Noise in cosmic ray plastic scintillator detectors: ambient room light getting into the detectors and pmt dark rate noise obscure the muon signal

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July 11, 2019

Part 1 includes plots of data, Part 2 includes pictures of detectors

Introduction

Three cosmic ray muon detectors, CUNY, Vaughn, and Quark Net, were setup in QCC physics lab S309 to measure cosmic ray rates over May-June 2019. The purpose of this study is to see how detector noise rates affect our ability to measure the cosmic ray muon rate.

Each detector consisted of two muon “counters” stacked one on top of the other; a counter is a plastic PVT scintillator with a photomultiplier tube (pmt) mated to one end; each detector also consisted of a QuarkNet DAQ board, a GPS antenna and receiver, atmospheric pressure and room-temperature sensors.

Each detector’s DAQ measured both counters pulse rates and the two-counter coincidence rate; a coincidence is when both pmts output an electrical pulse within 300 ns of each other; a “signal coincidence” occurs when a muon passes through a pair of stacked counters causing each to output a pulse within 300 ns; a “noise coincidence” occurs when two counters generate noise pulses within 300 ns of each other, which happens when their combined noise rates are high enough. Two types of noise measured in this study include noise caused by ambient light leaking into the detectors, and pmt dark rate noise. The absolute discriminator threshold levels used for signal and noise pulses were 3 mV for CUNY, 7 mV for Vaughn, and 7 mV for Quarknet (in 50 Ohms).

How the cosmic ray muon rate is defined for the purposes of this study, and how detector noise is expected to affect the rate measurement –

The theoretically expected cosmic ray muon rate incident on a detector is 1 per cm^2 per minute.

The measured cosmic ray muon rate is accepted to be the measured coincidence rate for two stacked counters in the absence of any noise coincidences; thus, it is necessary to subtract the noise coincidence rate from the overall measured coincidence rate.

The theoretically expected two-counter noise coincidence rate is calculated using the counter noise rates as: 2 x (counter 1 noise rate) x (counter 2 noise rate) x (gate width)

Detectors used in this study

1. **CUNY**: two stacked NE114 scintillators,106cm x 30cm x 2cm, and 109cm x 30cm x 2cm, with overlapping area ~ 104cm x 30cm = 3120 cm^2 (this scintillator has relatively low light output); H2431-50 PMTs, Ortec 456 adjustable HV power supply, Quarknet DAQ board, Quarknet GPS antenna and receiver (a receiver firmware glitch caused incorrect date-stamps). The pmt high voltages were set at about 2.9 kHz.

2. **Vaughn**: two stacked NE114 scintillators, each 30cm x 30cm x 2cm, overlap area 900 cm^2, (this scintillator has low light output), PDM9125-CN PMTs with internal LV-to-HV DC converters, variable resistor voltage divider for pmt power (PDU), Quarknet DAQ board, Quarknet GPS antenna and receiver (a receiver firmware glitch caused incorrect date-stamps).

3. **Quarknet**: two stacked Eljen EJ-200A scintillators, ~ 30cm x 25cm x 1cm and ~31cm x 26 cm x 1 cm, with overlap area 30cm x 25cm = 750 cm^2 (this scintillator has higher light output), P30CW5 PMTs with internal LV-to-HV DC converters, variable resistor voltage divider for pmt power (PDU), Quarknet DAQ board, Quarknet GPS antenna and receiver (a receiver firmware glitch caused incorrect date-stamps).

Data presentation and plots

The following plots are results from the three different detectors. Data was collected for three days continuously, then for between 19 and 23 days for the different detectors. In the Figures the upper left plots are individual counter noise rates, the bottom plots are two-fold coincidence rates for the stacked counters, and the upper right plots show atmospheric pressure and room temperature; the atmospheric pressure was measured with sensors on the DAQ boards, and room temperature measured with sensors in the lab.

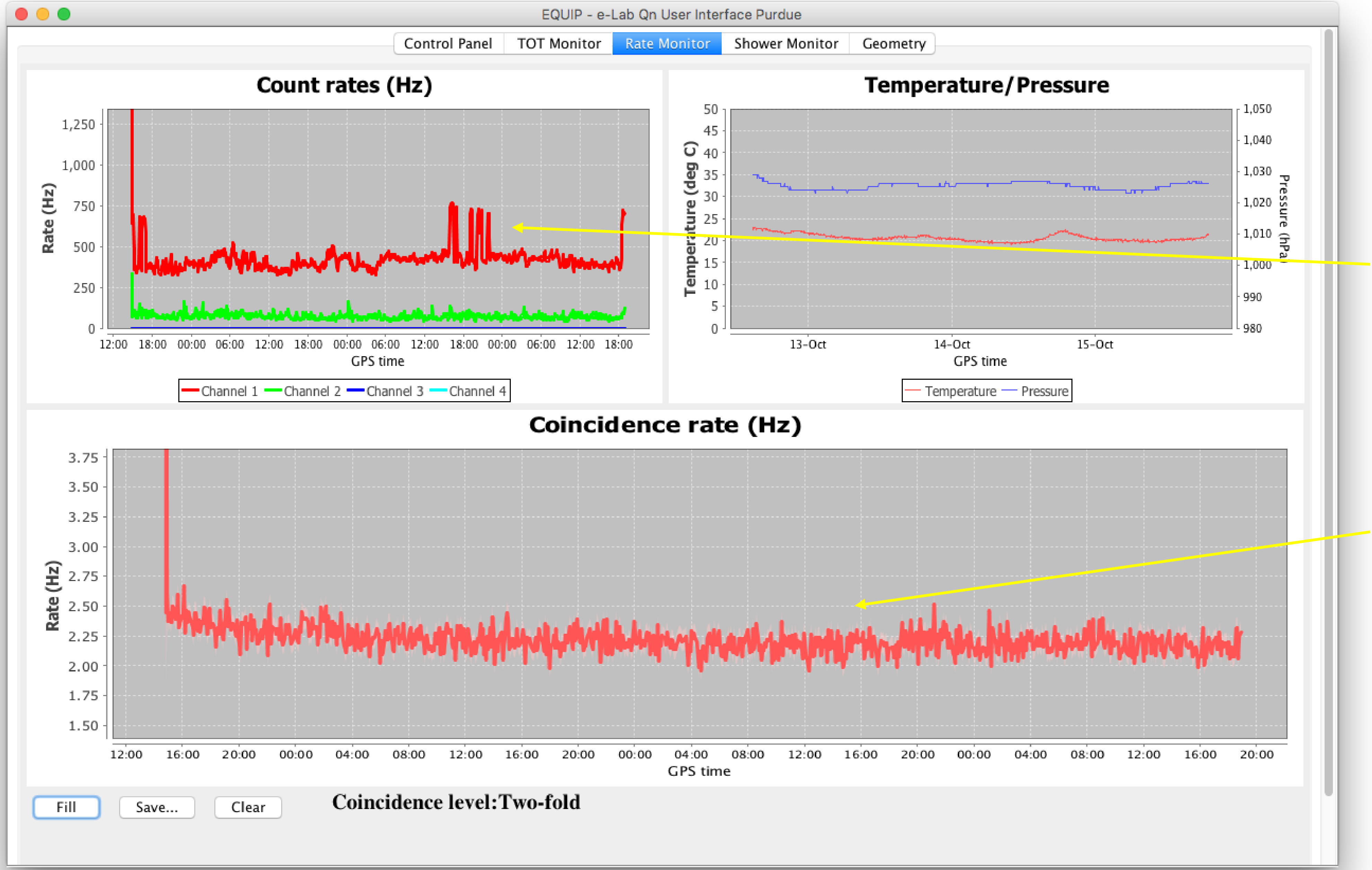

Fig 4: CUNY detector counters' single PMT rates and 2 fold coincidence rate over 3 days:

the spikes are increased noise when the lab room lights were turned on; when the lights were off Channel 1 and 2 baseline rates are 400 Hz and 75 Hz respectively, mostly pmt dark rate noise;

this detector performed very poorly as evidenced by the low coincidence rate of 2 Hz; the expected cosmic ray muon rate for this size scintillator is about 52 Hz;

The settings were 300 ns gate width, 3 mV (in 50 Ohm) discriminator thresholds, and pmt gains of ~ 10^6.

