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Radar Detection of Ultra High Energy Cosmic Rays: Searching for Coincident Events with Telescope Array Radar and Surface Detectors

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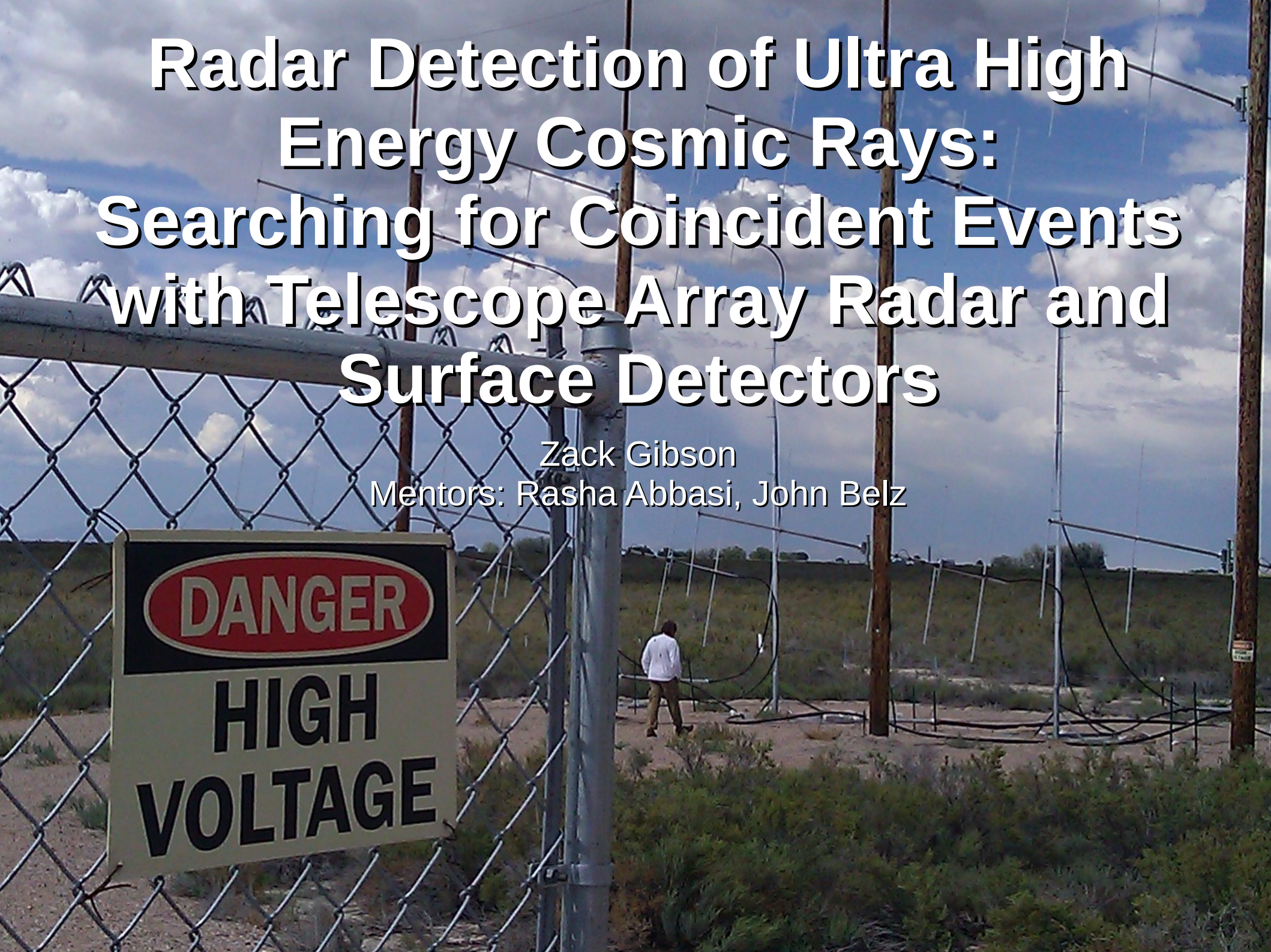
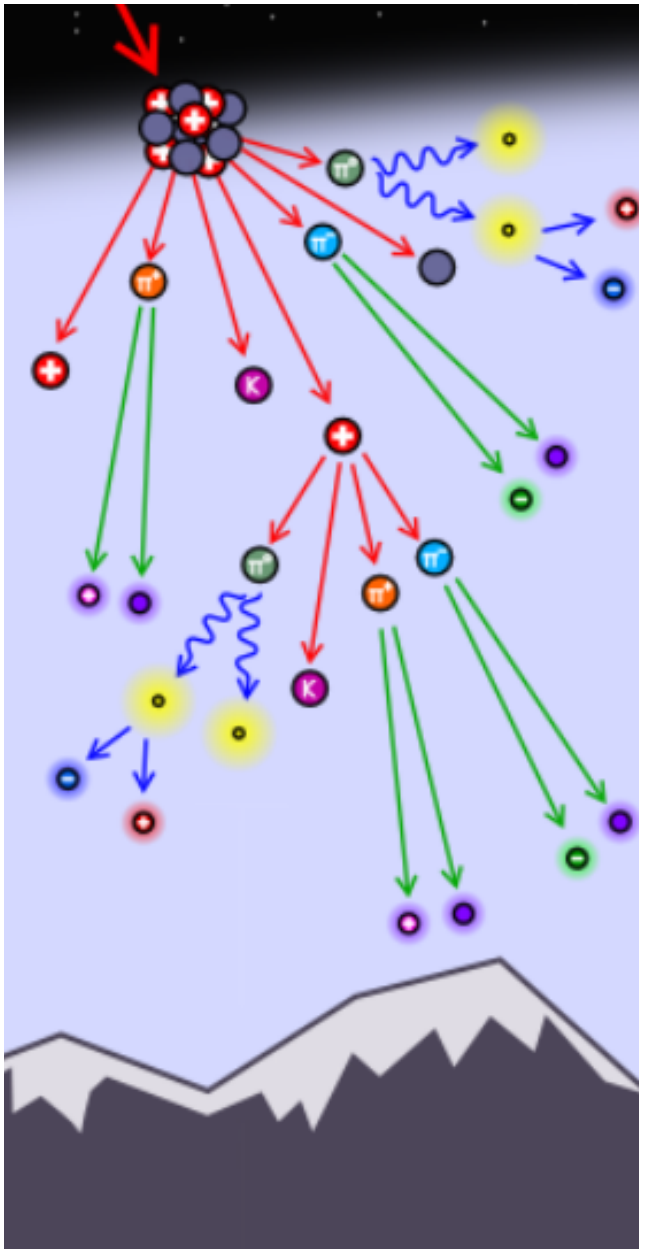
Zack Gibson
Mentors: Rasha Abbasi, John Belz



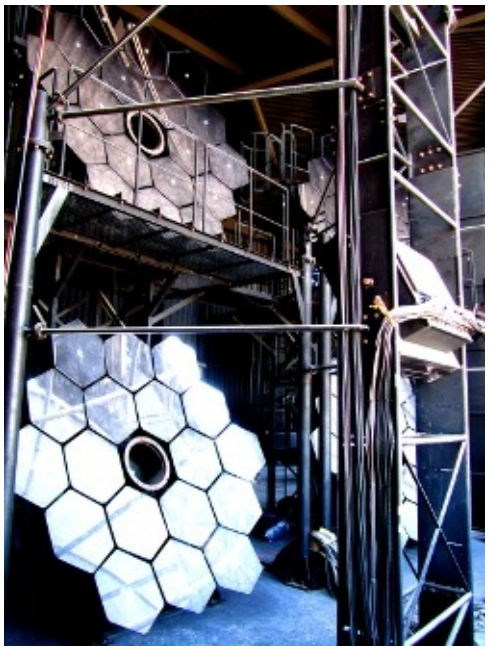
Overview of Presentation

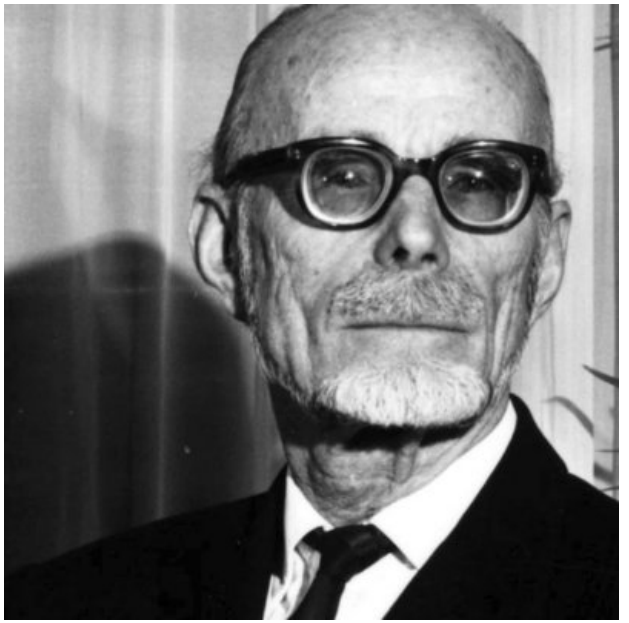
- Introduction of Cosmic Rays
- Radar Detection
- TARA
  - Set-Up
  - Past Work
  - Time Matching
  - Waveforms
  - Snapshots
- Conclusion and Future Work



Cosmic Rays

- High Energy protons, nuclei, gamma rays, and electrons
- Victor Hess – Electroscope (Nobel Prize)
- Pierre Auger – Extensive Air Showers
- Detection Methods:
  - Scintillation (Surface Detectors)
  - Fluorescence Detectors
  - Radar Detection



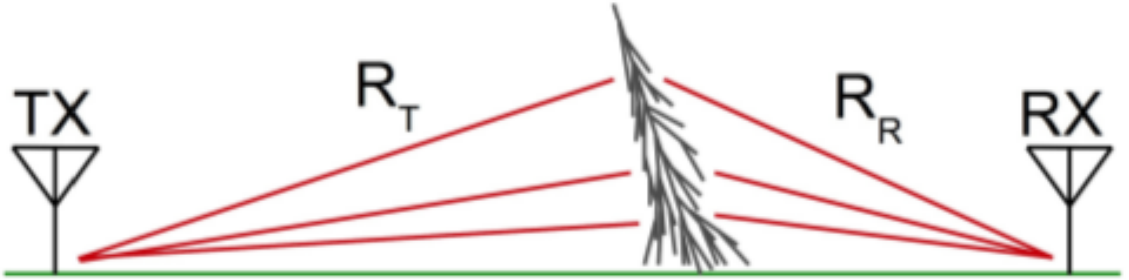


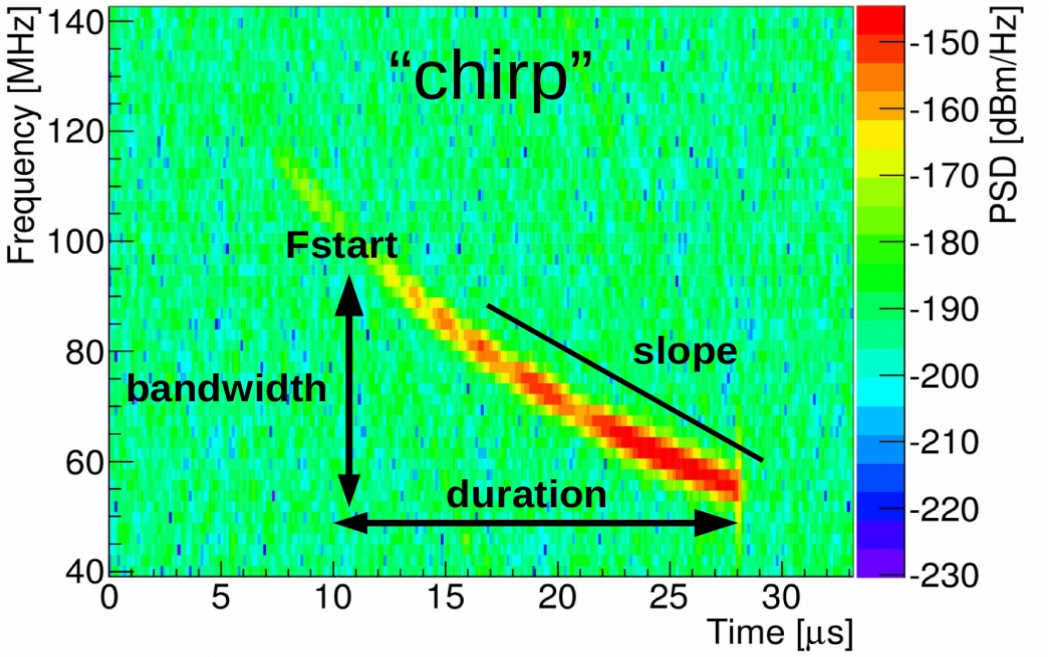
Radar Detection

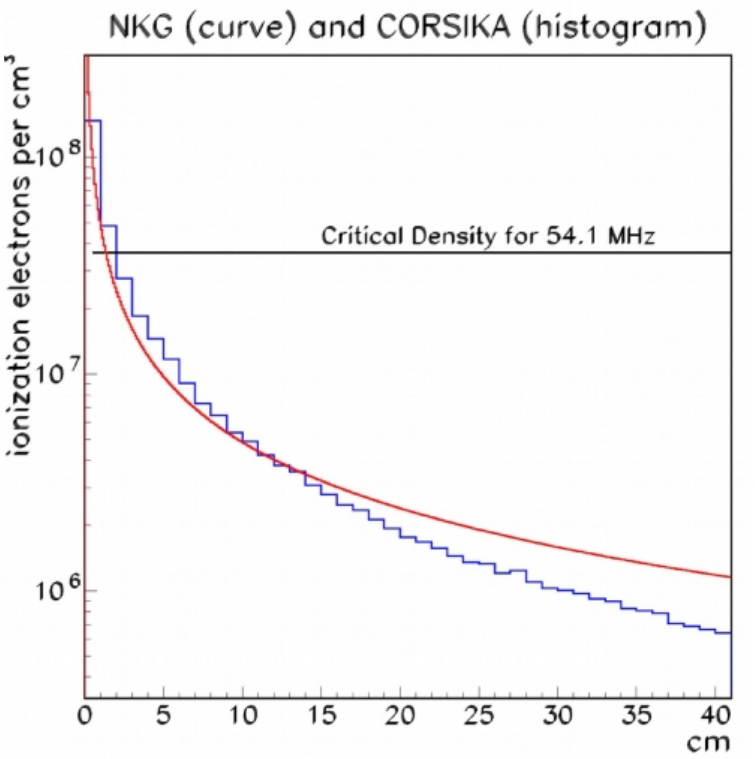
- Radio waves scattered off of ionization electrons in core of air shower
- “Chirp” from Doppler shift

$$P = \frac{P_T G_T}{4\pi R_T^2} \sigma_{TW} \frac{G_R \lambda^2}{(4\pi)^2 R_R^2}$$

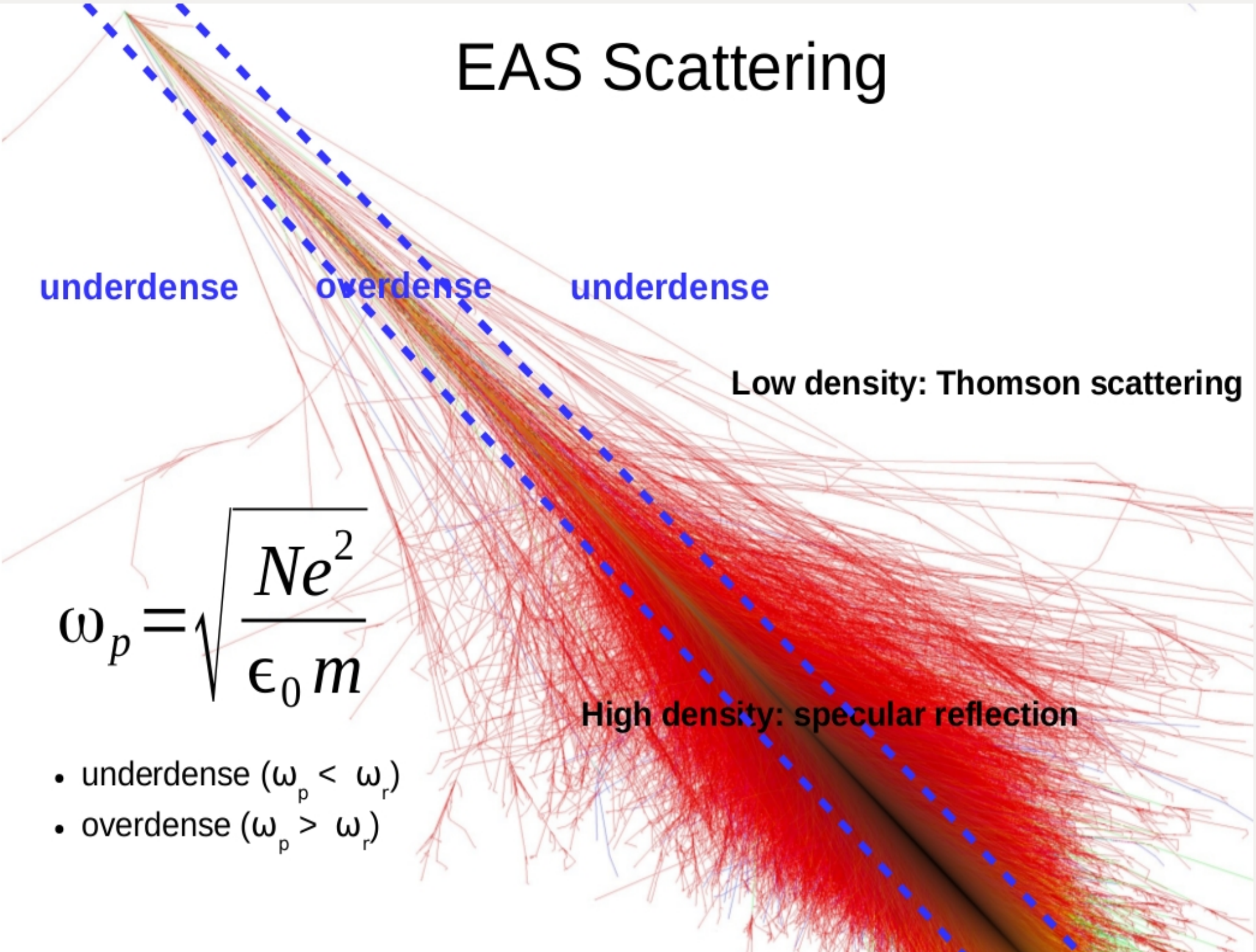
σ_{TW} = thin-wire radar cross section







EAS Scattering



$$\omega_p = \sqrt{\frac{Ne^2}{\epsilon_0 m}}$$

- underdense ($\omega_p < \omega_r$)
- overdense ($\omega_p > \omega_r$)

Why Radar Detection?

