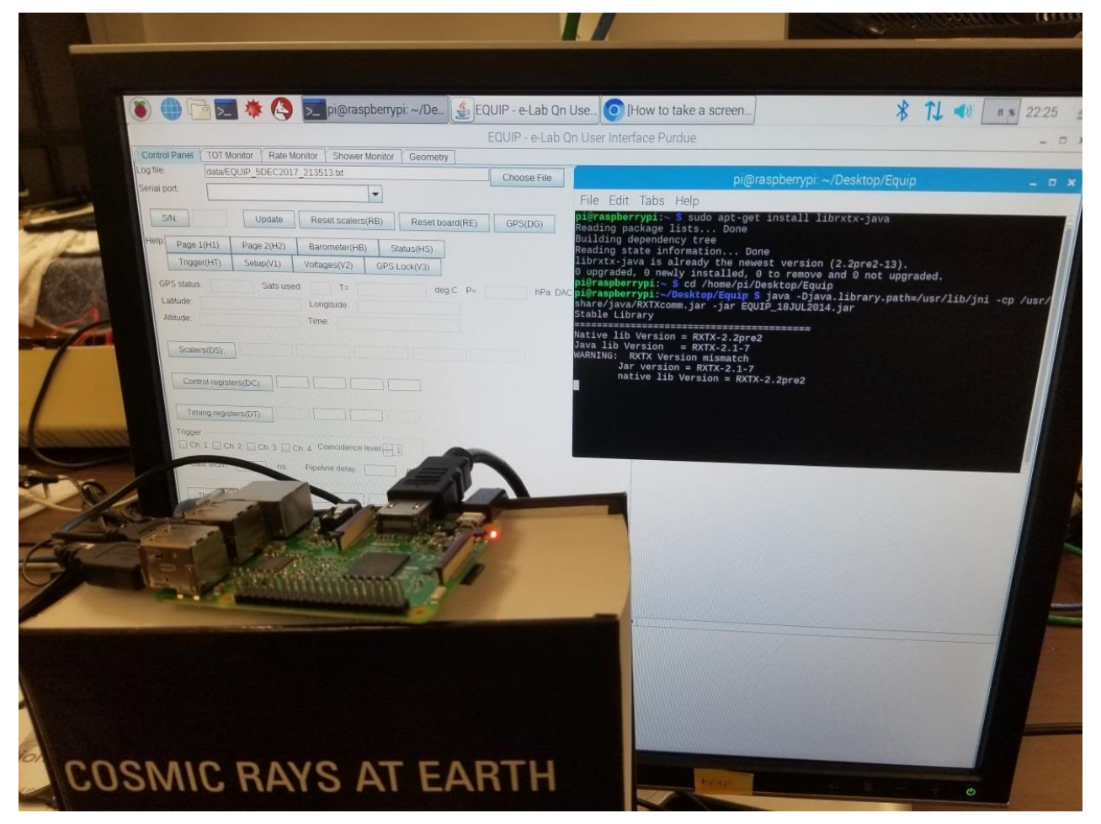
Reflectivity measurements of white Tyvek, colored letters on white Tyvek paper, and single vs. double wrapped counters:

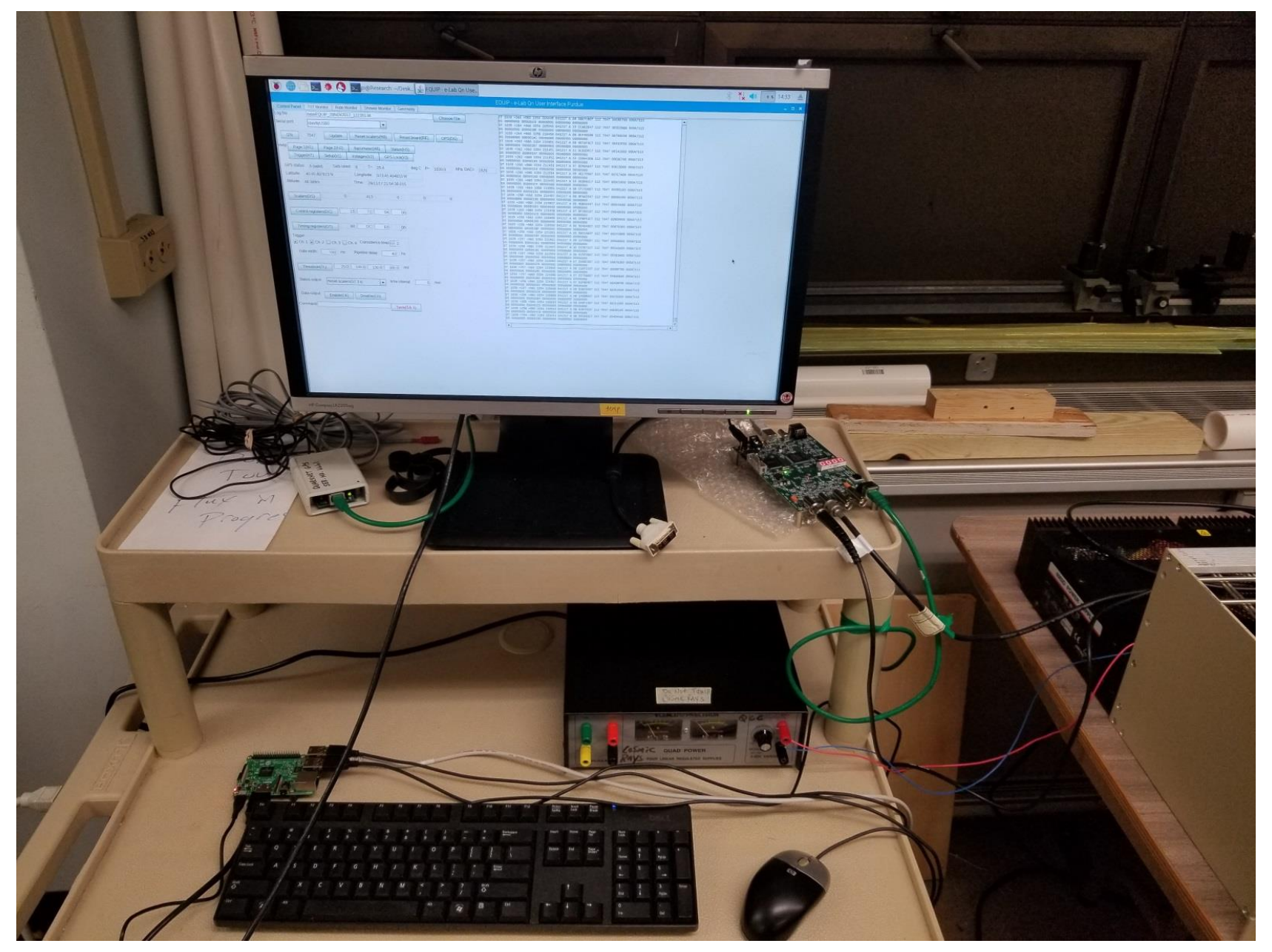
Our NE-114 scintillator max light output = 425 nm, at this wavelength the white Tyvek double wrapped is 97% reflective (measurements made for us at Brookhaven Lab)