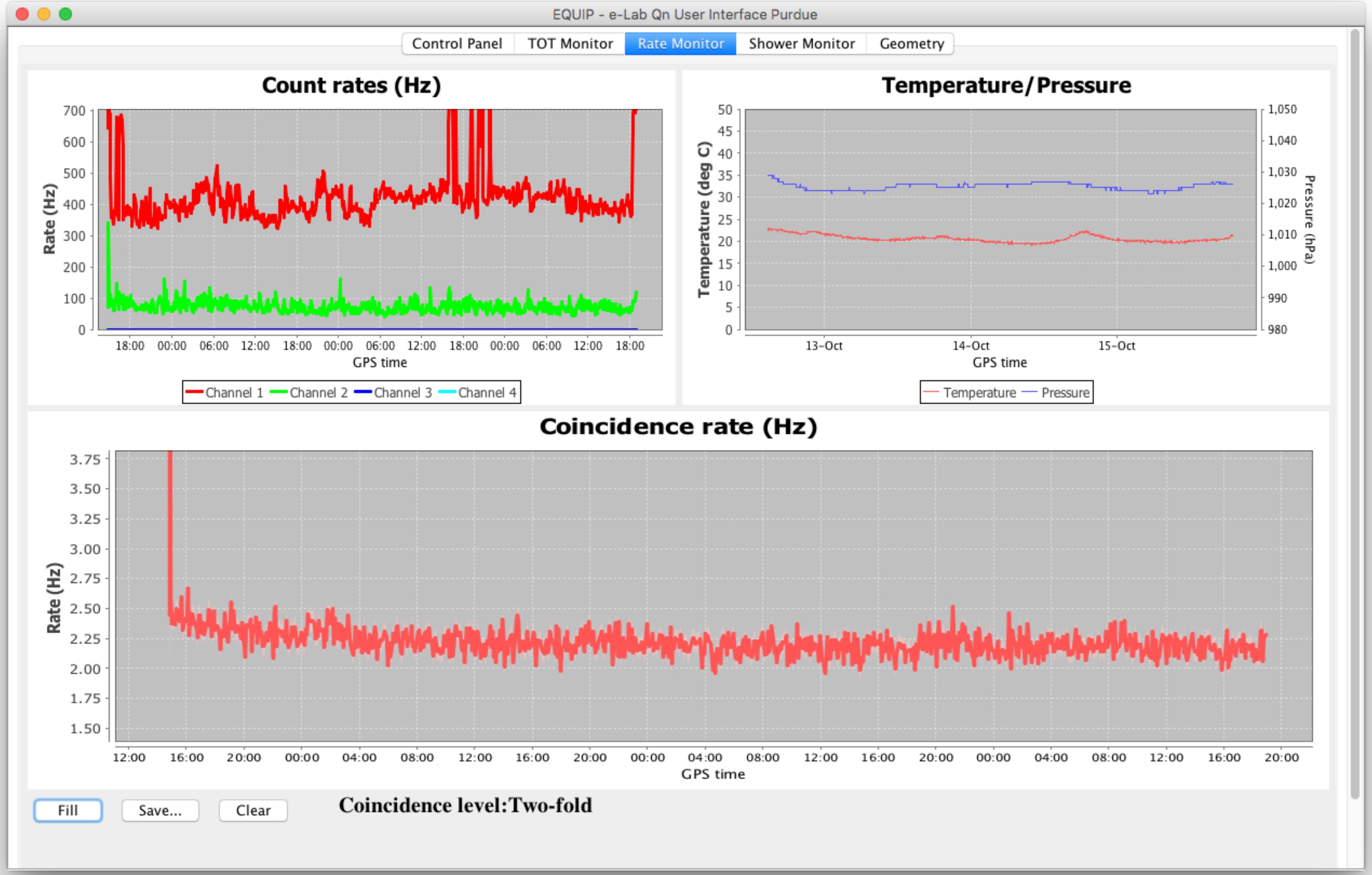

Fig 5: (this is a close up view of Fig 4) CUNY detector counters' single PMT rates and 2 fold coincidence rates over 3 days.

Observations:

1. The measured counter baseline rates are 400 Hz for Channel 1 and 75 Hz for Channel 2; the expected noise coincidence rate is:

2(400 Hz)(75 Hz)(300 ns) = 0.02 Hz;

2. With the room lights on the Channel 1 noise rate spiked to 750 Hz; the expected noise coincidence rate is:

2(750 Hz)(75 Hz)(300 ns) = 0.034 Hz;

3. The expected cosmic ray coincidence rate for a good scintillator detector of this size is 52 Hz:

1 cm^2/min x (104 cm x 30 cm) x 1min/60s = 52 Hz;

Conclusion: the measured coincidence rate of 2 Hz is much smaller than the expected 52 Hz, so this detector is not working well.