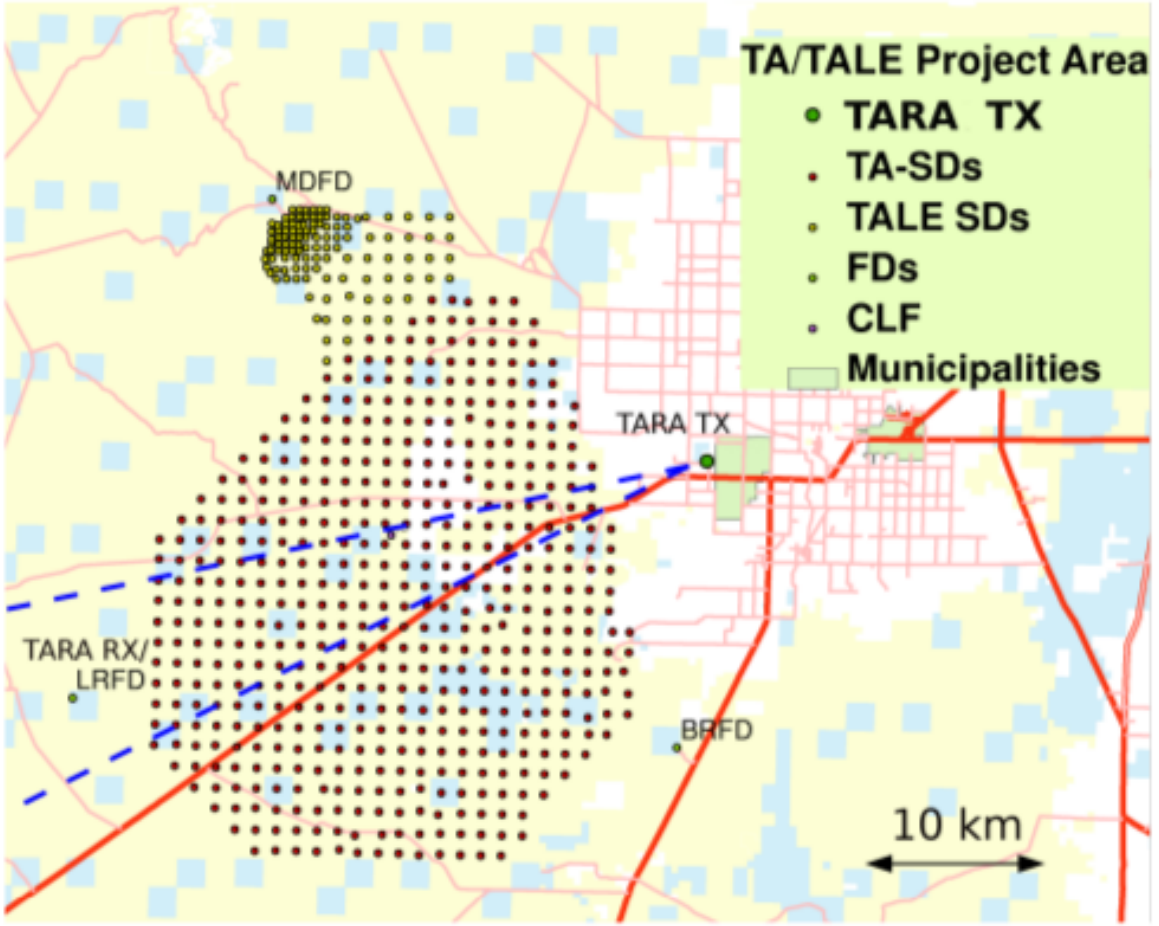

Jodrell Bank – 1940's

- Detection method has been tried before but has never been confirmed
- Remote sensing technique with 24 hour duty cycle

  Downfalls of FD and SD:
- FD ~10% duty cycle
- SD - large array of expensive detectors

Telescope Array Radar (TARA)

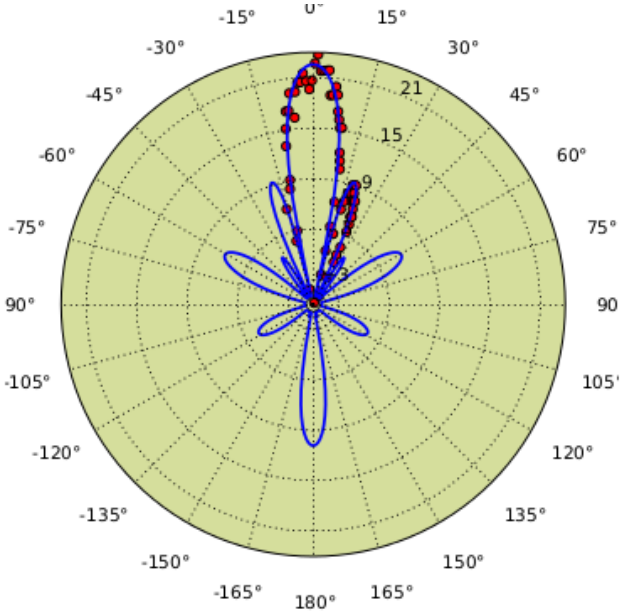
- Bi-static radar system
- Employs re-purposed analog TV transmitter equipment
- Radio-quiet area
- Co-located with TA



Transmitter

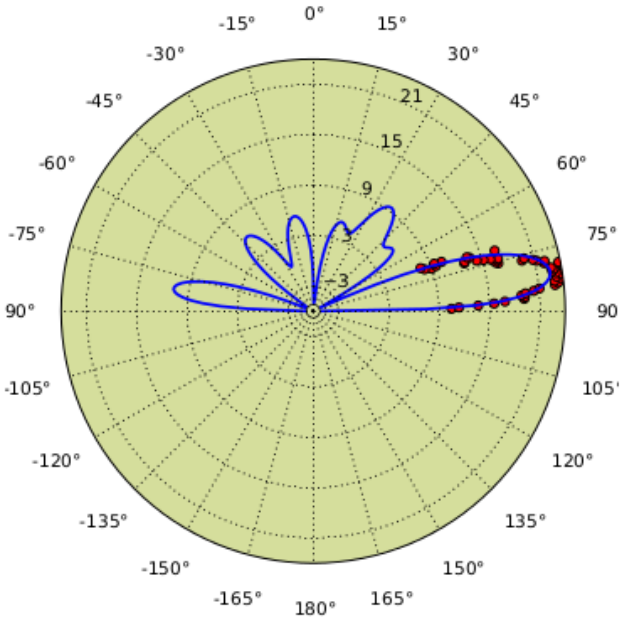
- 54.1 MHz CW
- 25 kW power output
- Effective power ~5MW
- Forward gain ~200 (focused rather than broadcasted)

Transmitter Radiation Pattern



Horizontal

Blue: Simulated
Red: Measurements



Vertical

Receiver

- Dual-polarized
- Broadband
- 12.6 dBi gain
- Records snapshots and self-triggers

TARA Self-Triggers

- GPS time-stamps accurate to +/- 20 ns
- 5 matched filters
- Take Vector Product of the waveform of the matched filter with the signal waveform
- Calculates standard deviation for each filter
- If matched filter response is greater than 5 sigma → Self-Trigger

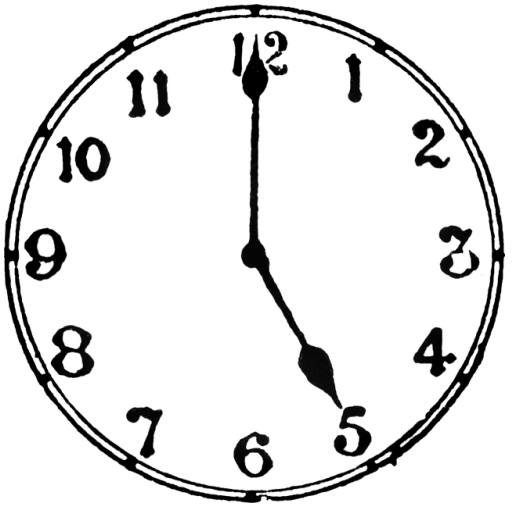
Past Work

- Time-matched FD and TARA self-triggers
- First quantified upper limit on the radar cross section of cosmic ray showers
- FD have ~10% duty cycle, whereas SD have ~100% duty cycle
- Much more data to be analyzed!

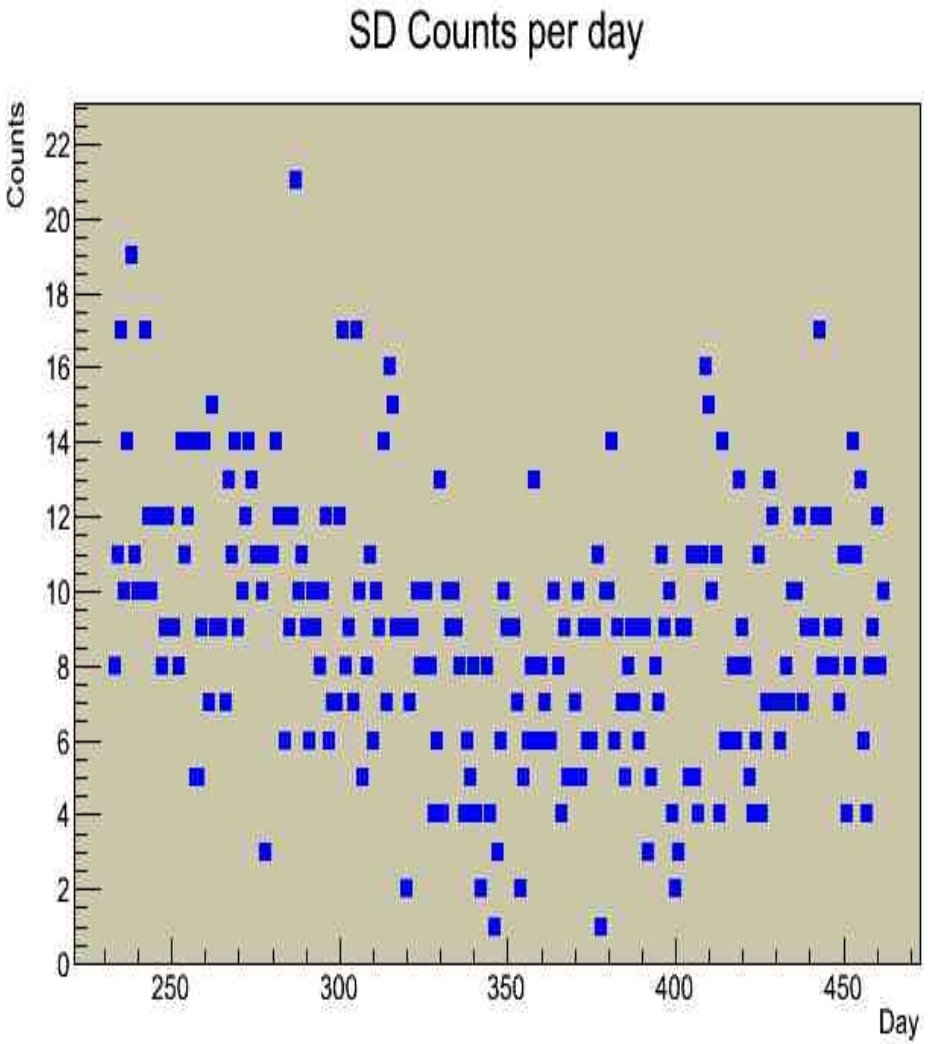
Time-Matching TARA and SD Triggers

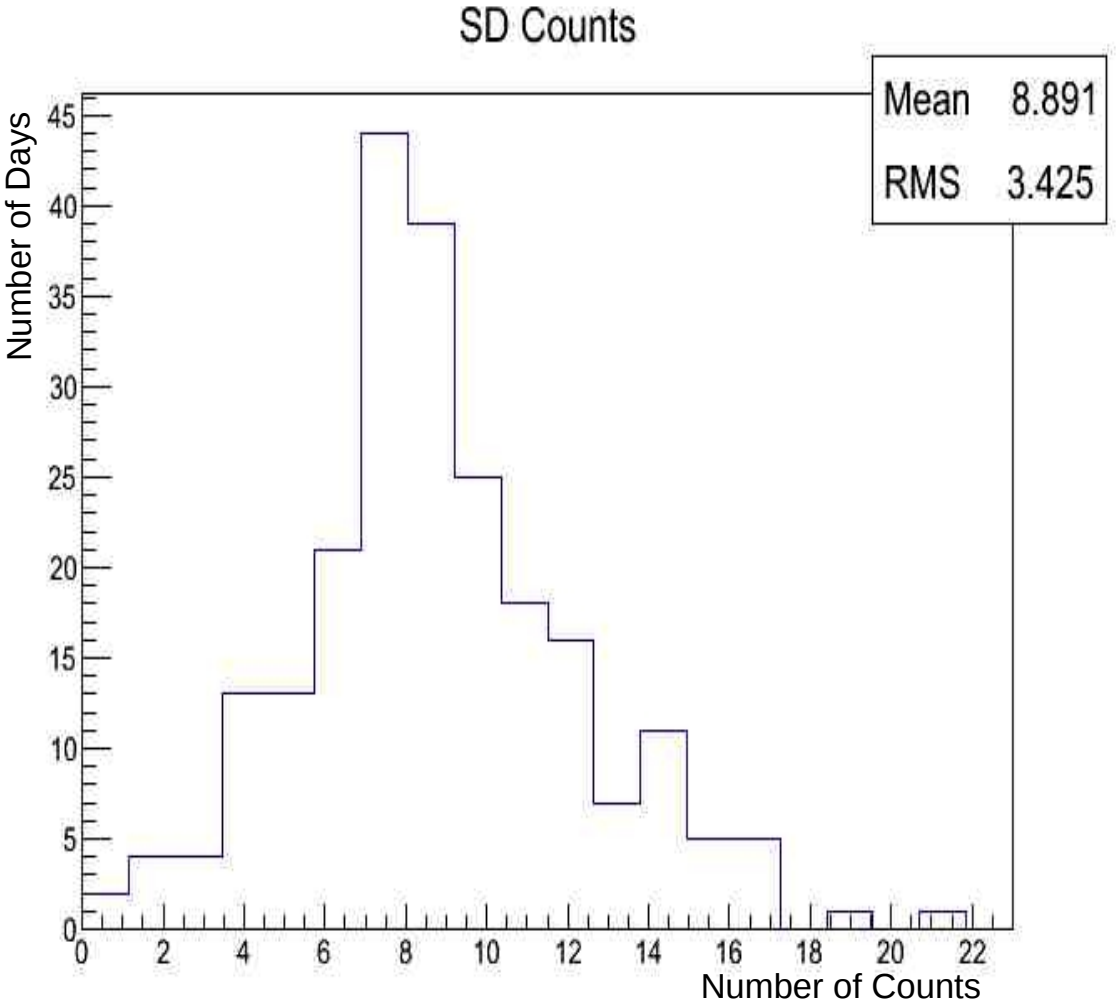
Data Set:

- From August 8th 2013 – April 7th 2014
- Standard cuts made for getting good well constructed cosmic ray events (for SD triggers)