Raspberry PI single-board processing computer, set up and data acquisition

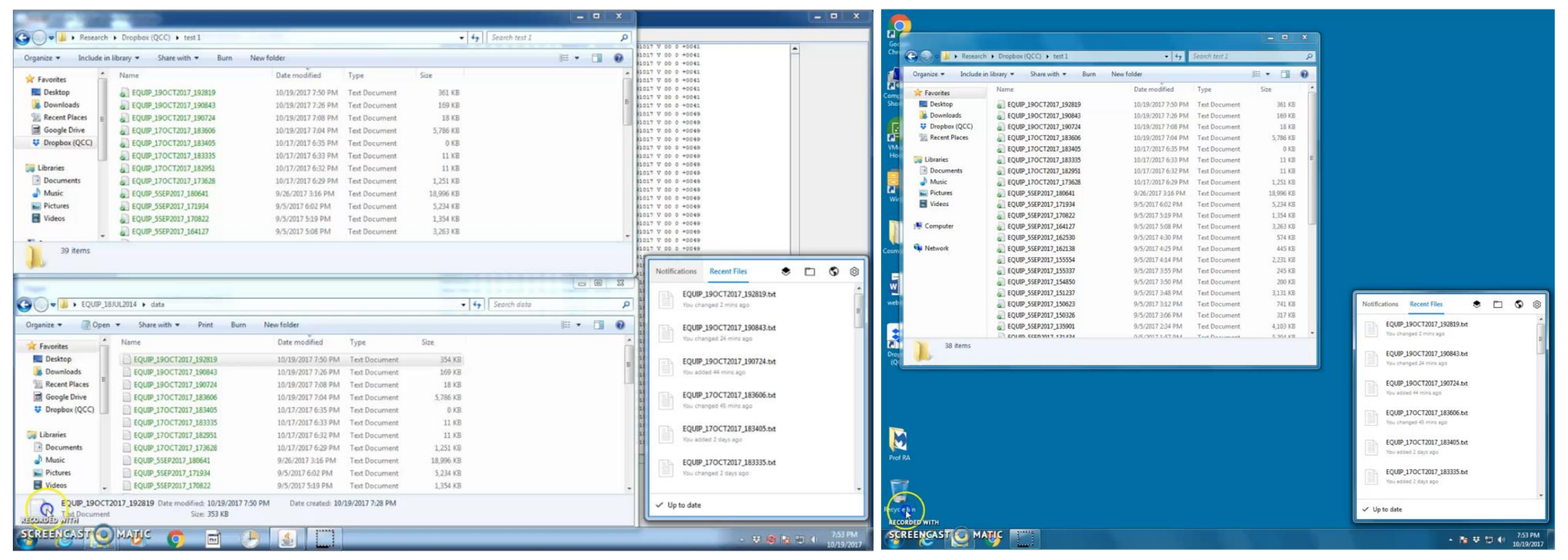
The pictures below illustrate the setup for a Raspberry Pi single board processing computer with our detectors replacing large computers; the size and low price of the PI makes it a much better and cutting edge alternative. The Raspberry PI uses the Linux Operating System which is different from Windows and MAC. It is set up working at the command line in Linux; our detector control software and data acquisition program "EQUIP" was installed on the Pi. The pictures below show the Linux commands and process of installing and running EQUIP, connecting it to a monitor, and data collection from two PMTs.





Drop-Box for Data Transfer

Automatic uploads and downloads of data from each detector to the central array computer will be done with DropBox. In the pictures below he left side shows a detector's computer collecting data and uploading it to DropBox, while the right side shows the data downloading, all automated.



Calculating the expected cosmic ray primary flux incident on Earth:

The plot below is widely used in the field of cosmic ray research as it illustrates the number of the primary cosmic ray particles (normalized per unit energy) hitting earth's atmosphere per m^2per sec. per steradian; from this plot the cosmic ray flux can be calculated for each cosmic ray energy. To show how to do this we use the integral's differential width to be the same as the x-axis's energy bin value, for example for a cosmic ray energy of 10^{10} electron Volts:

Expected Cosmic ray rate $= \int \frac{dy}{de} * de = average\left(\frac{dy}{de}\right) * intergal\ width = 10^{-10} * 10^{10} = 1\frac{1}{m^2sec}$