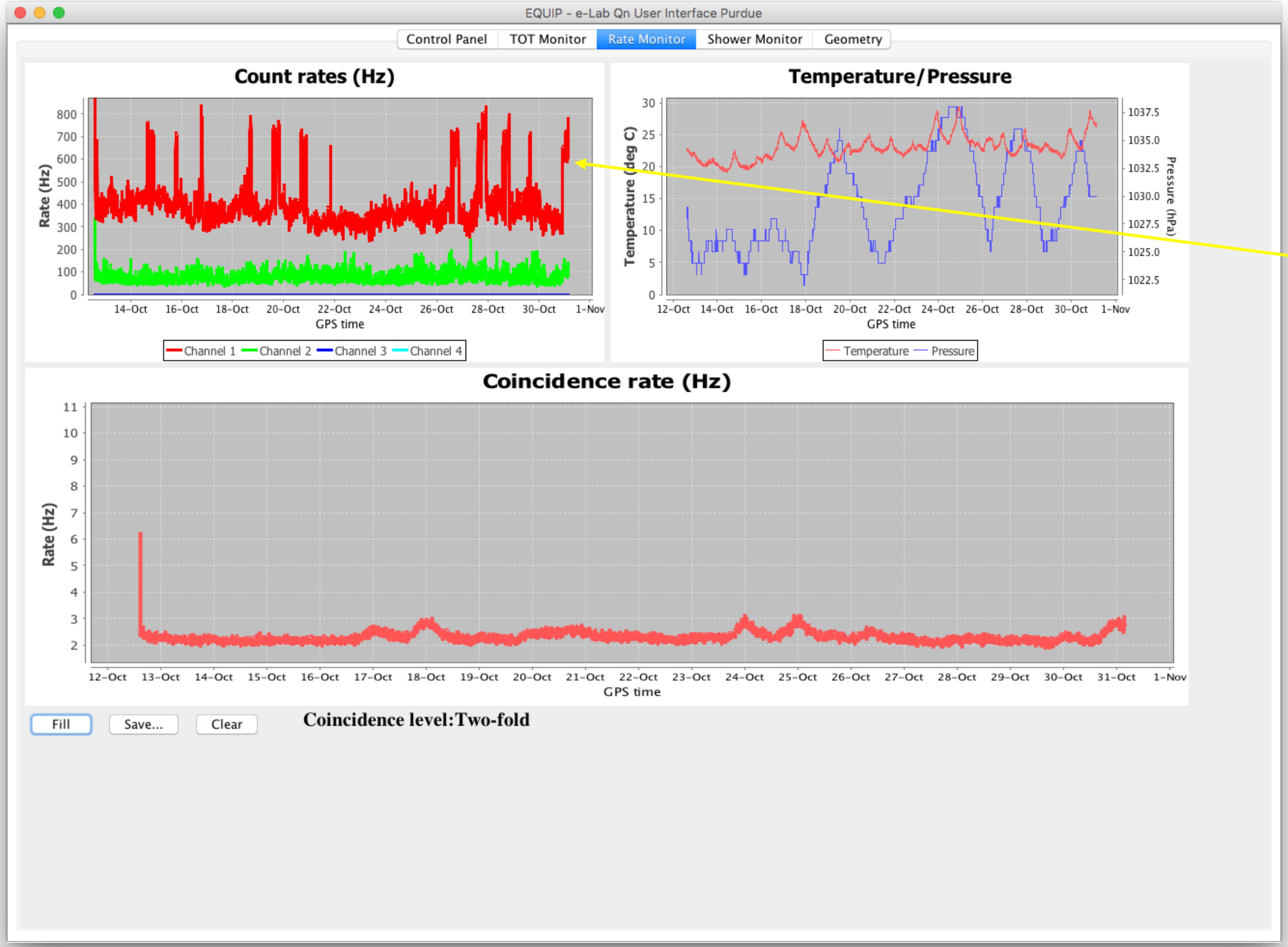

Fig 6: CUNY detector data taken over 19 days in May-June, 2019 (the date axes are incorrectly labeled October)

The Channel 1 noise rate rose whenever the lab room lights were turned on.

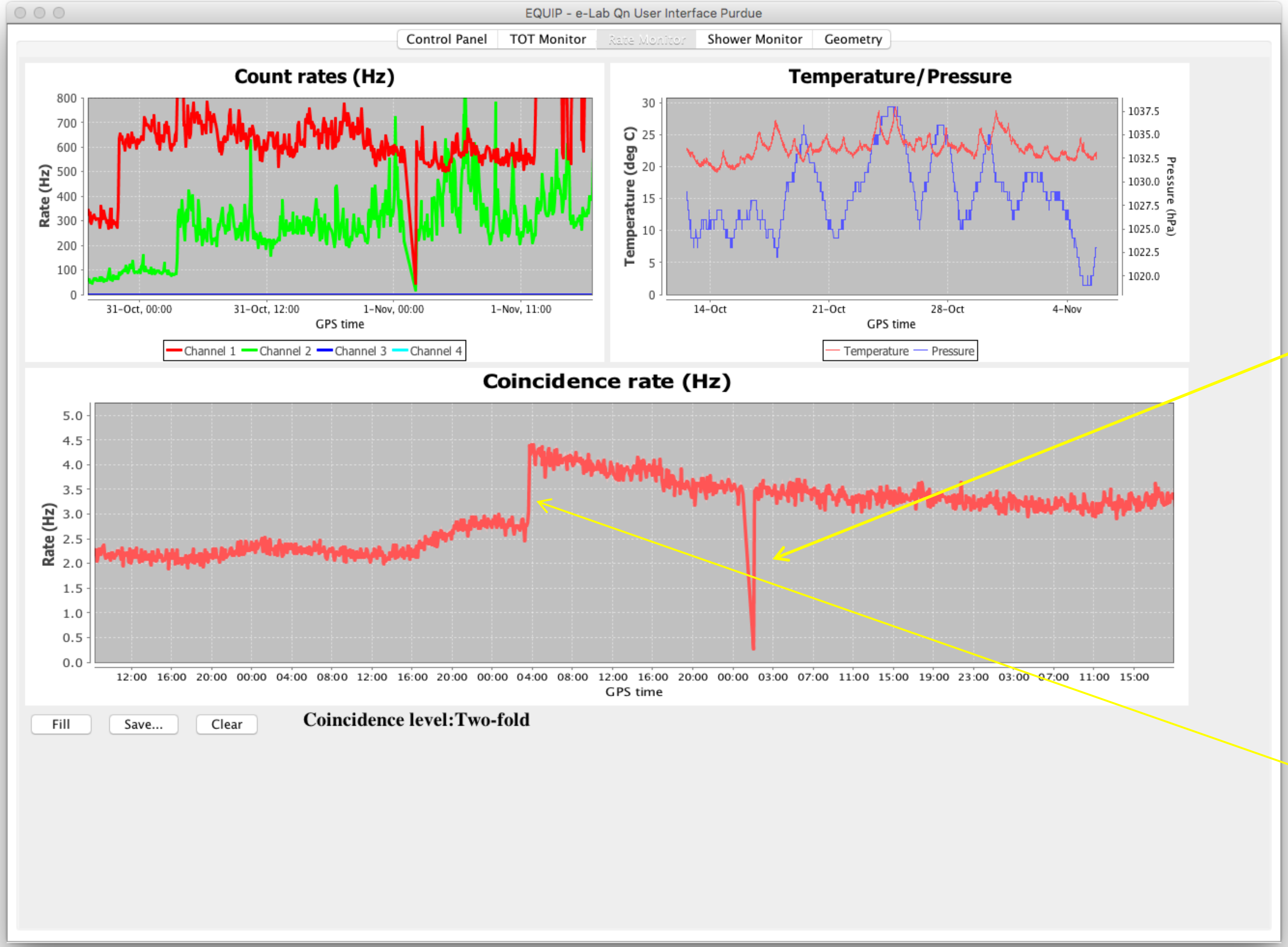

Fig 7: CUNY detector data taken over May-June, 2019 (the date axes are incorrectly labeled Oct-Nov)

For some unknown reason all three detectors CUNY, Vaughn, and QuarkNet lost data for about 30 minutes on the date indicated as Nov 1 st 0100, which may have been June 16th 9:00 pm EDT.

The HV to the pmts was increased which resulted in an increase in the coincidence rate. The measured counter baseline rates are about 600 Hz for Channel 1 and 400 Hz for Channel 2; the expected noise coincidence rate is:

2(600 Hz)(400 Hz)(300 ns) = 0.14 Hz;

The measured coincidence rate went up to about 3.5 Hz, which may be muons.