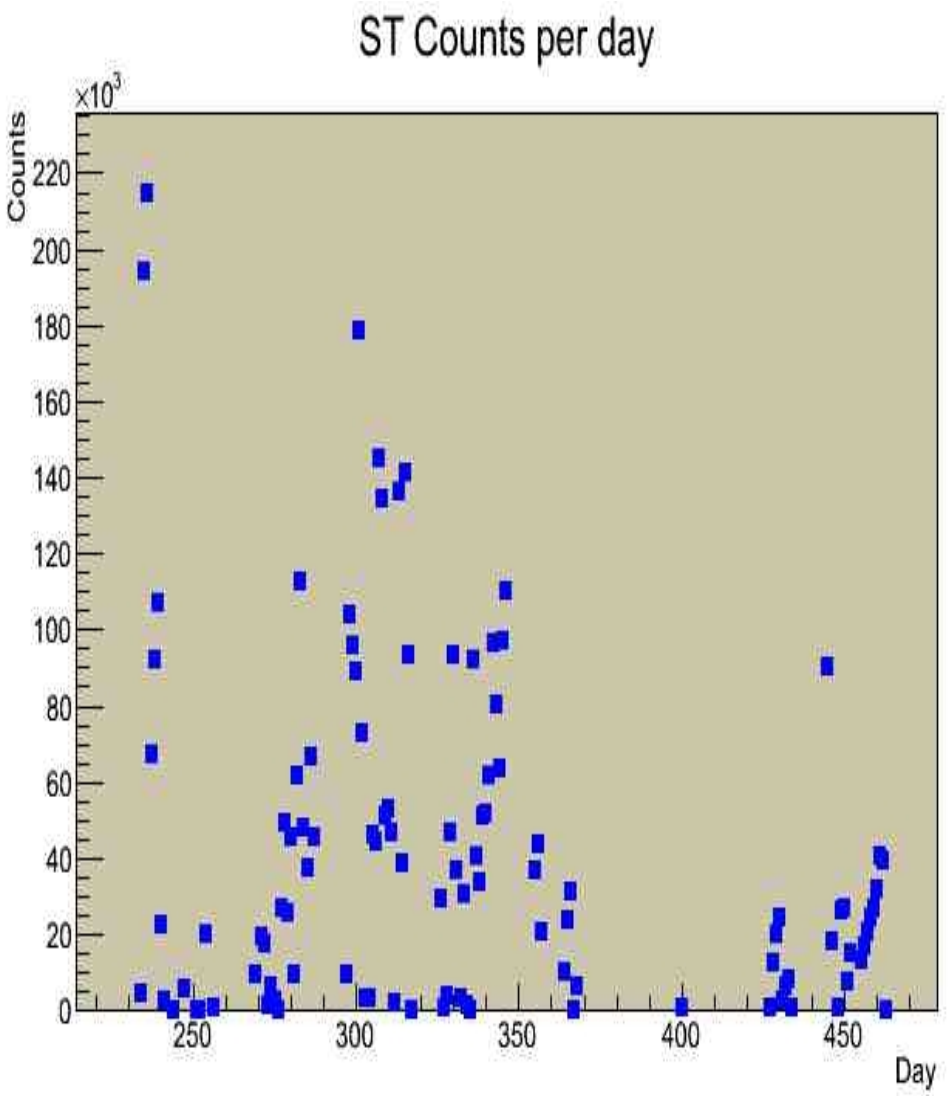
Surface Detectors Counts per Day

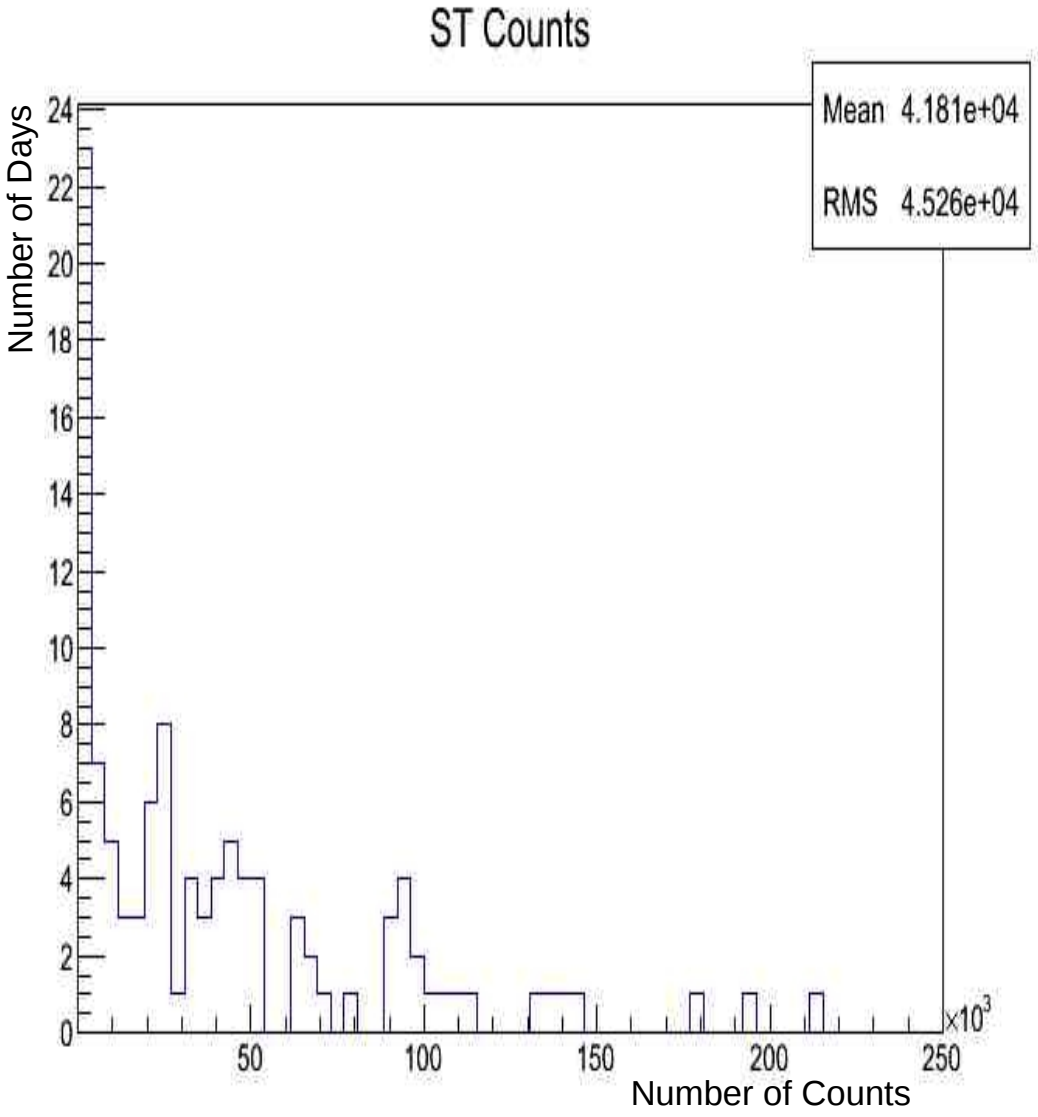




Days with events:229 Total number of events: 2036

TARA Self-Triggers per Day



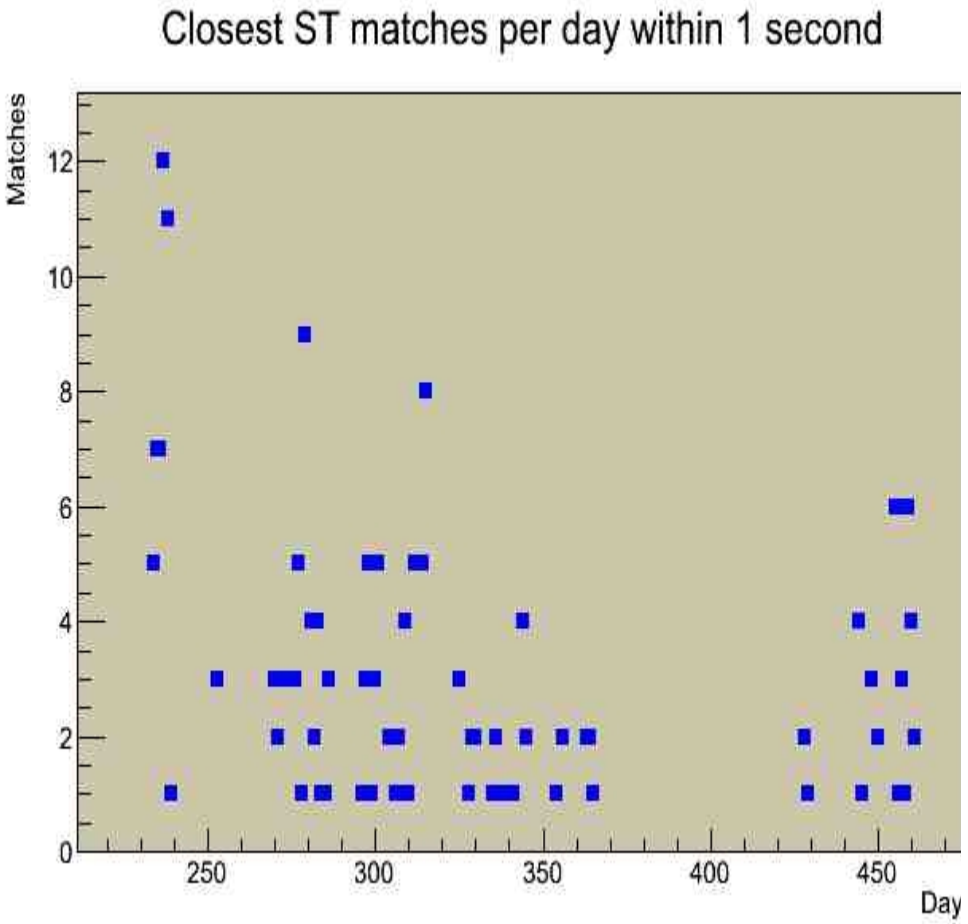


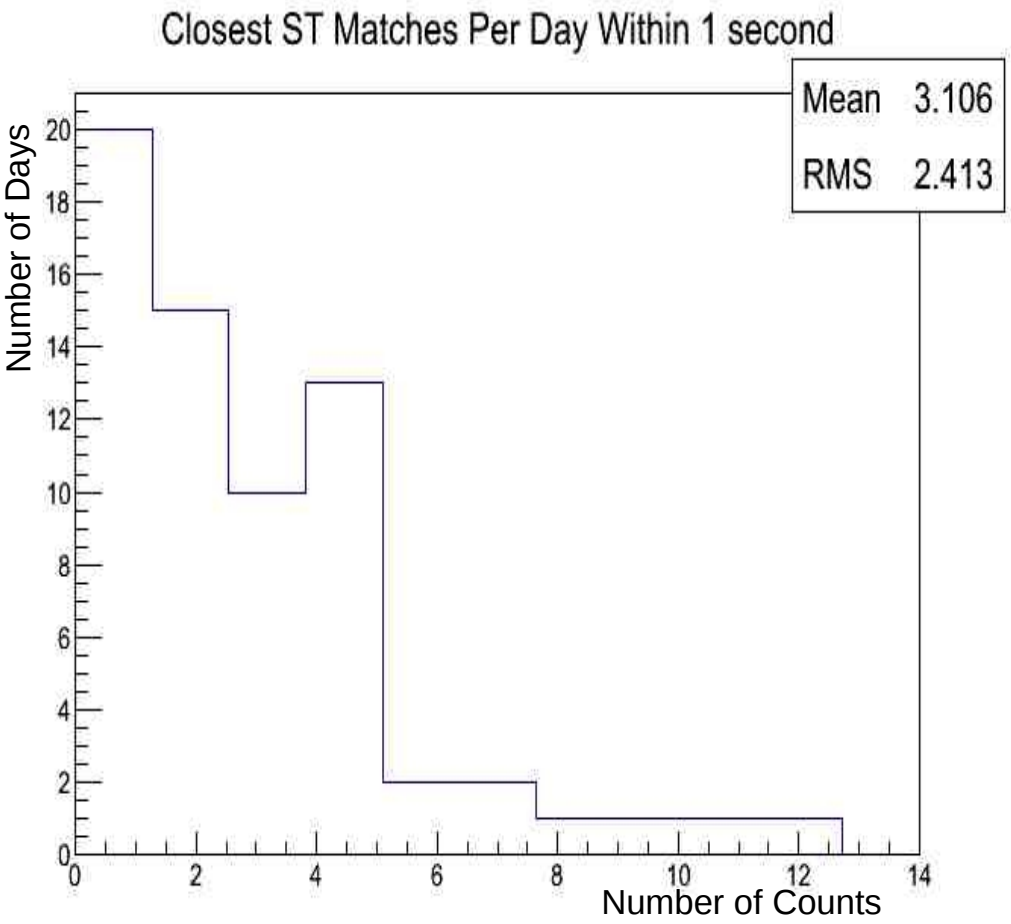
Days with triggers: 107 Total number of triggers: 4473630

Searching for Coincident Events

- **Closest** Time matched events within time windows of:
  - 1 second
  - 500 milliseconds
  - 100 milliseconds
  - 1 millisecond
  - 500 microseconds
  - 100 microseconds