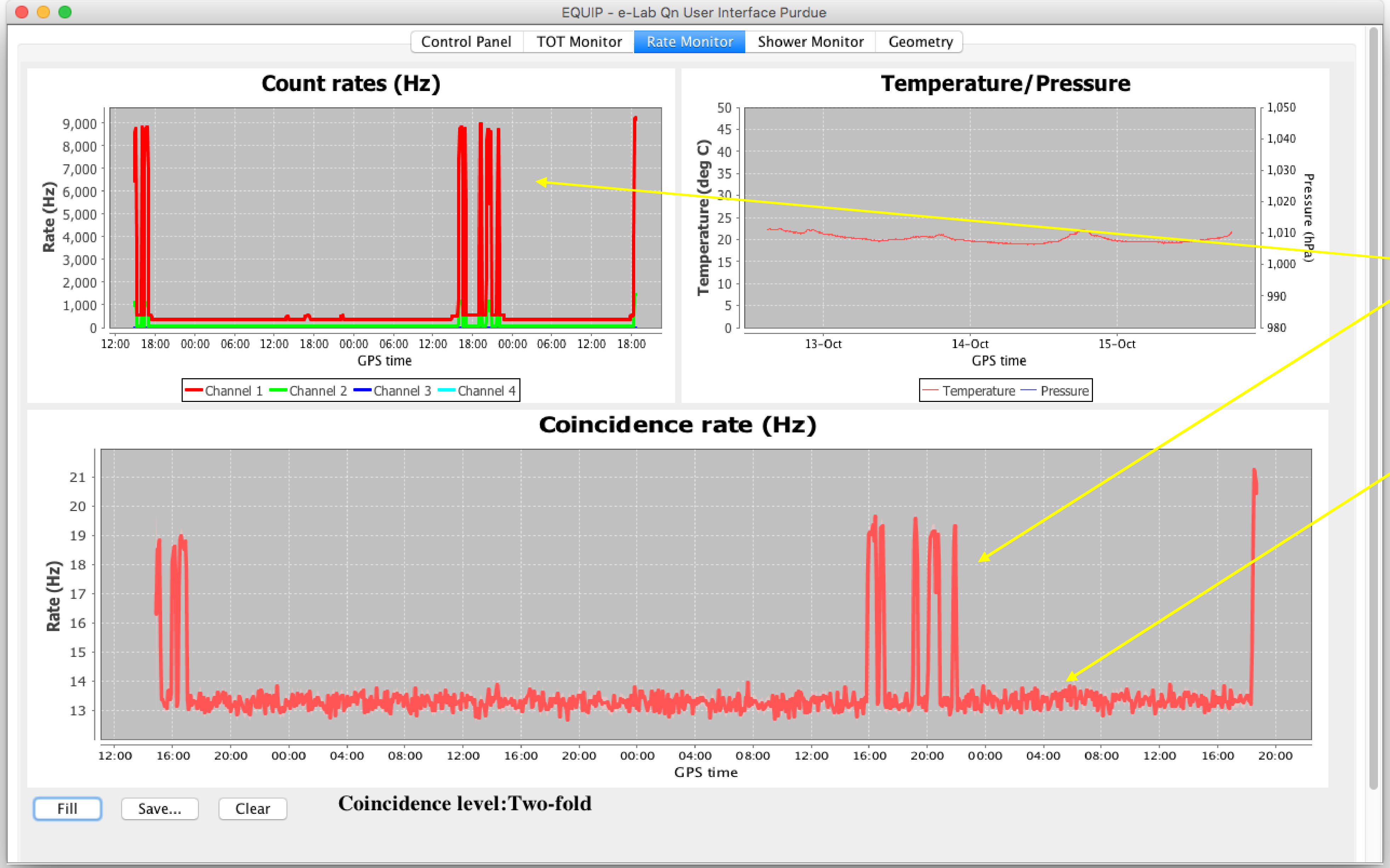

Fig 8: Vaughn detector counters' single PMT rates and 2 fold coincidence rate over 3 days:

the spikes are increased noise when the lab room lights were turned on; when the lights were off the Channel 1 and 2 baseline rates are 350 Hz and 50 Hz respectively, mostly pmt dark rate noise.

The measured 13 Hz coincidence rate is close to the expected 15 Hz rate of cosmic ray muons for this size scintillator.

The settings were 300 ns gate width, 7 mV (in 50 Ohm) discriminator thresholds, and pmts' gains ~ 10^6.

Fig 9: (this is a close up view of Fig 8)
Vaughn counters' single PMT rates and 2 fold coincidence rates over 3 days.

Observations:

1. The measured counter baseline rates are 300 Hz for Channel 1 and 50 Hz for Channel 2; the expected noise coincidence rate is:

2(300 Hz)(50 Hz)(300 ns) = 0.009 Hz;

2. With the room lights on the Channel 1 noise spiked to 9 kHz, and Channel 2 noise to 1.2 kHz; the expected noise coincidence rate is:

2(9000 Hz)(1200 Hz)(300 ns) = 6.5 Hz;
the coincidence rate went up accordingly by 6.5 Hz (19.5 Hz - 13 Hz).

3. The expected cosmic ray coincidence rate for a good scintillator detector of this size is 15 Hz:

1 cm^2/min x (30 cm x 30 cm) x 1min/60s = 15 Hz;

Conclusions: 1) the ambient light noise coincidence rate went up by the amount expected due to the individual counter noise rates. 2) When the room lights were off the measured coincidence rate was 13 Hz which is close to 15 Hz; however the measured coincidence rate was expected to be lower because this scintillator is known to produce low levels of light output, more investigation is needed.

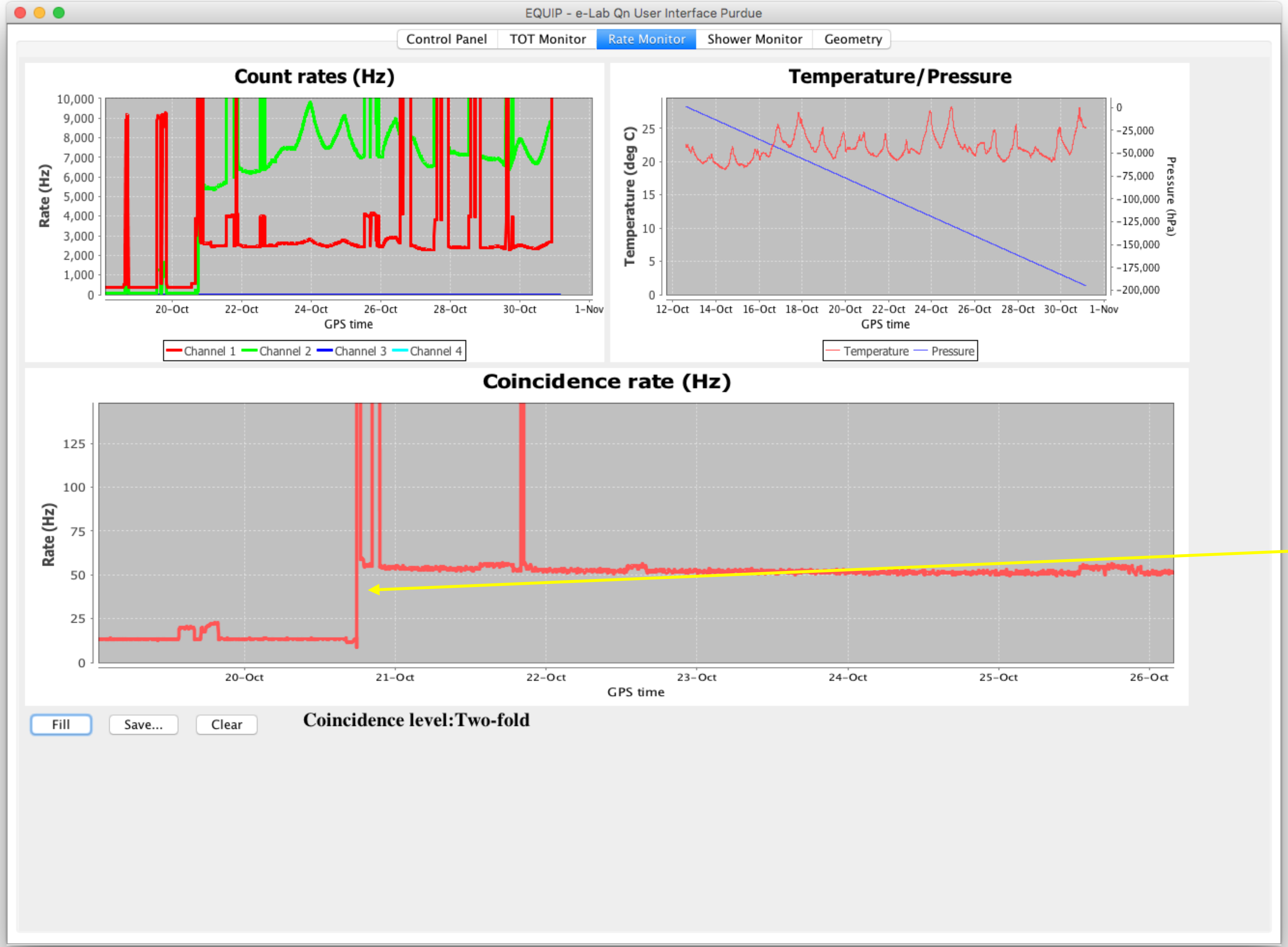

Fig 10: Vaughn detector data taken over 19 days in May-June, 2019 (the date axes are incorrectly labeled October, and the pressure sensor data is not right)

On Oct. 20 the pmt operating high voltages were raised causing the Channel 1 noise rate to rise to 2.5 kHz, and the Channel 2 noise rate to rise averaging around 8 kHz; the expected noise coincidence rate is

2(2.5 kHz)(8 kHz)(300 ns) = 12 Hz;

the measured coincidence rate rose by 30 Hz (53 Hz – 13 Hz); thus the rise in the measured noise coincidence rate is 2.5 times higher than expected.

The coincidence gate width was 300 ns, discriminators' thresholds 7 mV, and pmts' gains ~ 10^6

Conclusions: when the pmts' high voltages were increased the detector's noise coincidence rate increased by 30Hz, a few times higher than expected based on the individual counter noise rates.

Fig 11: Vaughn detector data taken over 19 days in May-June, 2019 (the date axes are incorrectly labeled October, and the pressure sensor data is not right)

The spikes are increased noise when the lab room lights were turned on

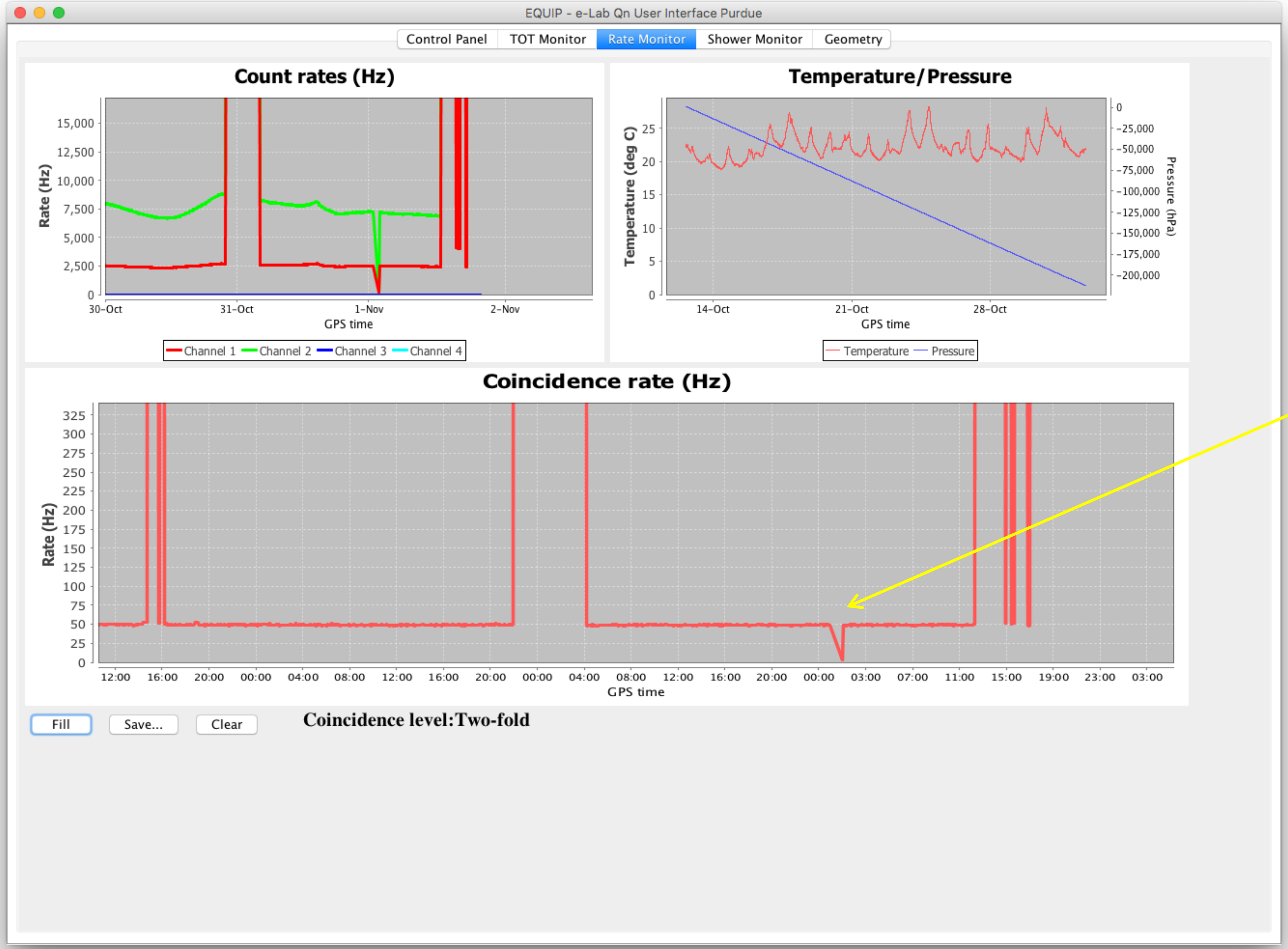

Fig 12: Vaughn detector data taken over May-June, 2019 (the date axes are incorrectly labeled Oct-Nov, and the pressure sensor data is not right)