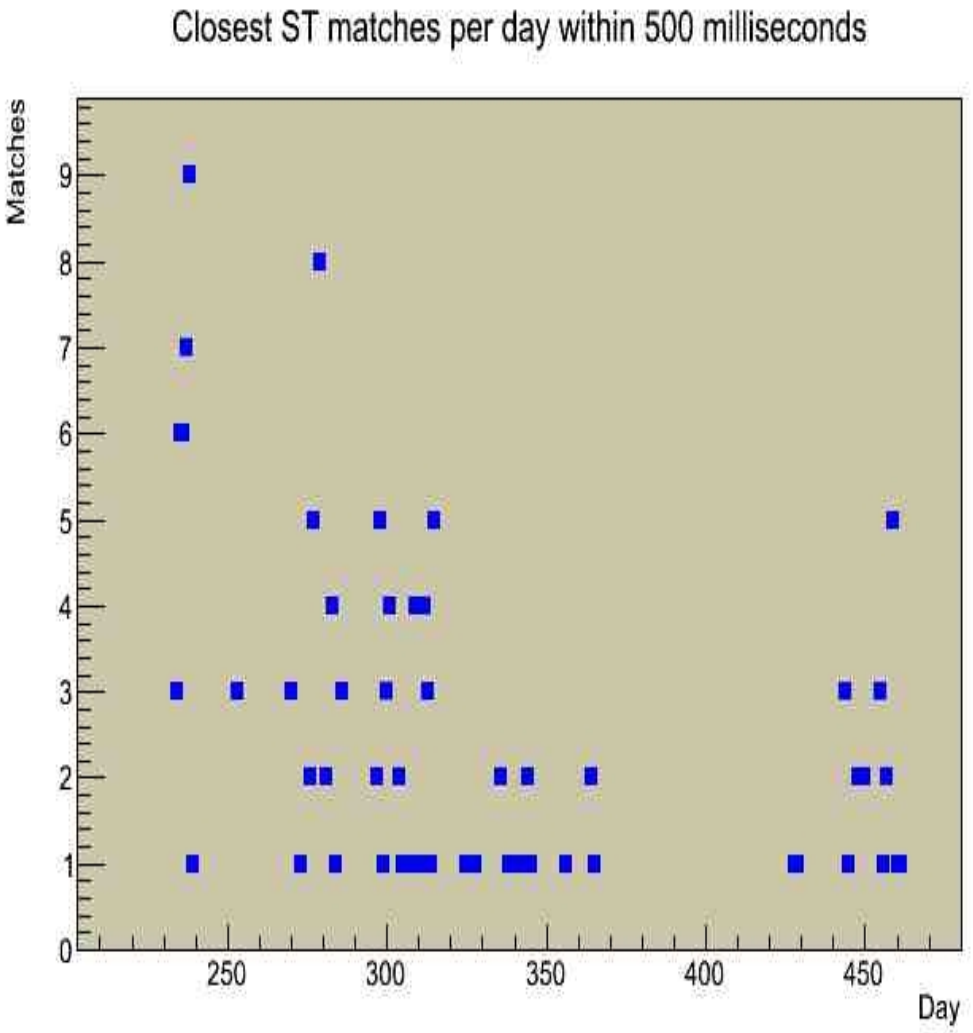
Within 1 second

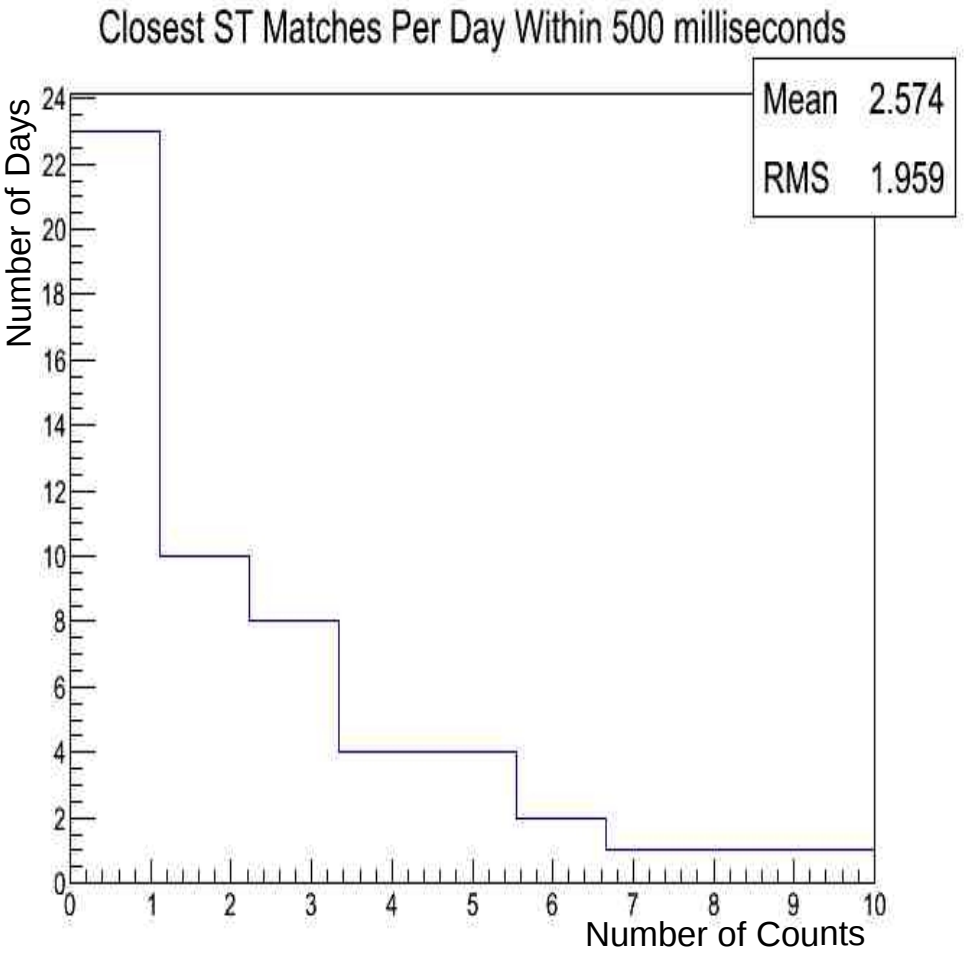




Days with matches: 66 Total number of matches: 205

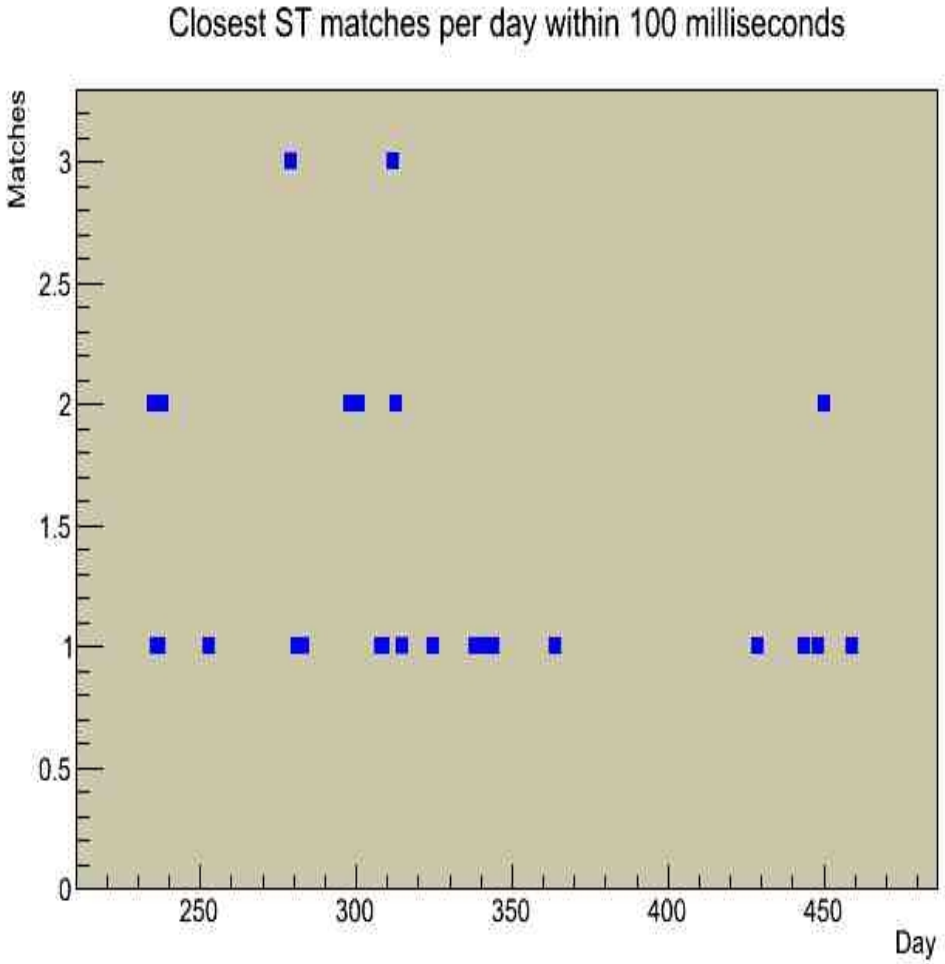
Within 500 milliseconds

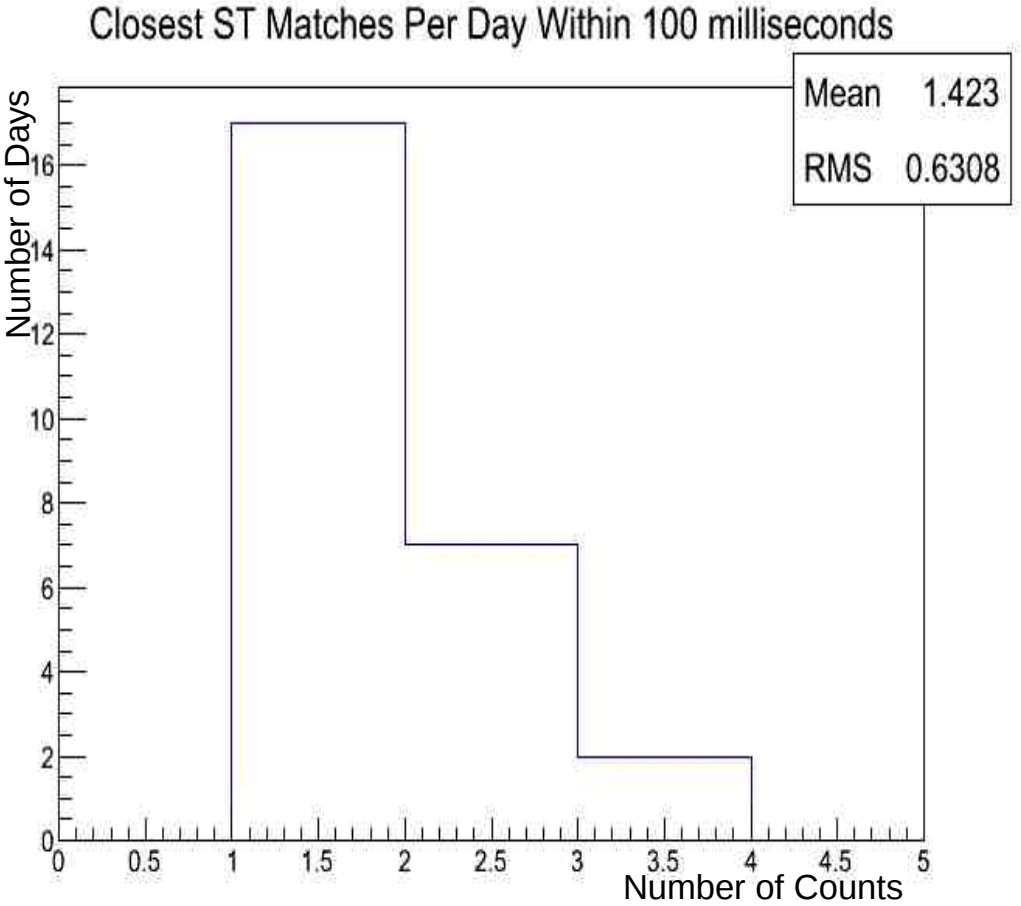




Days with matches: 54 Total number of matches: 139

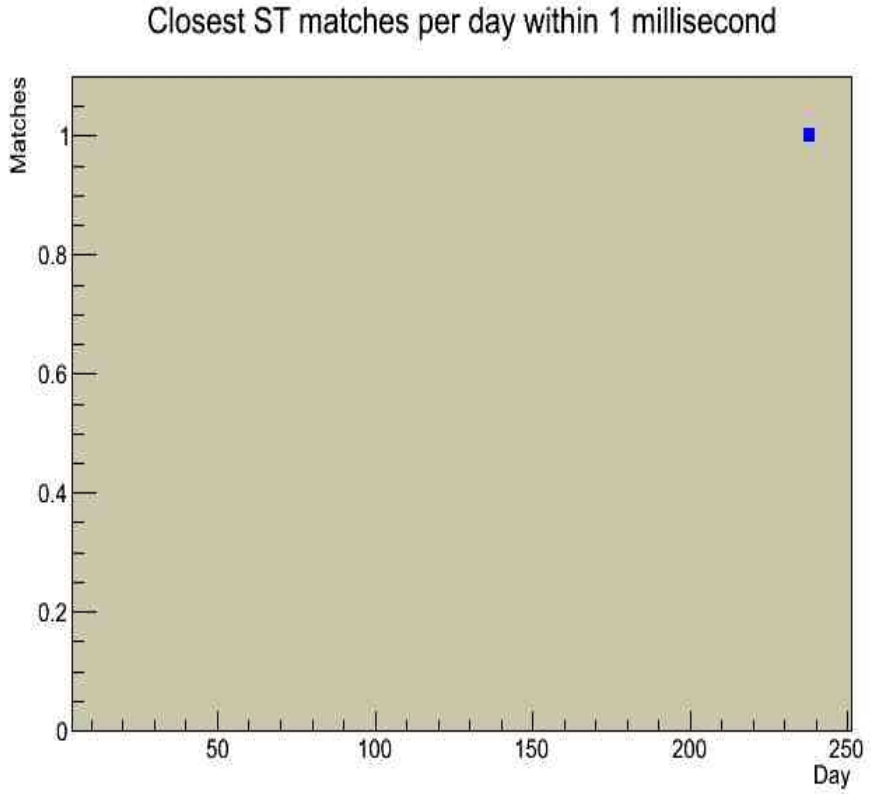
Within 100 milliseconds

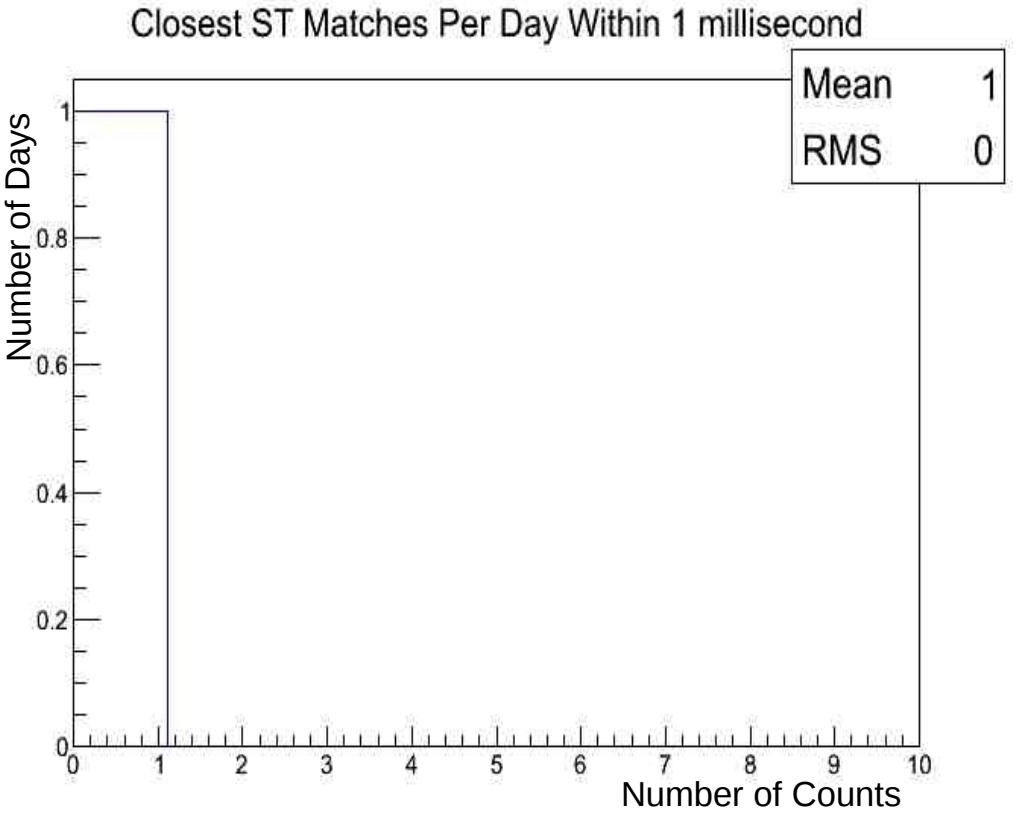




Days with matches: 26 Total number of matches: 37

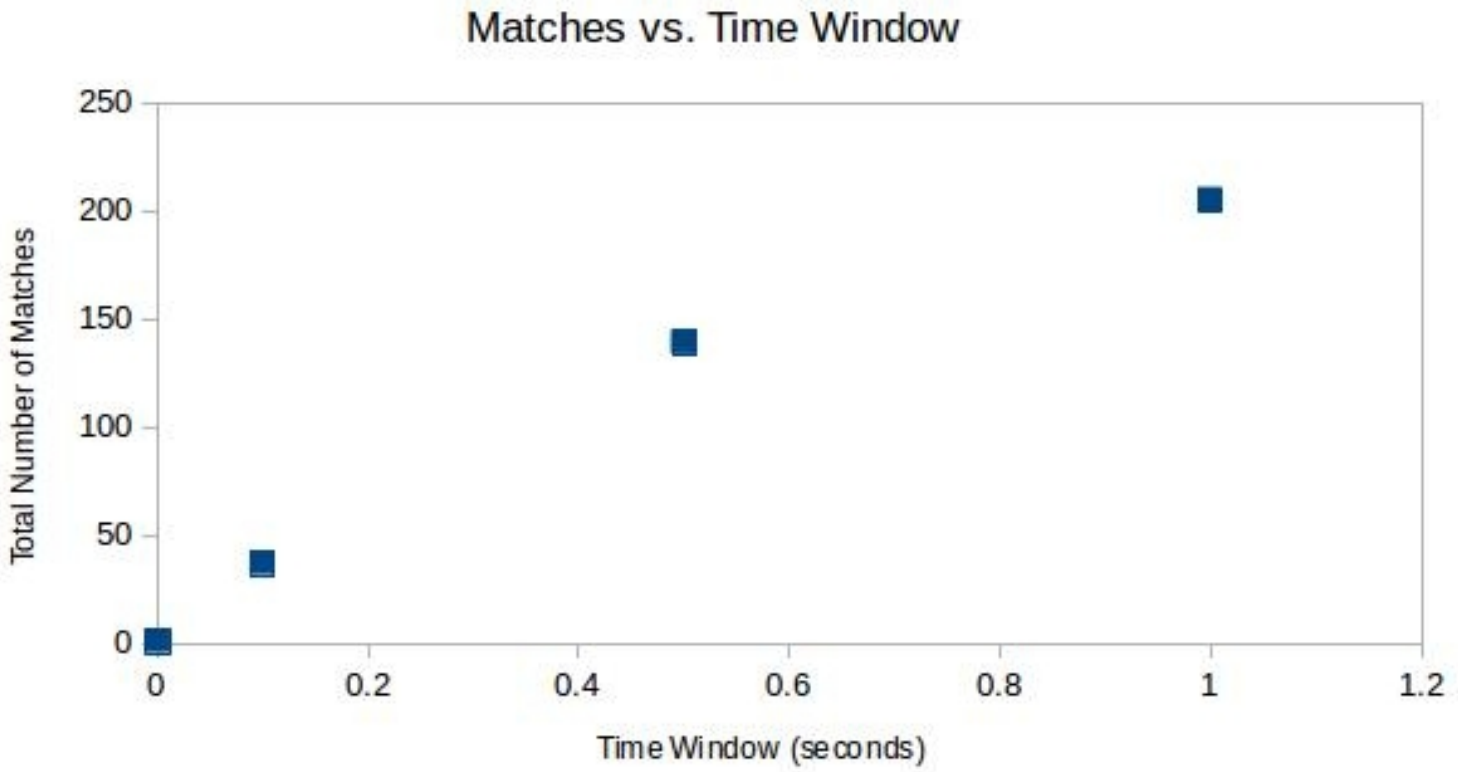
Within 1 millisecond



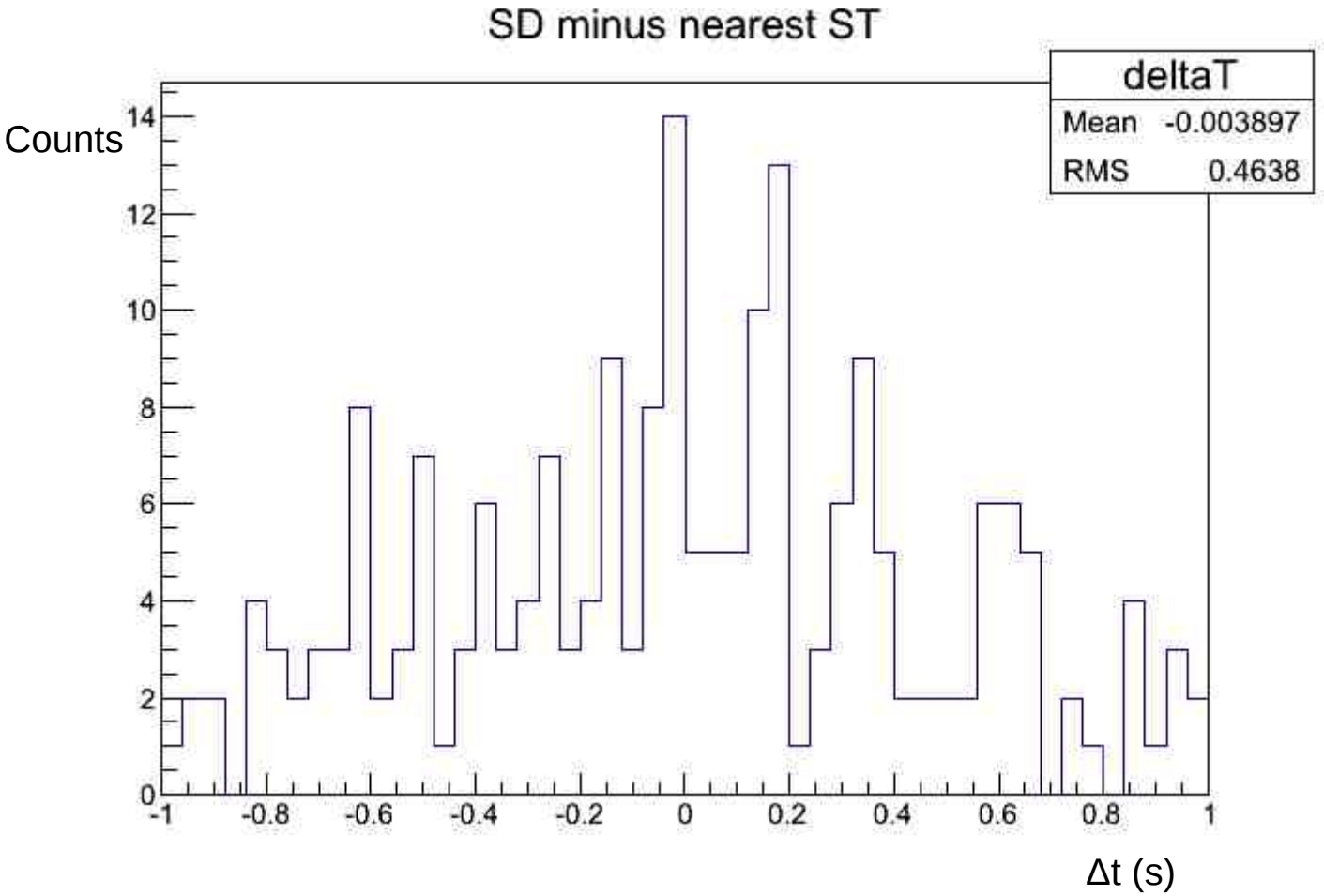


Days with matches: 1 Total number of matches: 1

Comparing Rates