For some unknown reason all three detectors CUNY, Vaughn, and QuarkNet lost data for about 30 minutes on the date indicated as Nov 1 st 0100, which may have been June 16th 9:00 pm EDT

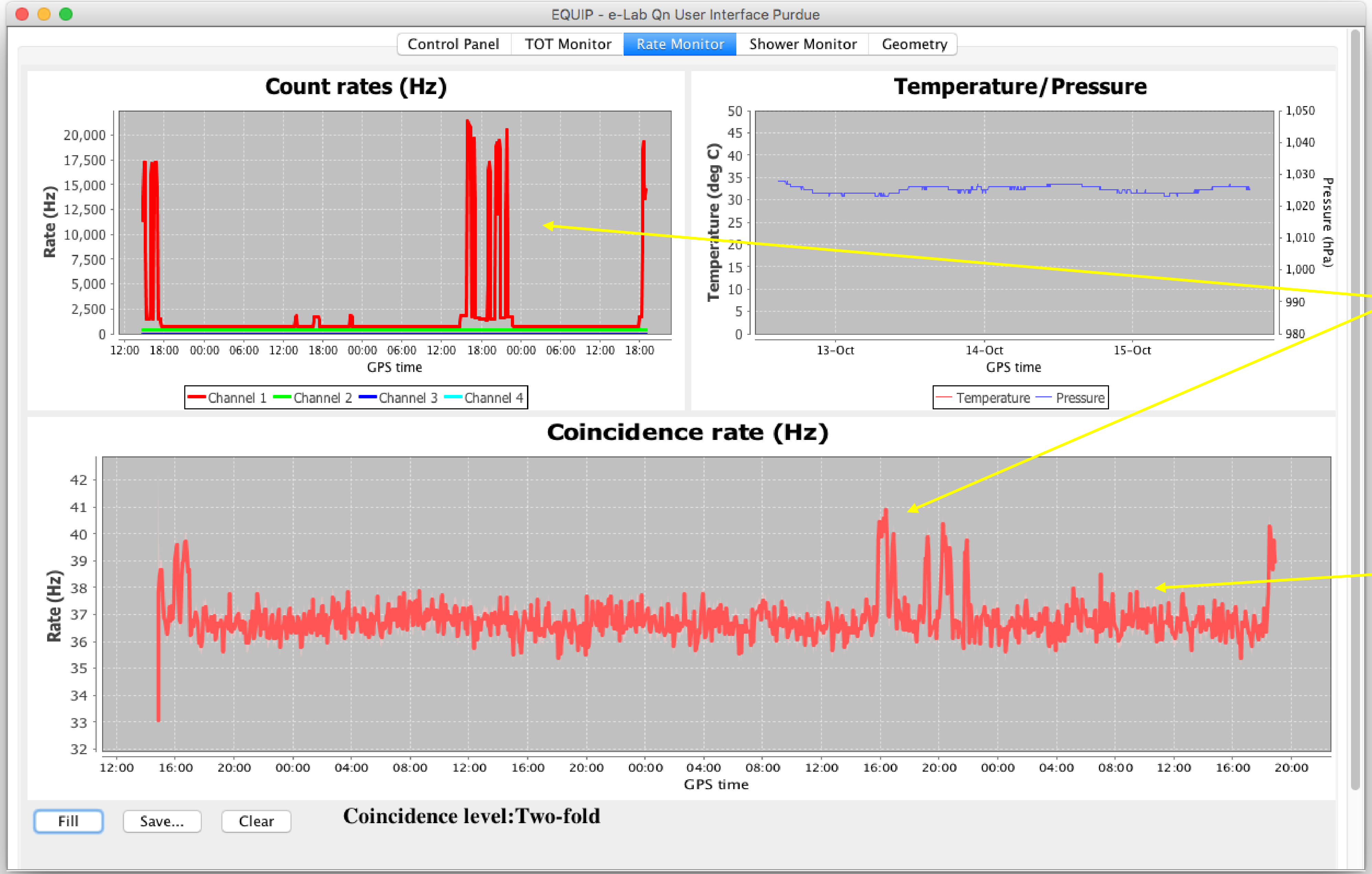

Fig 13: Quarknet detector counters' single PMT rates and 2 fold coincidence rate over 3 days:

the spikes are increased noise when the lab room lights were turned on; when the lights are off the Channel 1 and 2 rates are 750 Hz and 400 Hz respectively, mostly pmt dark rate noise;

The measured coincidence rate of 36 Hz is higher than expected rate of 12.5 Hz for cosmic ray muons in this size detector.

The settings were 300 ns gate width, 7 mV (in 50 Ohm) discriminator thresholds, and pmts' gains ~ 10^6.