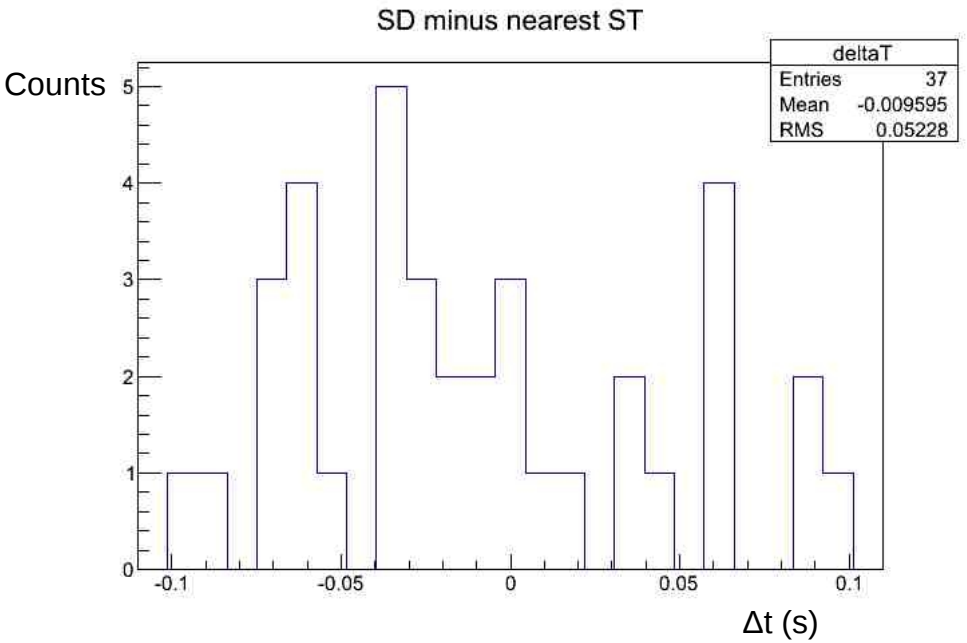
Significance of Matches



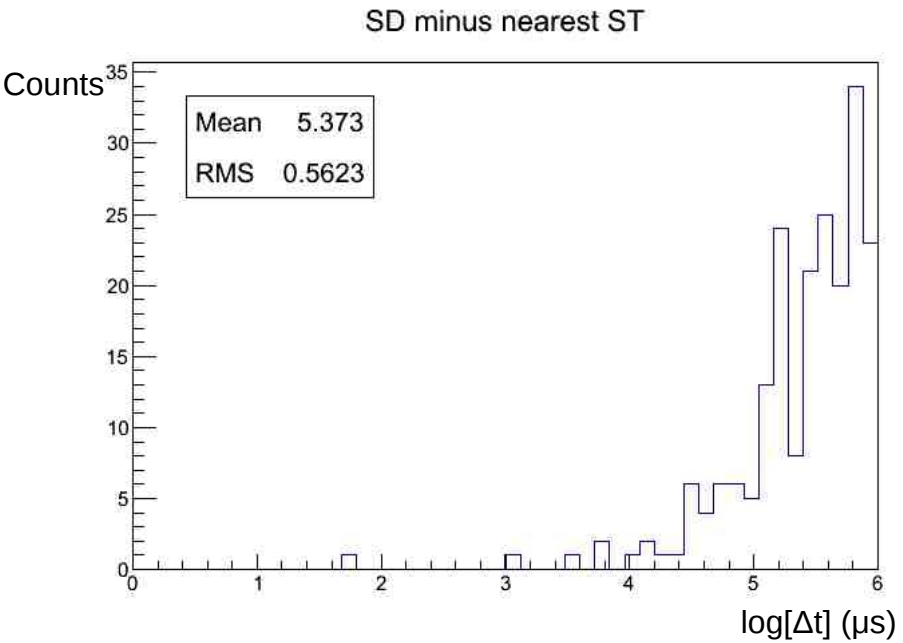
Δt = SD time – Closest ST time
Shape from 100 Hz trigger rate

Significance of Matches

Zoomed in:



Log plot:



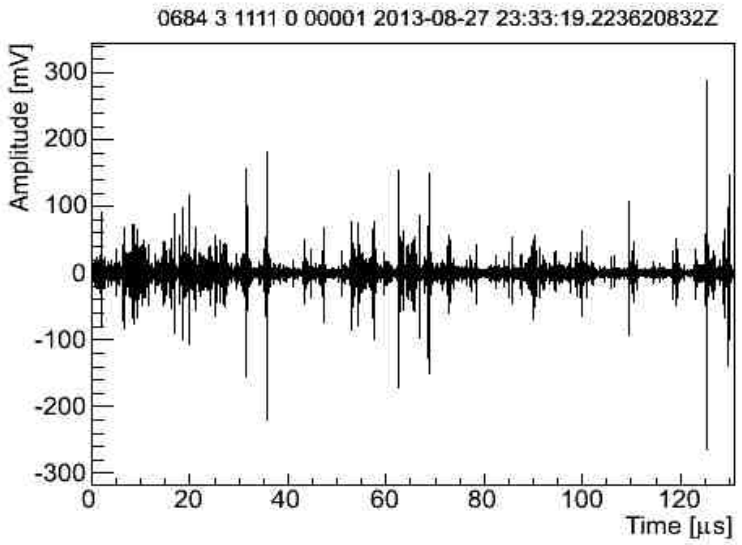
Δt = SD time – Closest ST time

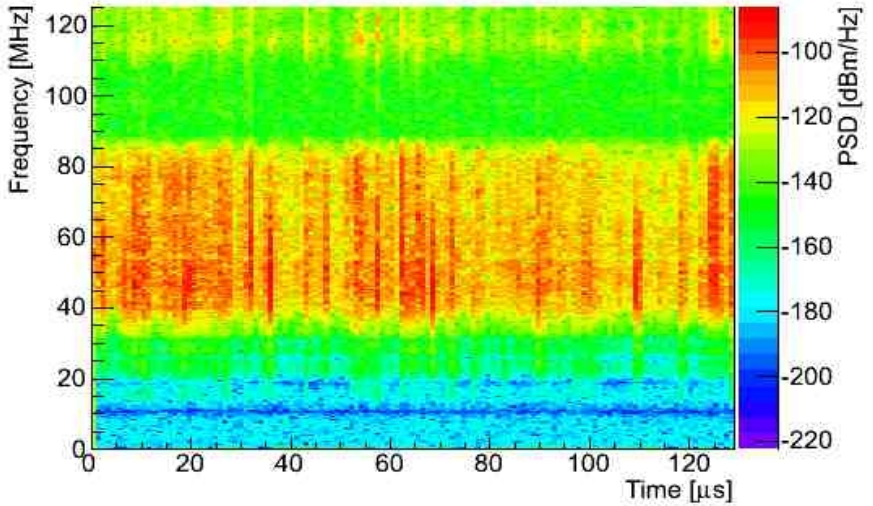
Wave Forms

Example Event Display:

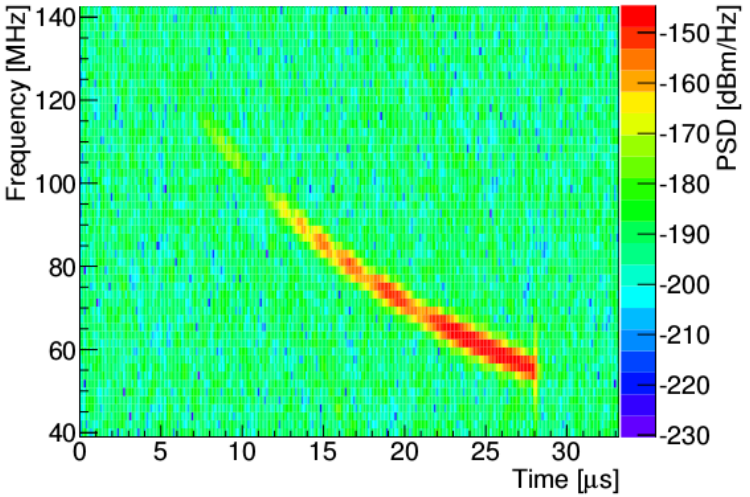
Amplitude versus Time (top)

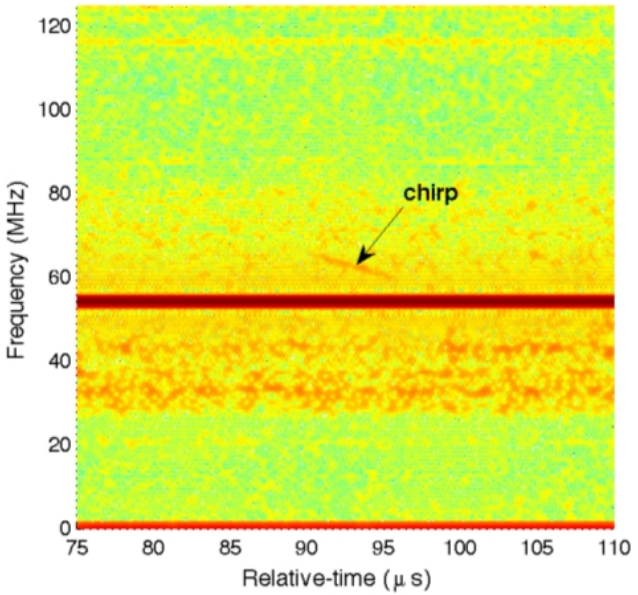
Fourier Transform to get frequency versus time (bottom)

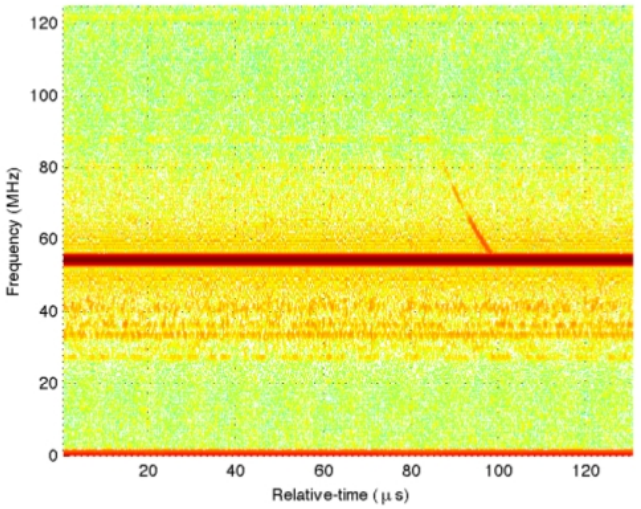




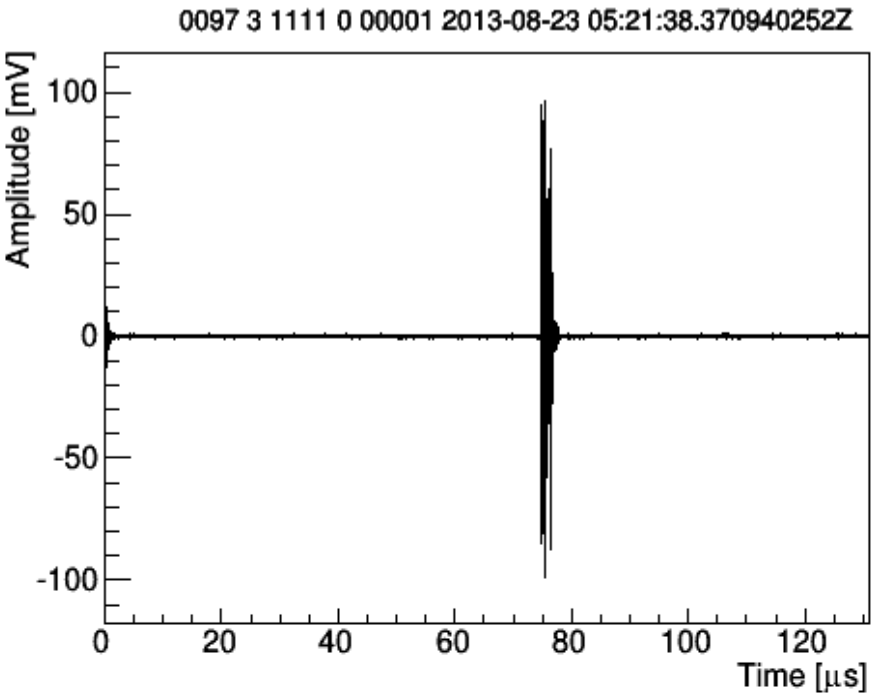
Simulated “Chirp”

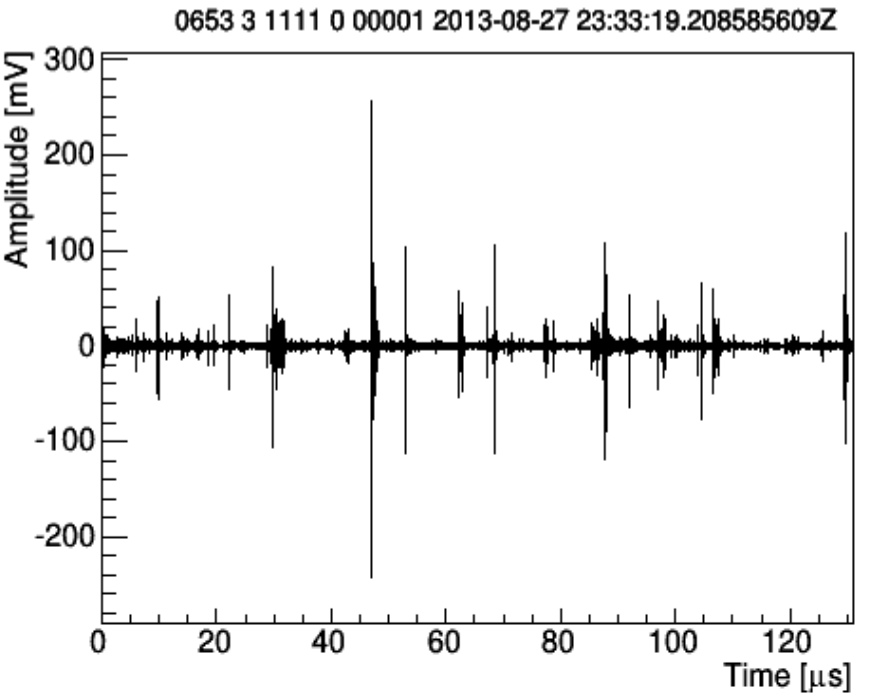


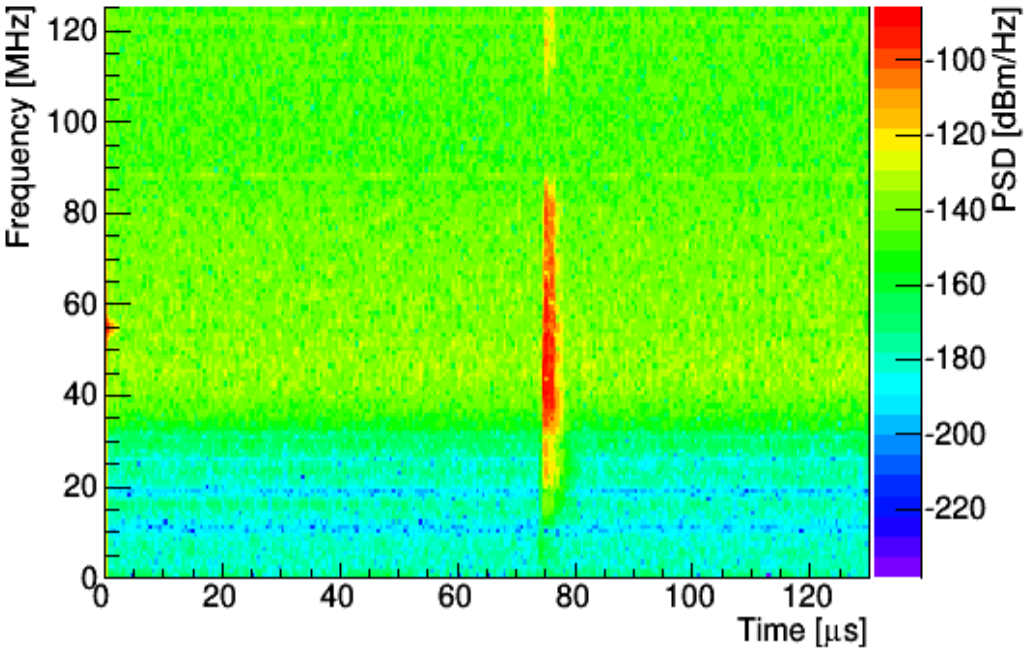


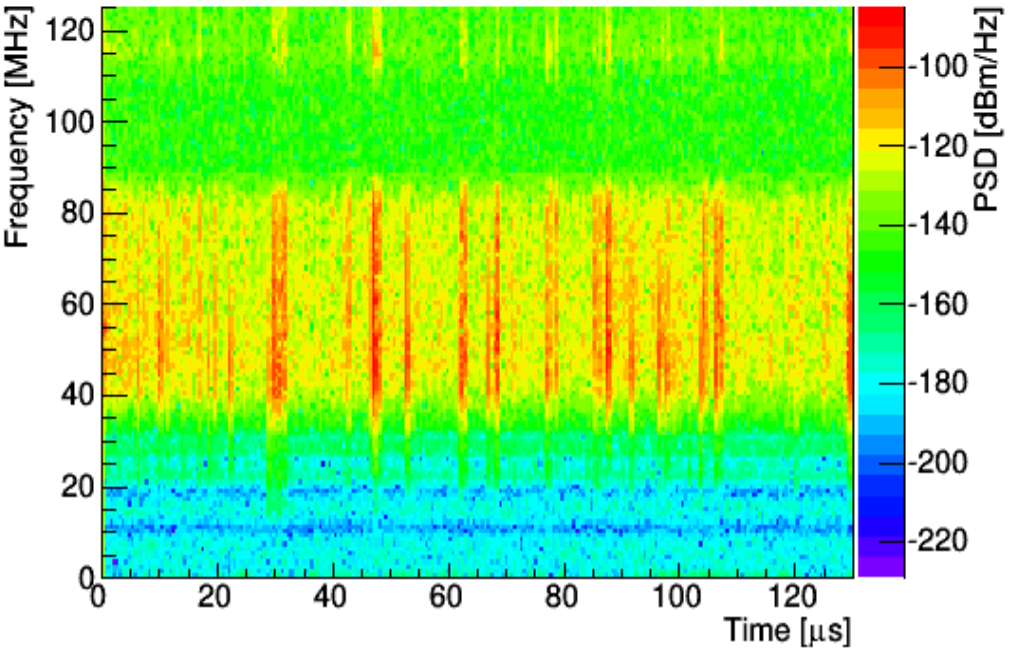


Collected Data









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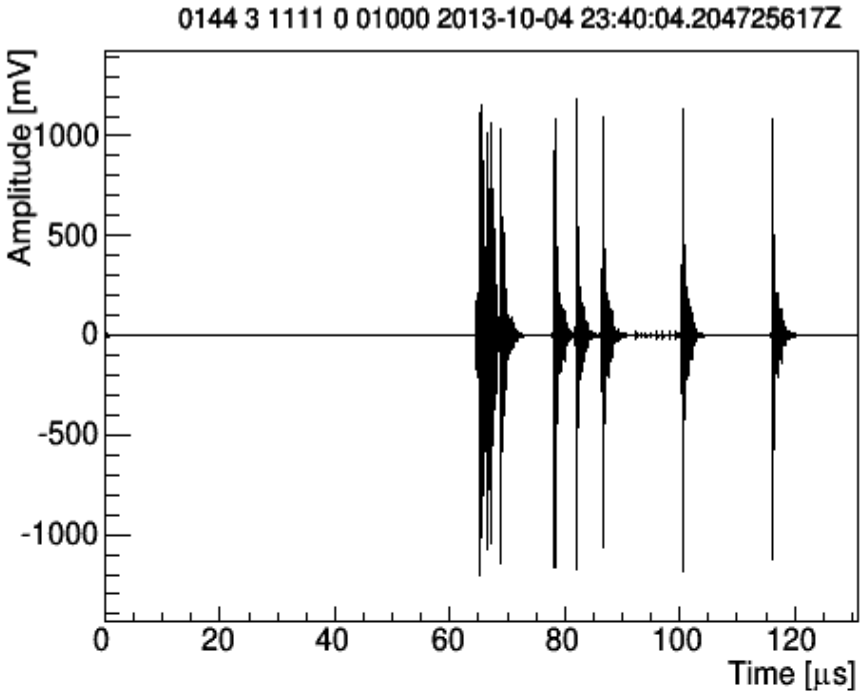
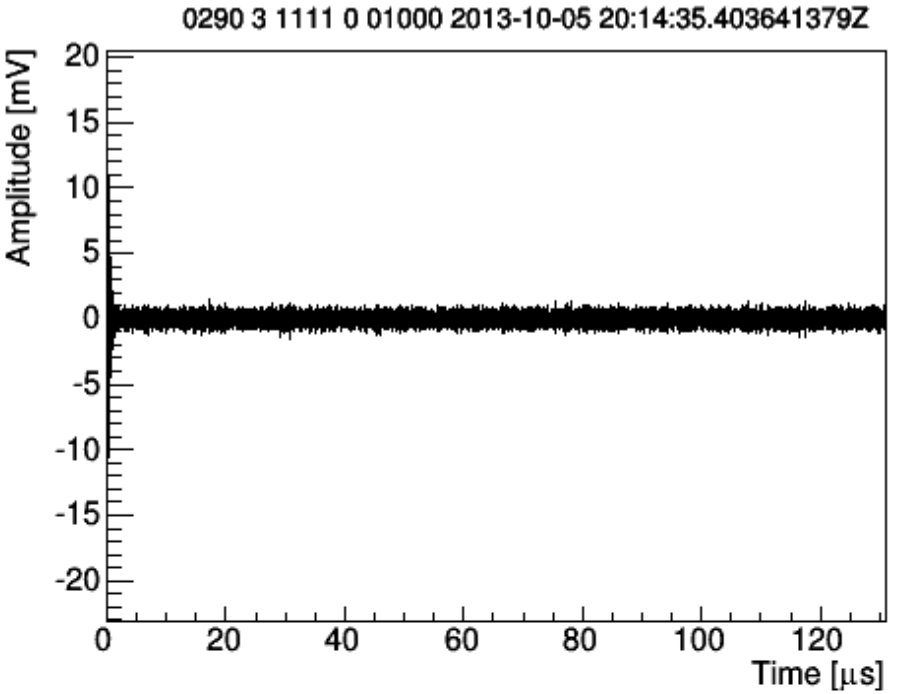
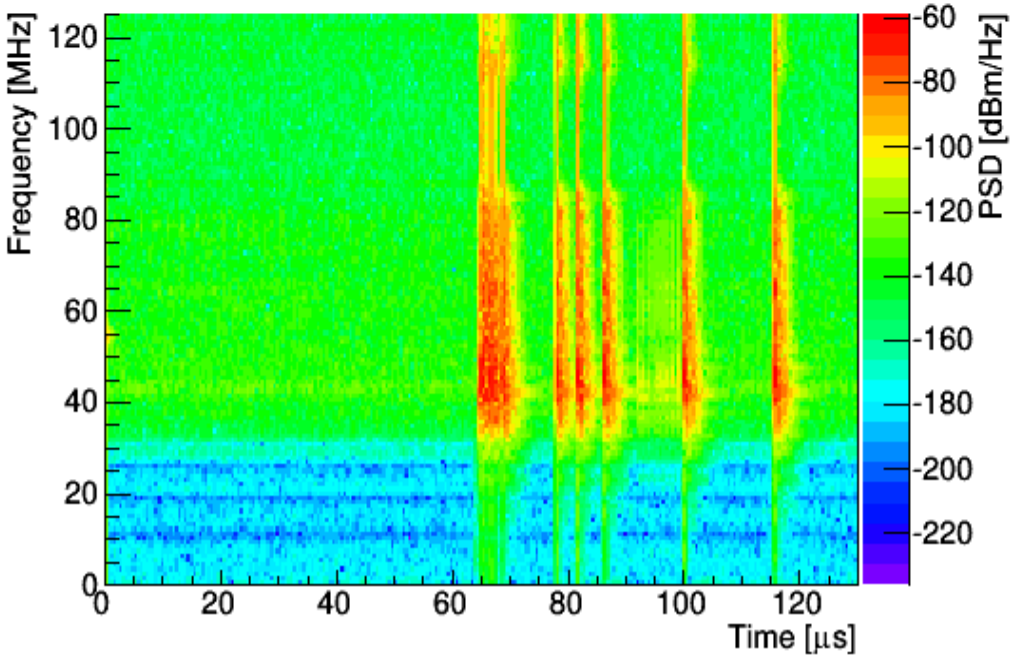
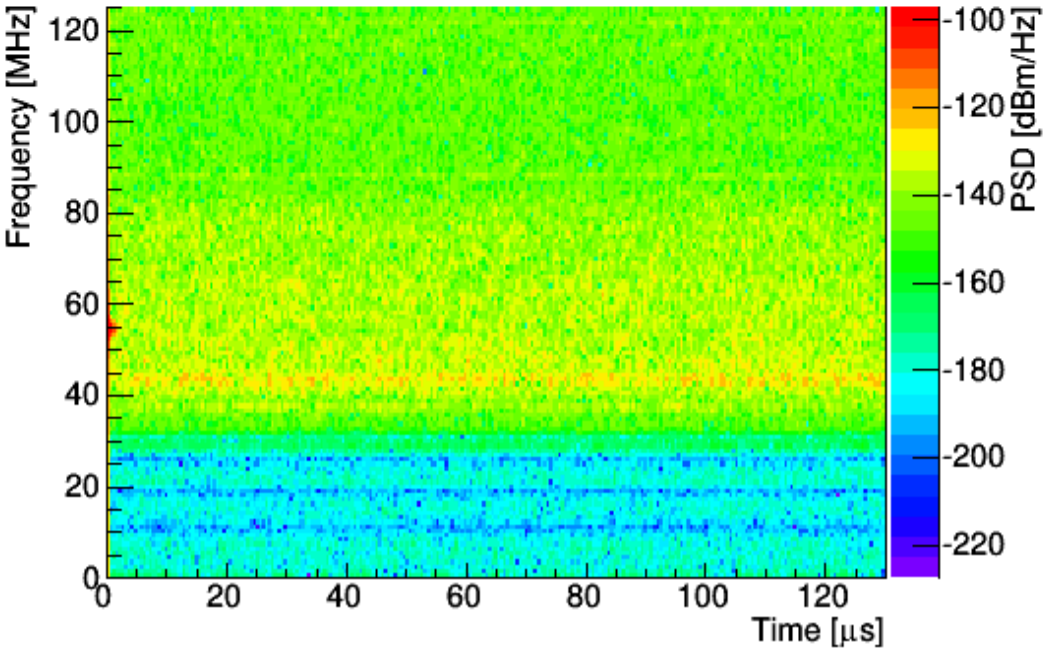








Conclusion and Future Work

With the matches we've found we can now:

- Use the snapshots and self-trigger waveforms along with reconstructed SD events to quantify limits on the radar cross section of cosmic ray showers

In the future:

- There are a few weeks here and there that we could go back and analyze (We focused on FD run time windows and excluded 2014 because the transmitter was only on sporadically)
- Look at uncut SD data
- Analyze the data currently being collected with a new transmitter polarization

Questions?

Backup slides

Transmitter Diagram

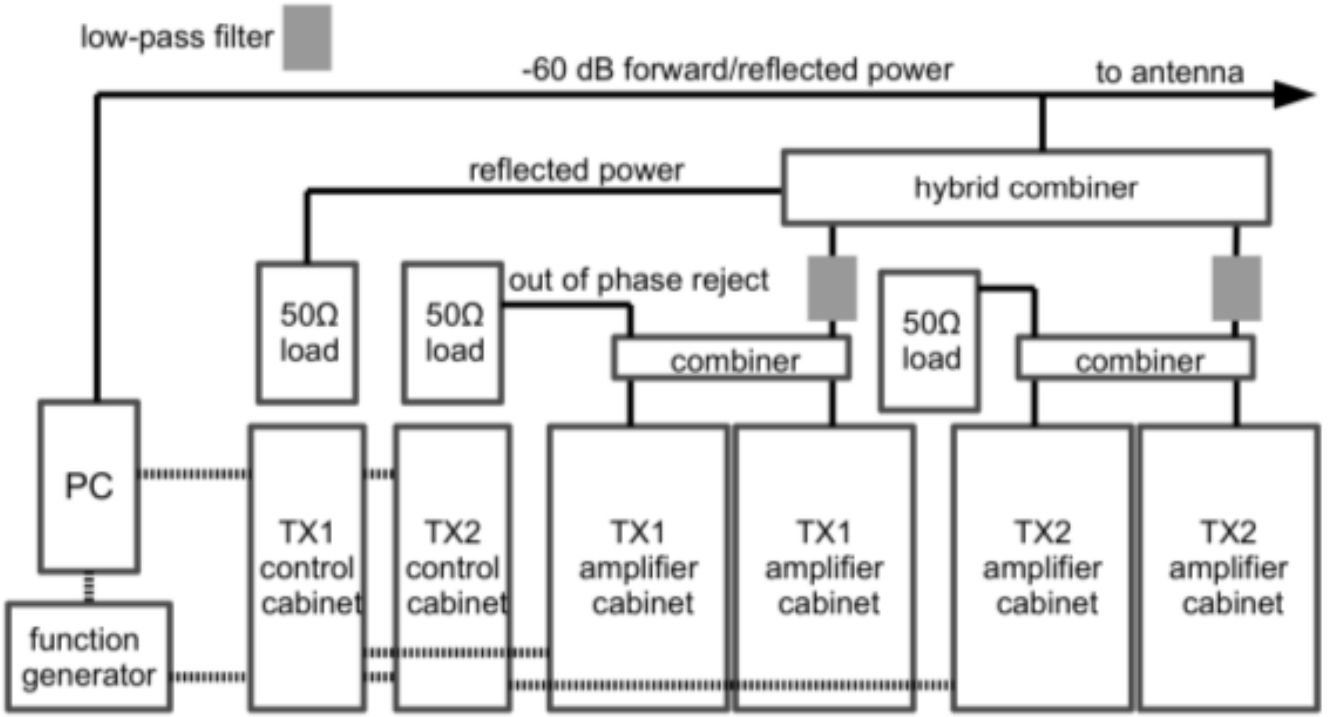
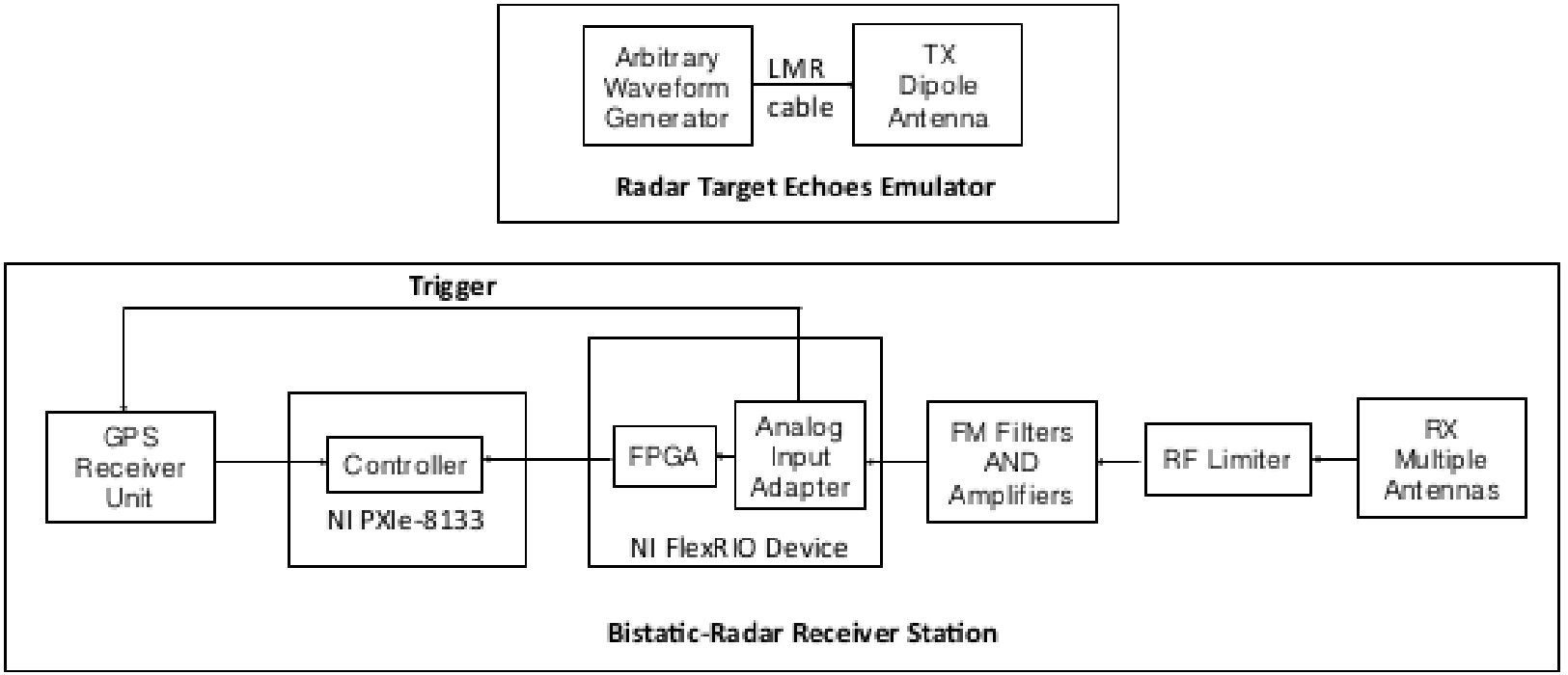