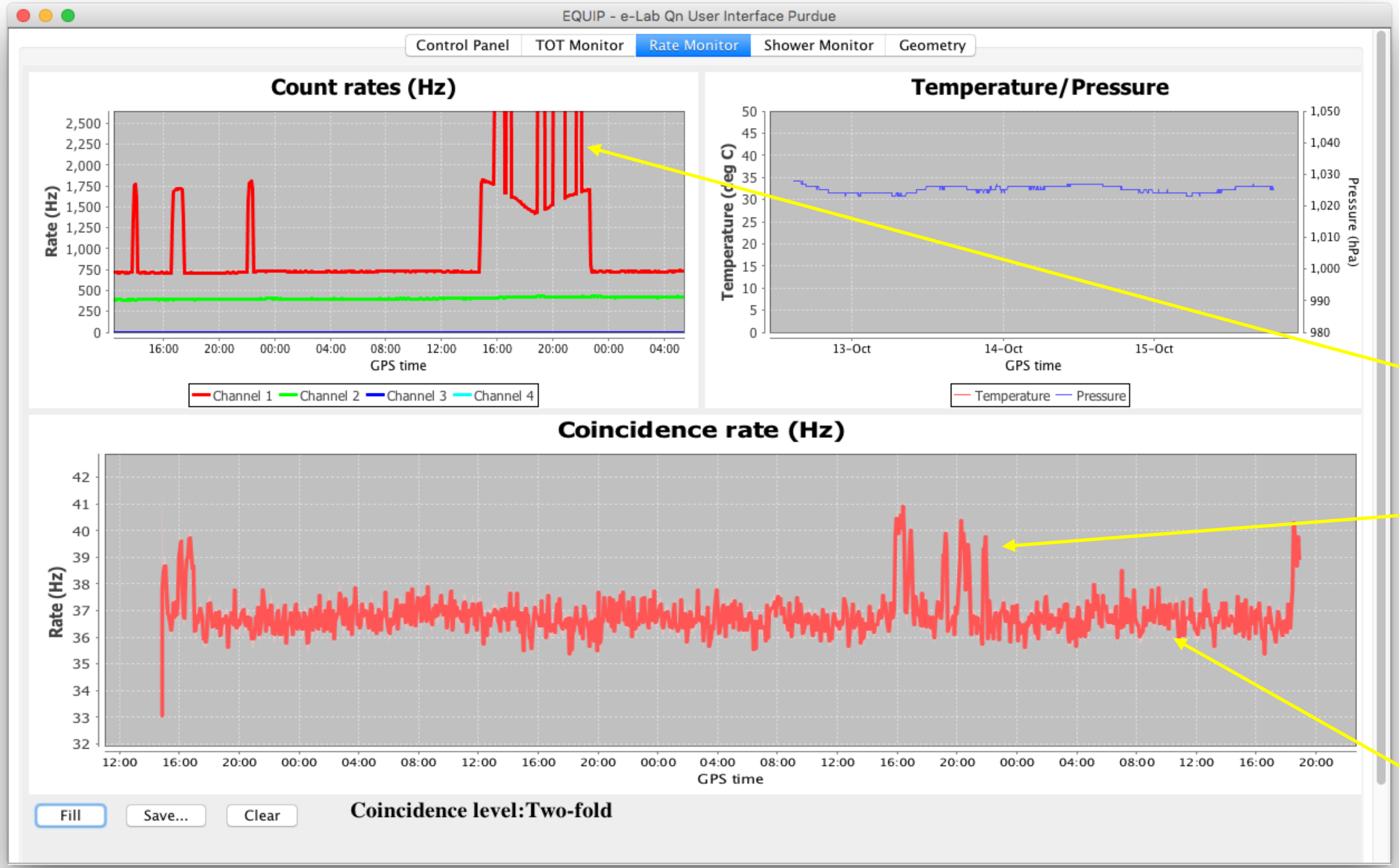

Fig 14: (this is a close up view of Fig 13)
Quarknet counters' single PMT rates and 2 fold coincidence rates over 3 days; the spikes are increased noise from ambient room light.

Observations:

1. The measured counter baseline rates are for Channel 1 750 Hz and Channel 2 400 Hz; the expected noise coincidence rate is:

2(750 Hz)(400 Hz)(300 ns) = 1.8 Hz;

2. When the room lights were turned on Channel 1 noise spiked at 21 kHz, and Channel 2 noise stayed at 400 Hz; the expected noise coincidence rate is:

2(21,000 Hz)(400 Hz)(300 ns) = 5 Hz;
the measured coincidence rate rose accordingly by about 5 Hz (41 Hz – 36 Hz)

3. The expected cosmic ray coincidence rate for a good scintillator detector of this size is 12.5 Hz:

1 cm^2/min x (30 cm x 25 cm) x 1min/60s = 12.5 Hz;
the coincidence rate was measured at about 36 Hz.

Conclusions: 1) when the room light were turned off the measured coincidence rate of 36Hz is about 3 times higher than the expected muon coincidence rate; it is not known why the measured rate was so much higher than the expected rate. When the room lights were turned on the detector's noise coincidence rate increased by 5Hz as expected based on the individual counter noise rates.

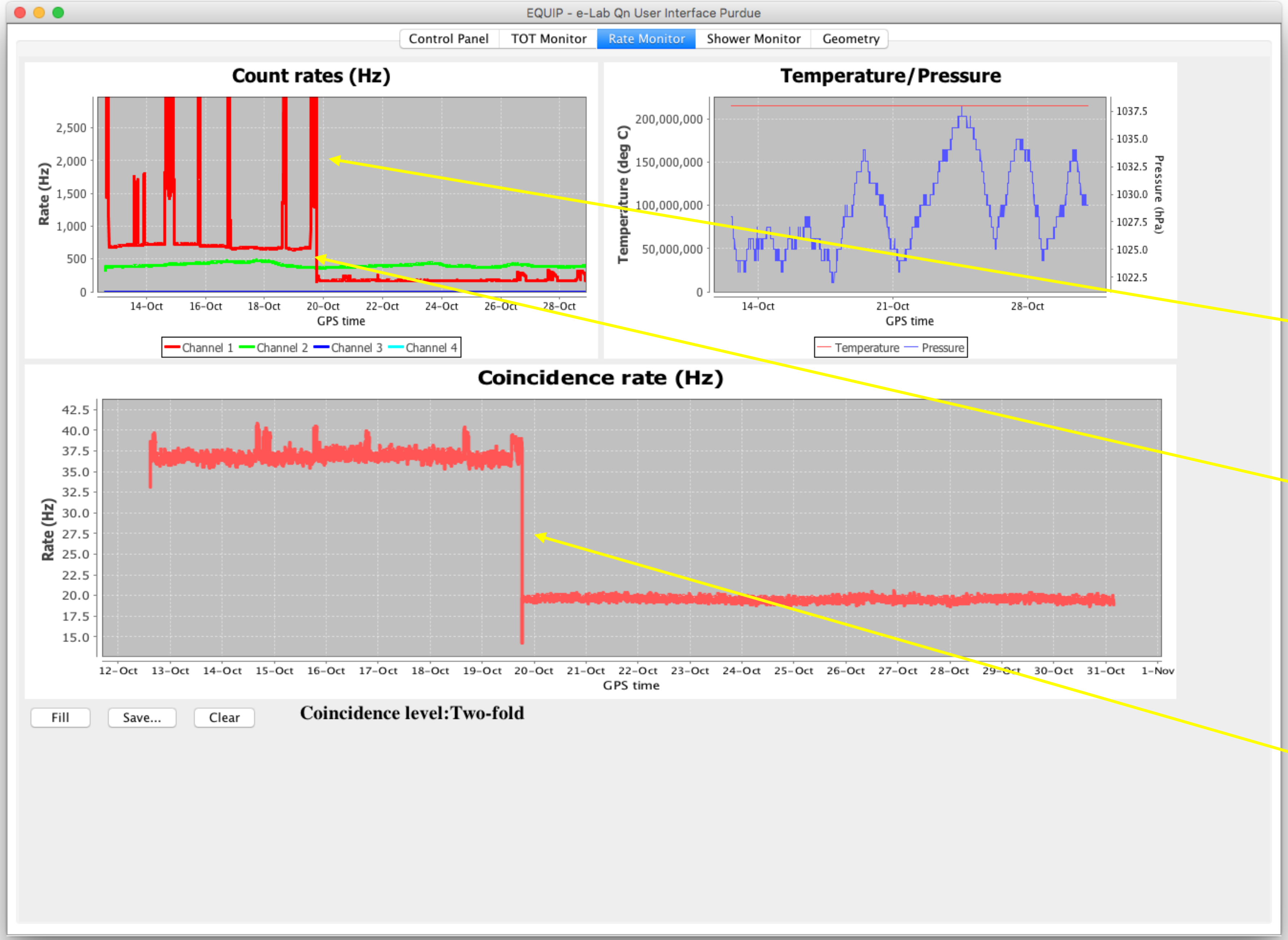

Fig 15: Quarknet detector data taken over 19 days in May-June, 2019 (the date axes are incorrectly labeled October, and the temperature sensor data is not right)

The large spikes are increased counter noise when the room lights were turned on.

On Oct. 19 the Channel 1 noise rate dropped to about 200 Hz when the pmt operating high voltage was lowered; the noise coincidence is expected to have dropped to

$$2(200\ \text{Hz})(400\ \text{Hz})(300\ \text{ns}) = 0.048\ \text{Hz}$$

The measured noise coincidence rate was 20 Hz; the rate dropped by 16 Hz (36 Hz – 20 Hz); it is not known why the rate dropped so dramatically.