Figure 3.4: Schematic of the transmitter hardware configuration. A computer connected to RF sensor equipment, an arbitrary function generator and transmitter control electronics orchestrates the two distinct transmitters and provides remote control and logging. RF power from each transmitter's two amplifier cabinets is combined with out of phase power rejected into a 50 Ω load. A hybrid combiner sums the combined output of each transmitter and sends that power to the antenna. Power reflected back into the hybrid combiner is directed to a third RF load.

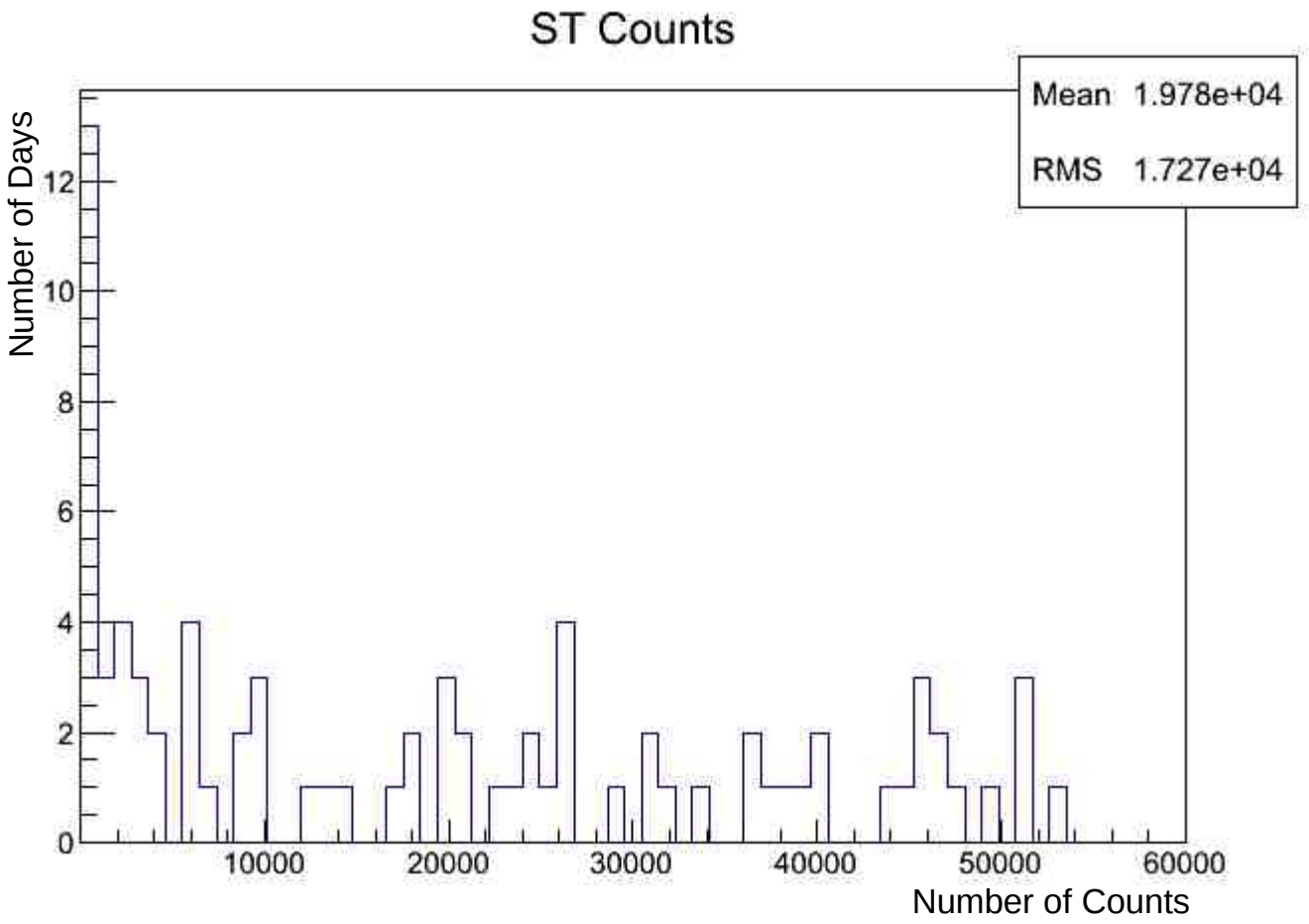
Receiver Diagram




HARRIS
HT 20LS
HARRIS
HT 20LS

Standard Cuts

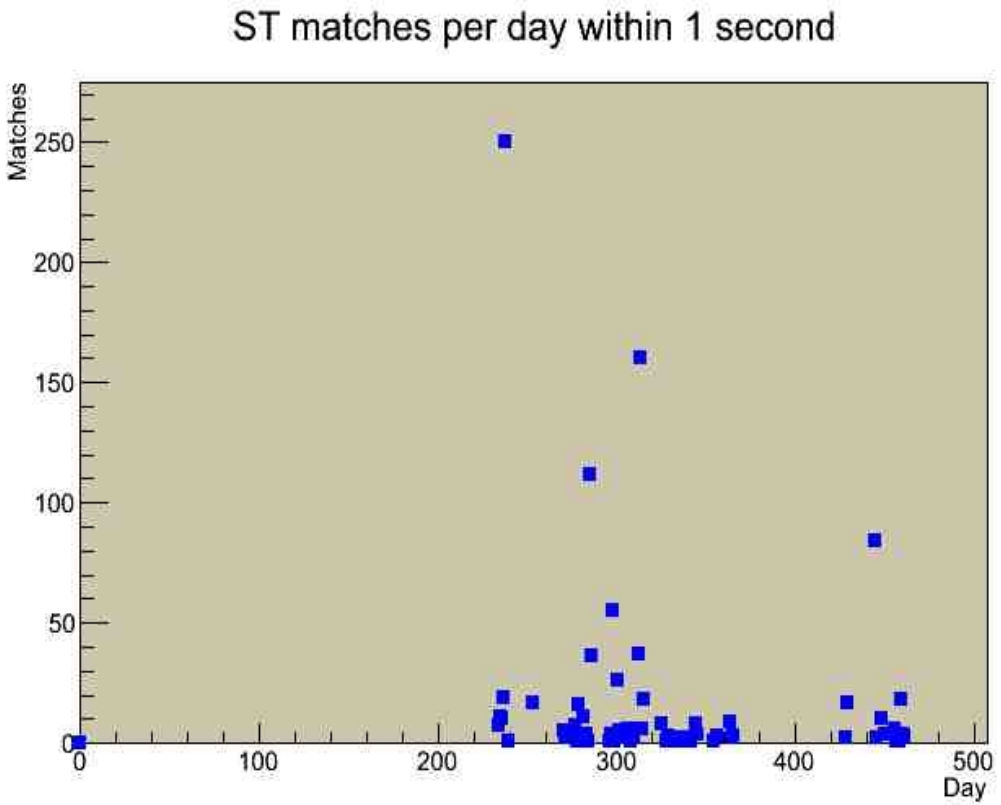
1. $N_{\mathrm{SD}} \geq 5$. At least 5 good counters per event.
2. $\theta < 45^{\circ}$. Zenith angle less than 45 degrees.
3. $D_{\mathrm{Border}} \geq 1200$ m. Core position is at least 1200 m away from the edge of the array.
4. $\chi^2_{\mathrm{G}}/\mathrm{d.o.f.} < 4$ and $\chi^2_{\mathrm{LDF}}/\mathrm{d.o.f.} < 4$. Reduced values of χ^2 of geometry ($\chi^2_{\mathrm{G}}/\mathrm{d.o.f.}$) and LDF ($\chi^2_{\mathrm{LDF}}/\mathrm{d.o.f.}$) fits are less than 4.
5. $\sqrt{\sigma_\theta^2 + \sin^2\theta\,\sigma_\phi^2} < 5^{\circ}$. Pointing direction uncertainty is less than 5 degrees. σ_θ and σ_ϕ are the uncertainties on zenith and azimuthal angles from the geometry fit.
6. $\sigma_{S800}/S800 < 0.25$. Fractional uncertainty of $S800$ determination (from the LDF fit) is within 25%.

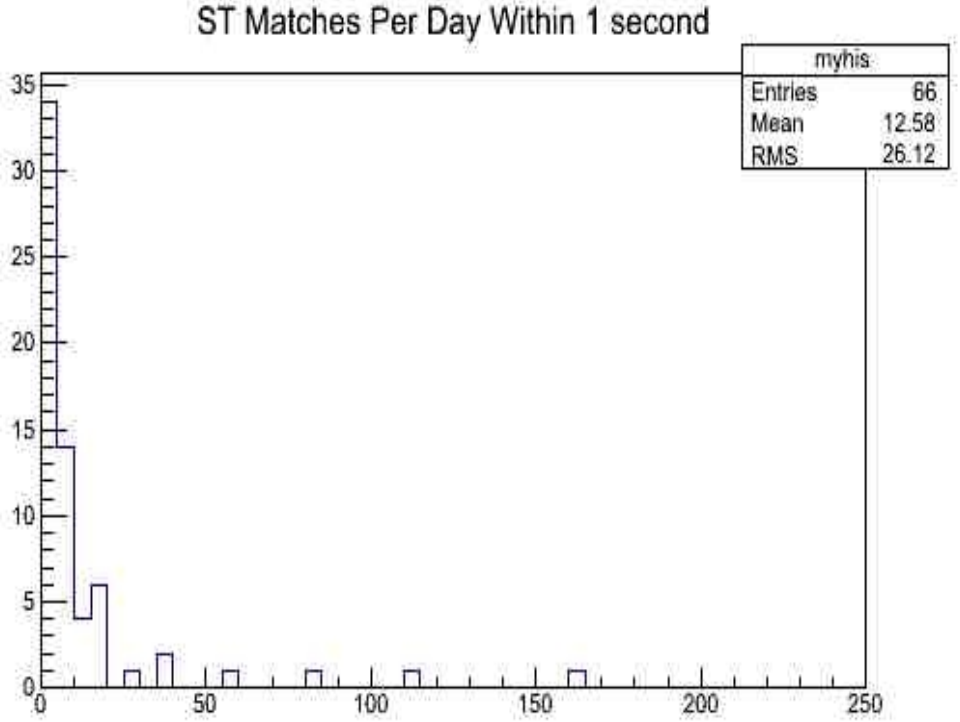

ST Counts
Mean 1.978e+04
RMS 1.727e+04
Number of Days
0
2
4
6
8
10
12
10000
20000
30000
40000
50000
60000
Number of Counts

Time Matching: Self Triggers for the same time window

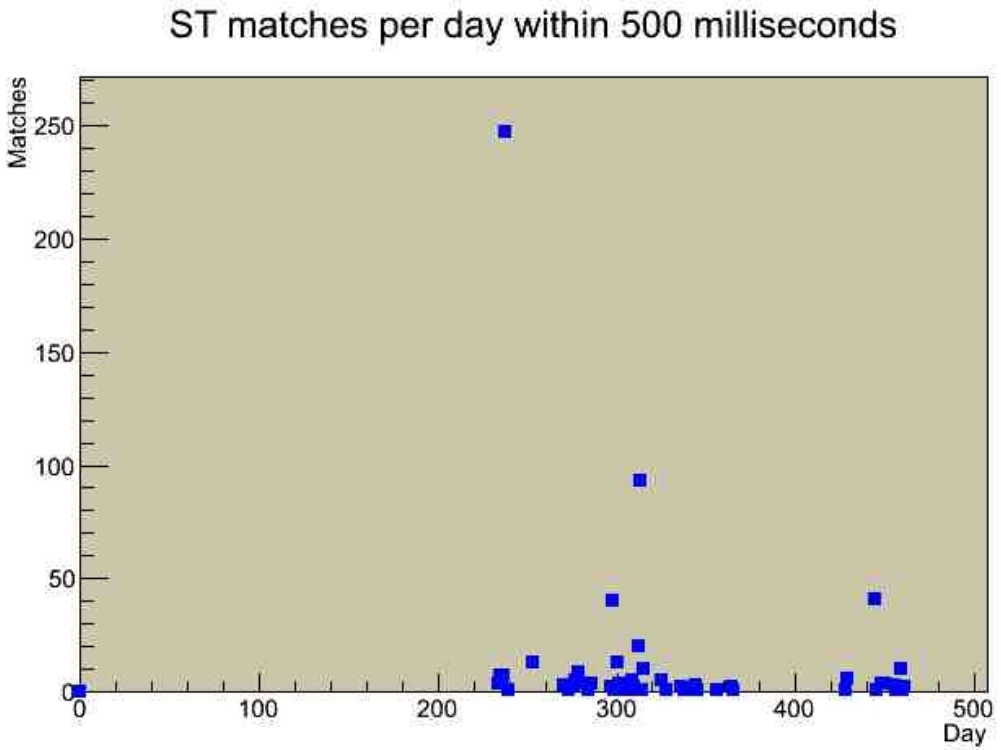
- Time matched events within time windows of:
  - 1 second
  - 500 milliseconds
  - 100 milliseconds
  - 1 millisecond
  - 500 microseconds
  - 100 microseconds
  - (1 microsecond, No Matches)

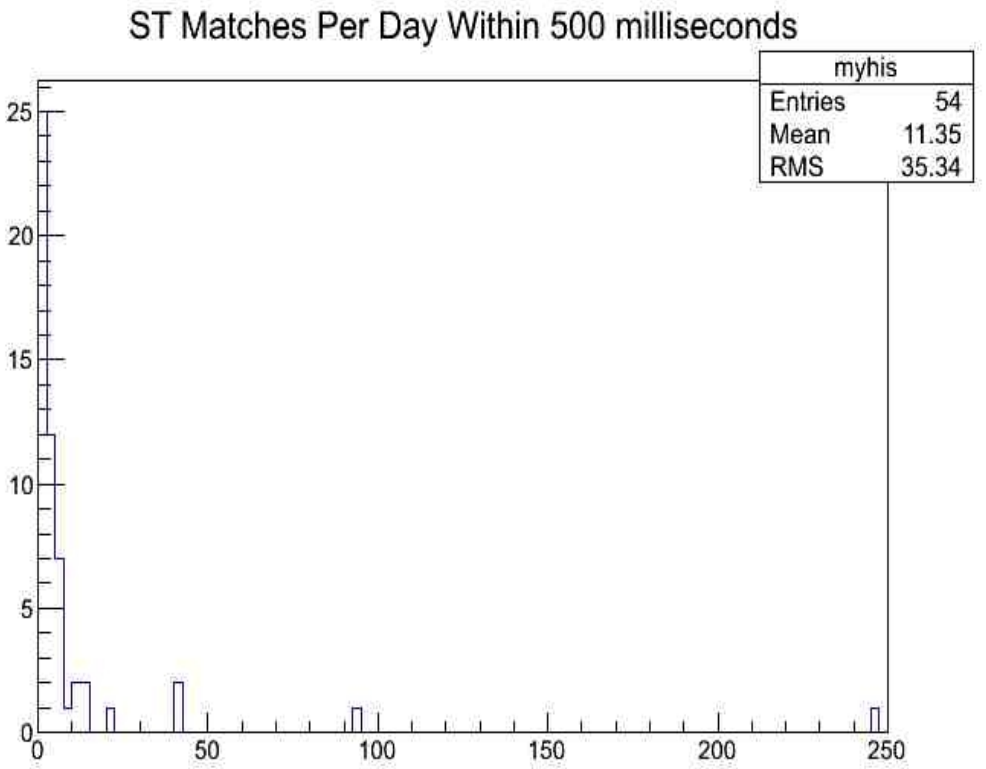
Within 1 Second



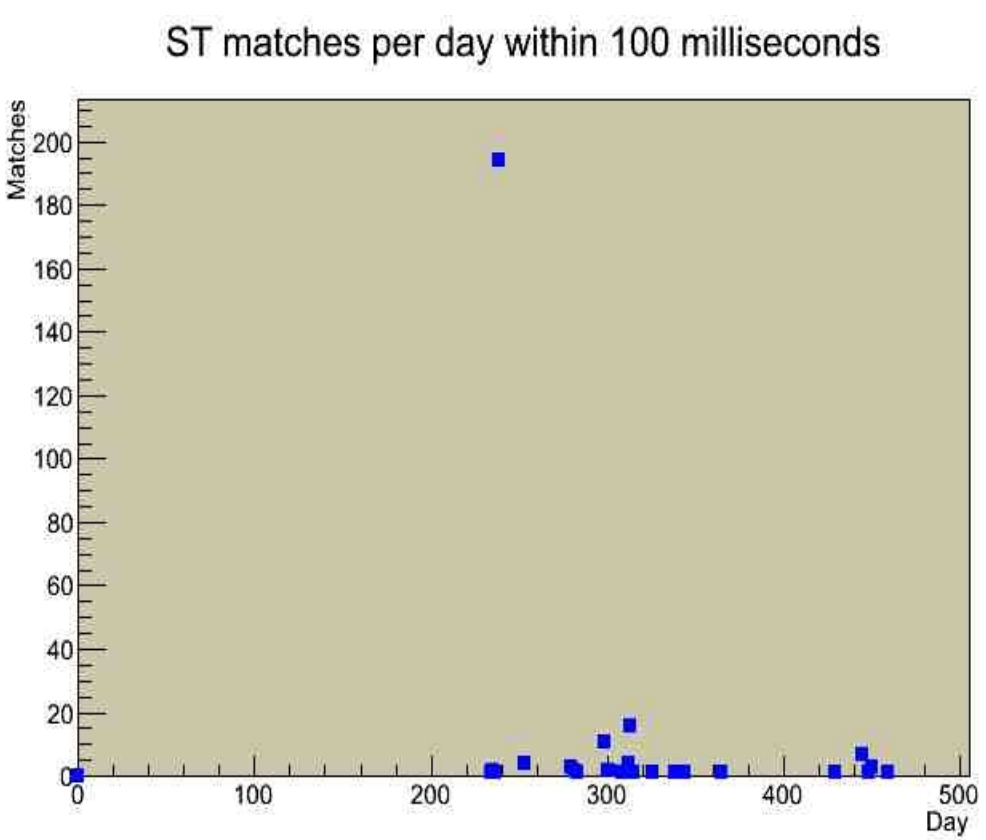


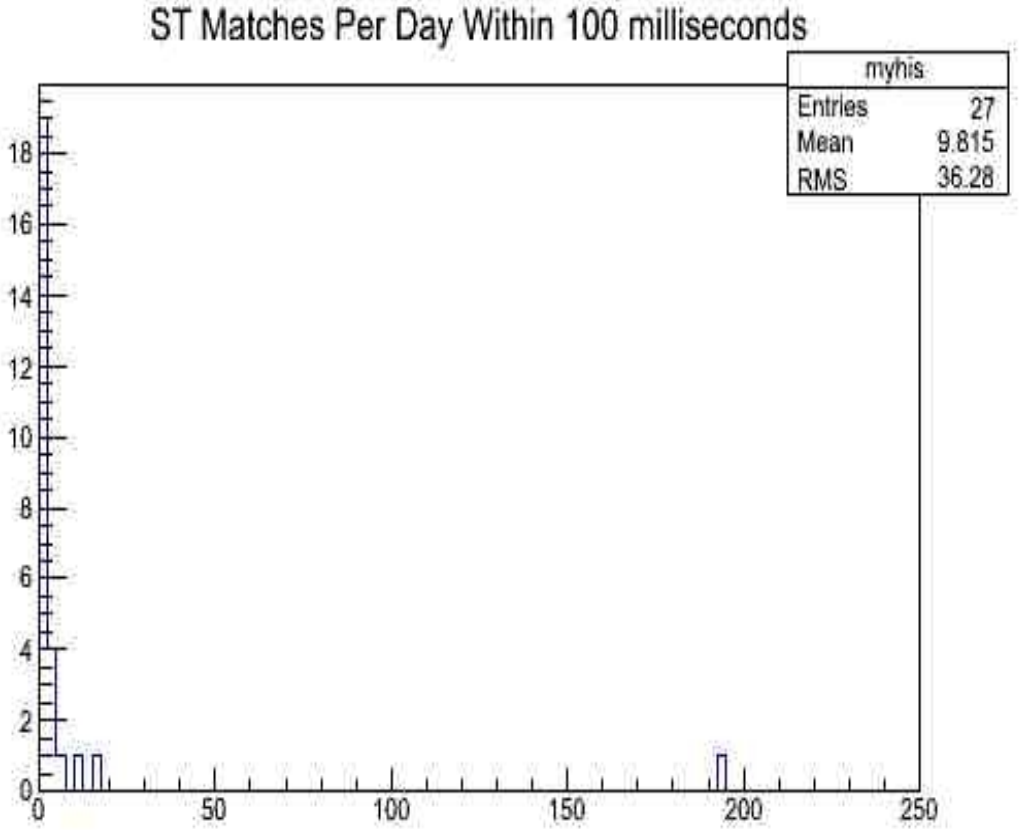
Within 500 milliseconds



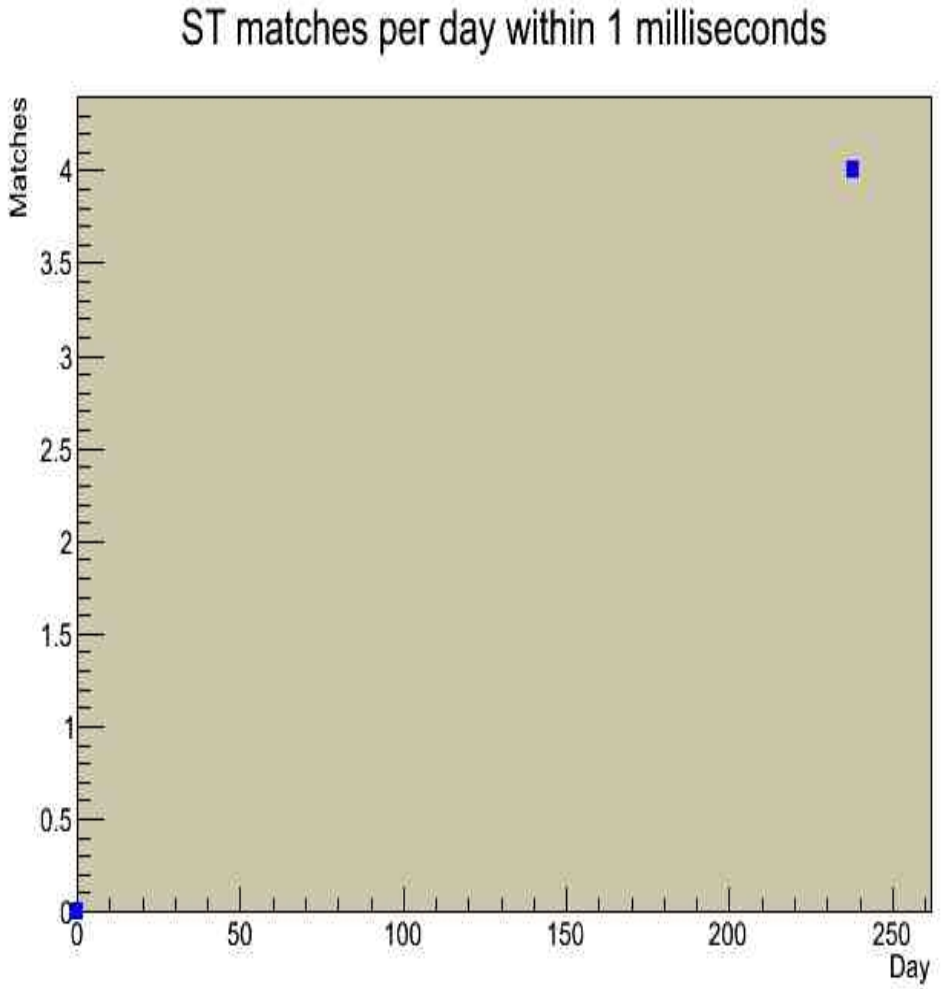


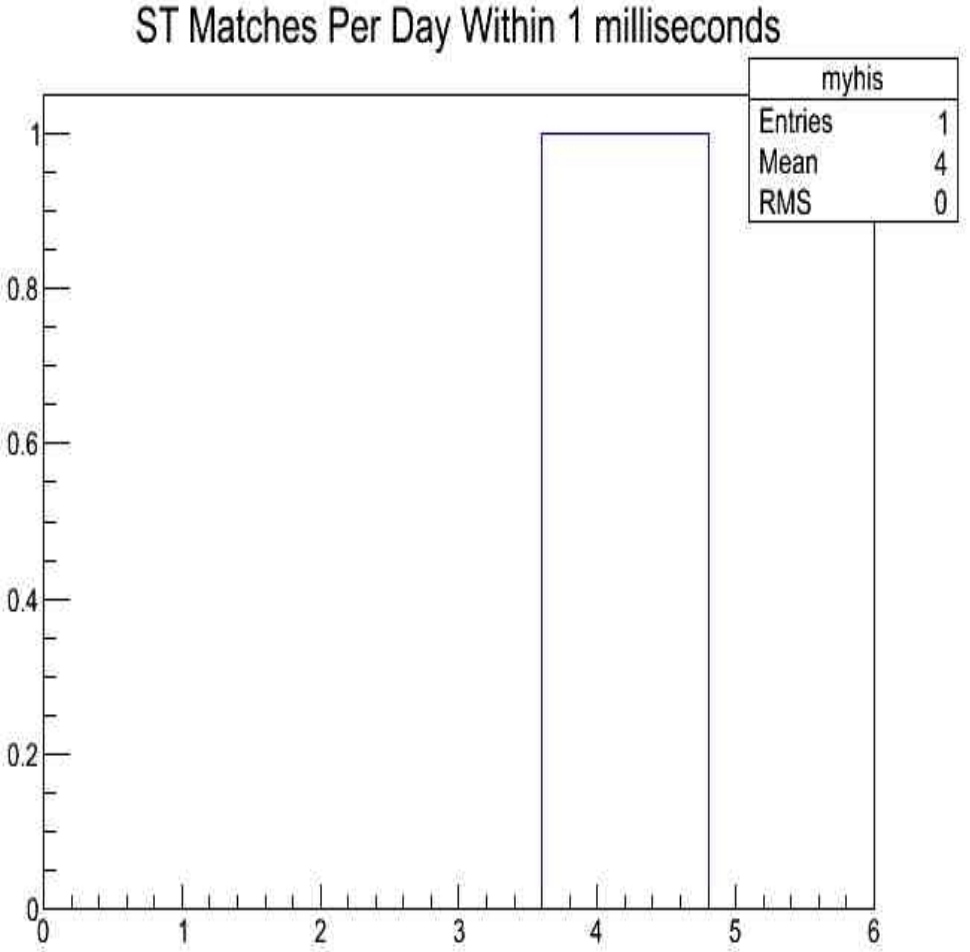
Within 100 milliseconds



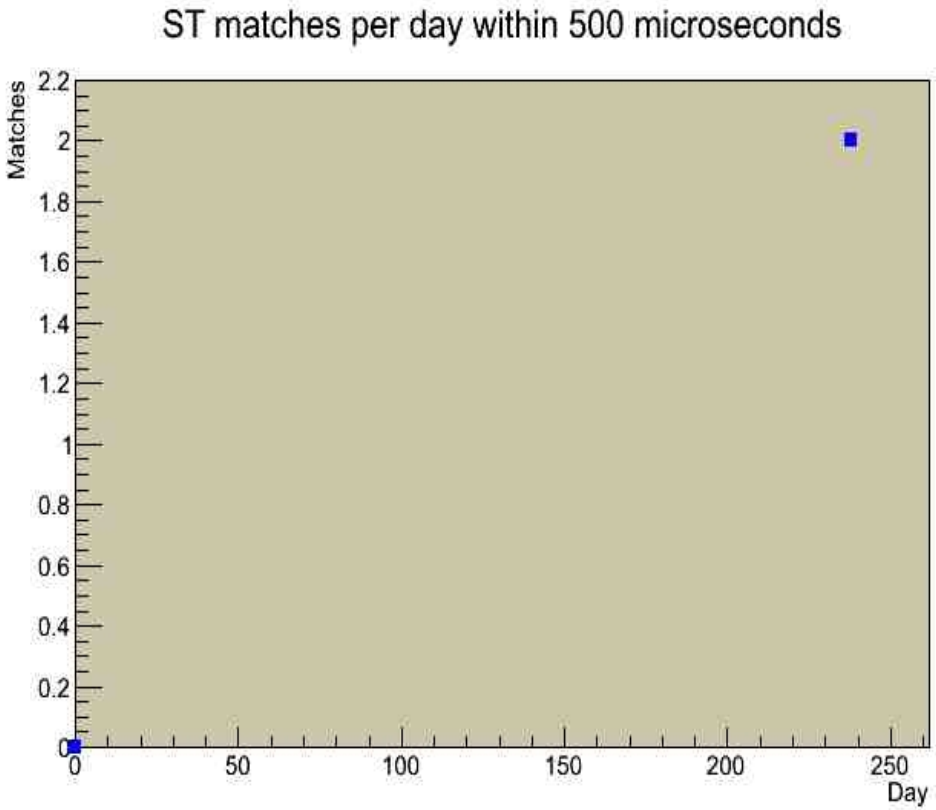


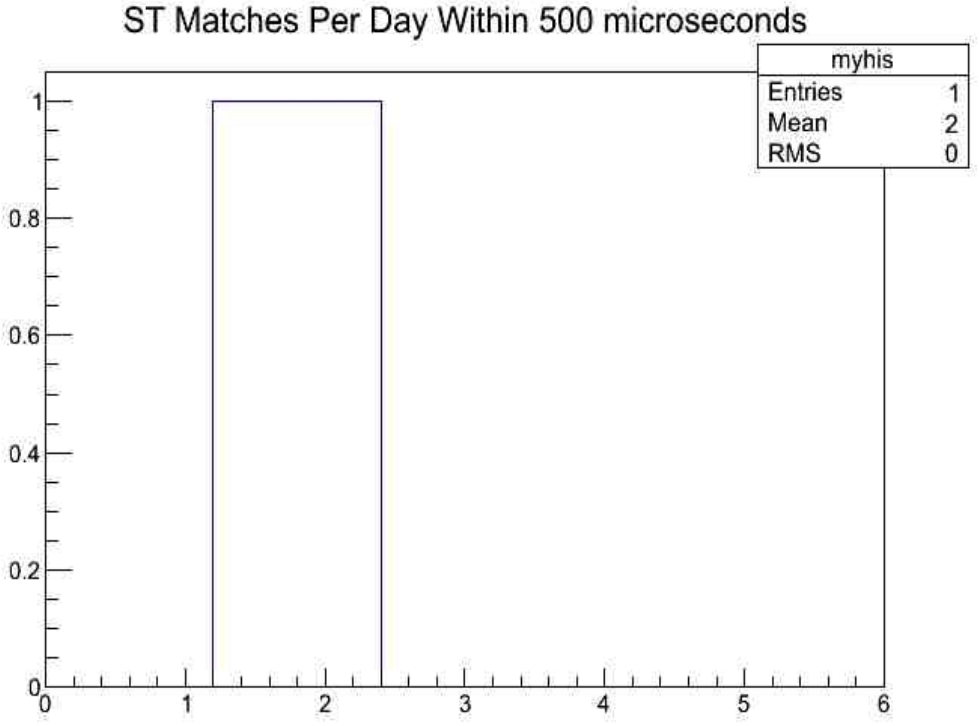
Within 1 millisecond





Within 500 microseconds





Within 100 microseconds