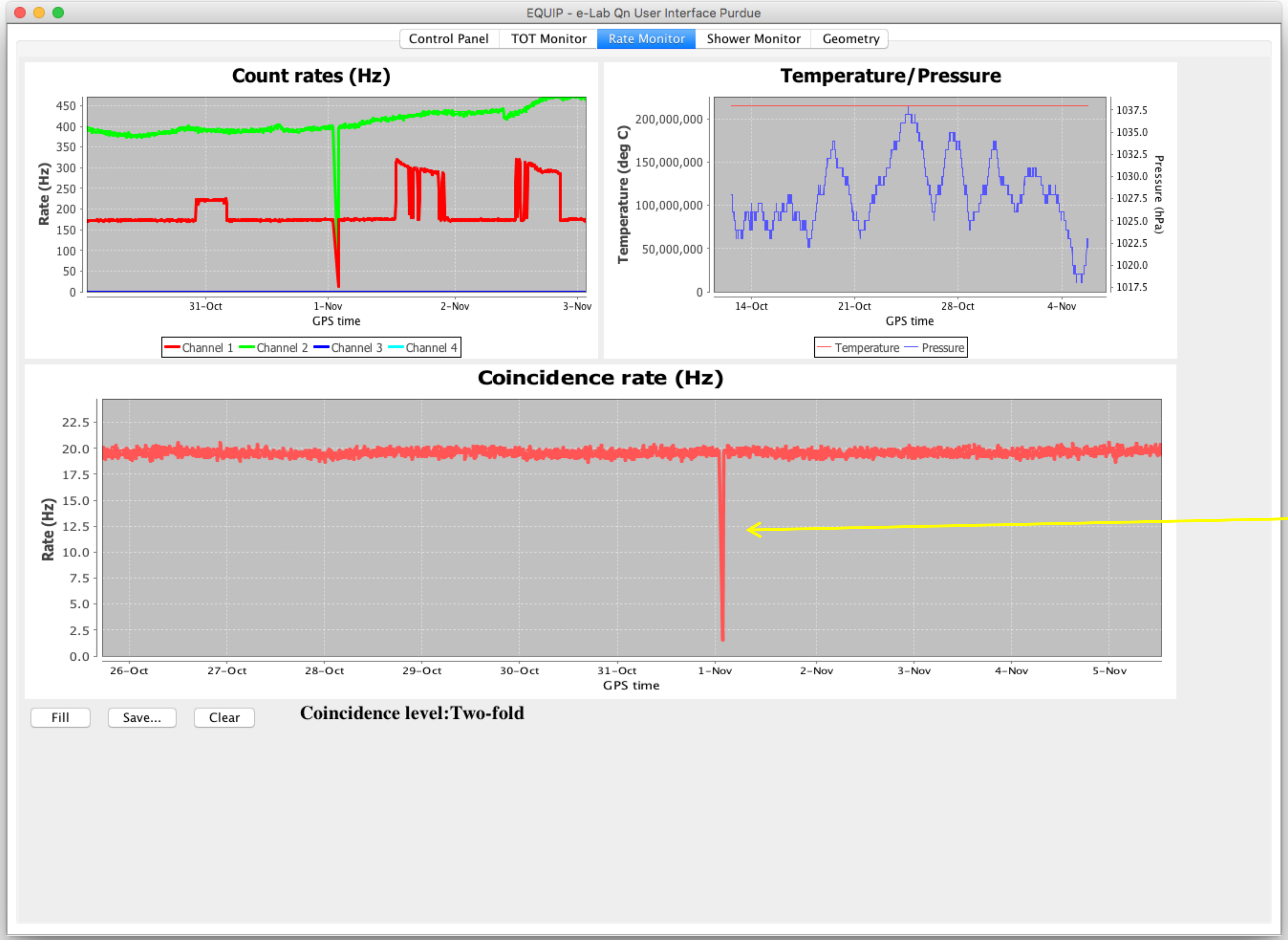

Fig 16: Quarknet detector data taken over May-June, 2019 (the date axes are incorrectly labeled Oct-Nov, and the temperature sensor data is not right)

For some unknown reason all three detectors CUNY, Vaughn, and QuarkNet lost data for about 30 minutes on the date indicated as Nov 1 st 0100, which may have been June 16th 9:00 pm EDT

Results and conclusions:

1. Over the ~ 20 days of data collection at one point for about a half hour all three detectors lost data, for some unknown reason, and then resumed collecting data; we know the computers did not lose power because they did not reboot and the Equip data collection programs remained open; we wonder if the cause was a fast fluctuation in line power.
2. When the pmt high voltages are increased or decreased the noise coincidence rate increases and decreases respectively by an amount larger than expected based on the individual noise rates of the counters; this was observed for both the Vaughn and Quark Net detectors.

CUNY detector:
1. Ambient room light is getting into counter 1 (the 106cm x 30cm x 2cm scintillator); a light leak was found and the counter was wrapped better but light is still getting in; the amount of light was not large enough to increase the measured noise coincidence rate.
2. The pmt dark rates were low and did not contribute to the coincidence rate.
3. When the room lights were off the measured two-fold coincidence rate was only 2 to 4 Hz; the expected cosmic ray muon rate for a good scintillator detector of this size is 52 Hz; thus this detector is not working well. The pmts' high voltages were set at 2.9 kHz (providing ~ 10^6 gain), 3 mV discriminator thresholds were used, and a 300 ns coincidence gate width.

Vaughn detector:
1. Ambient room light is getting into both counters; when the room lights were turned on the noise coincidence rate went up by 6 Hz as expected based on the individual counter noise rates.
2. When the room lights were off the measured coincidence rate was 13 Hz which is close to the 15 Hz expected for cosmic ray muons through a good scintillator detector of this size; however, we are not convinced these 13 Hz are all muons because we known this scintillator produces low levels of light output, and we expected the rate to be lower -- more investigation is needed.
3. The pmts' high voltages were increased resulting in an increase in the detector's coincidence rate by 30Hz, which is a few times higher than expected based on the individual counter noise rates (the room lights were off during this).

Quarknet detector:
1. Ambient room light is getting into counter 1; when the room lights were turned on the detector's noise coincidence rate increased by 5Hz as expected based on the individual counter noise rates.
2. With the room lights off the measured coincidence rate was 20 Hz while the pmts were powered at a lower voltage, and 36 Hz when powered at a higher voltage; the expected cosmic ray muon rate for a good scintillator detector of this size is 12.5 Hz; it is not known why the measured rates were 2 to 3 times higher than the expected cosmic ray rates.
3. When the pmts' high voltages were decreased the coincidence rate decreased by 16 Hz, but it was only expected to decrease by less than 1 Hz based on the individual counter noise rates.

Summary of the results from this study

1. **Detector performances** -- the CUNY detector did not perform well as its measured coincidence rate was far below the expected cosmic ray muon rate; the Vaughn and Quarknet detectors measured rates from close to, to a few times higher than the expected muon rate.

2. **Light leaks and ambient light noise** – light gets into four of the six counters causing large noise rates. In Vaughn and Quarknet counters the light leaks are so bad they caused an increase in their noise coincidence rates. When the room lights were on the increases in noise coincidence rates were as expected based on the individual counter noise rates.

3. **PMT dark rate noise** -- increasing (and decreasing) the pmt operating high voltages increased (and decreased respectively) the counter noise rates, and subsequently the two-fold coincidence rate; however, the increase (and decrease) in the coincidence rate was larger than expected based on the individual counter noise rates.