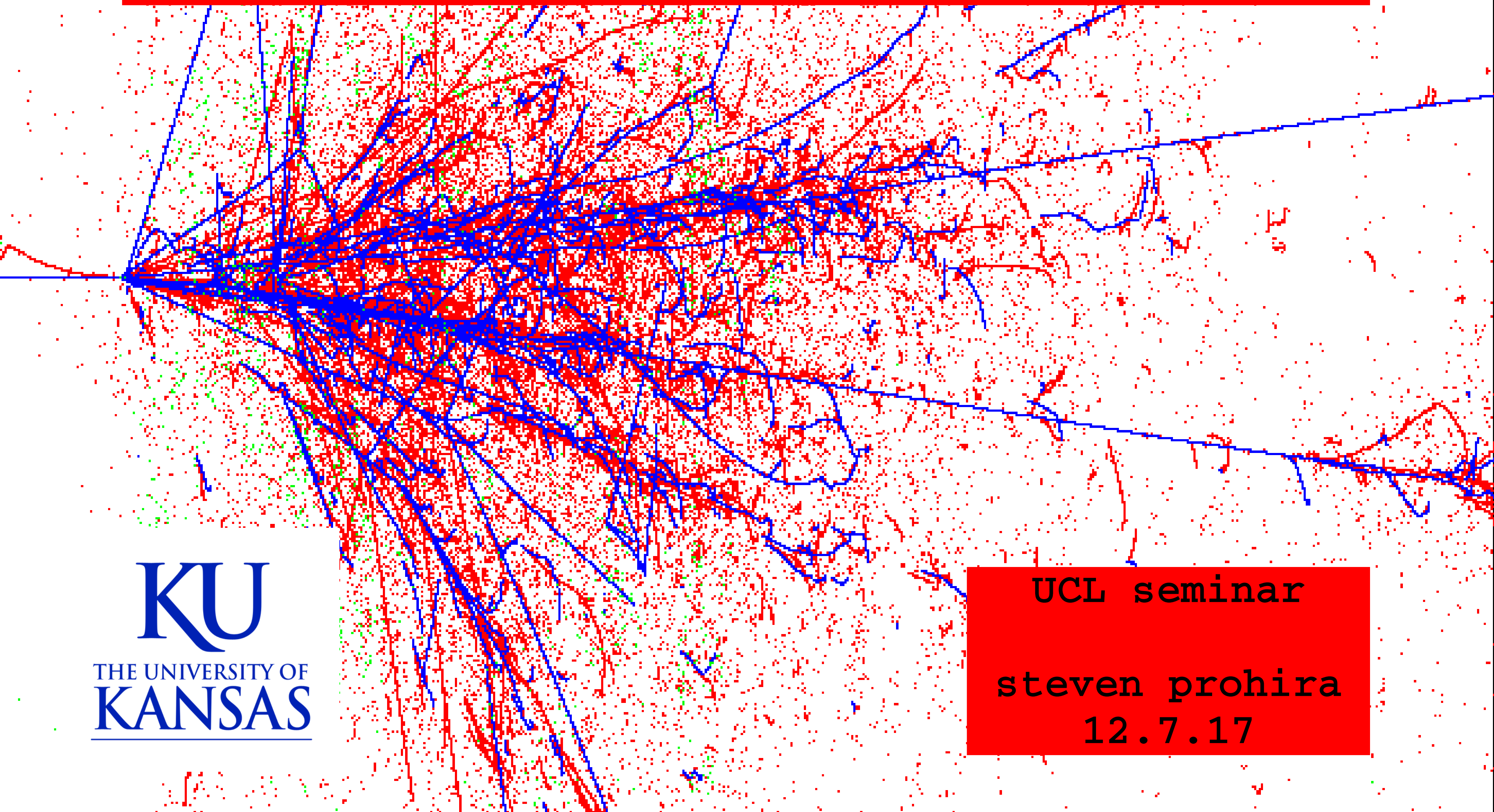
Radio interactions with particle-shower plasmas: implications for high-energy astro-particle physics



THE UNIVERSITY OF KANSAS

UCL seminar

steven prohira

12.7.17

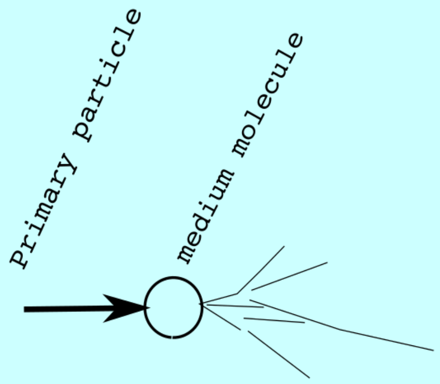
plan

- Introduction of the problem
  - particle shower plasmas, radio scatter, plasma
- RADAR detection of particle-shower plasmas
  - (brief) history
  - meteors
  - Telescope Array RADAR (TARA)
    - experiment and initial analysis
- Theory/Upcoming Experiments
  - station redeploy
  - lab test
    - GEANT4 simulation package RadioScatter
    - aims and objectives
    - SLAC (pending)

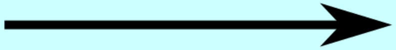
part one:
Introduction of the problem

- Particle-shower plasmas; Radio scatter; who cares?

particle-shower plasmas (PSP)



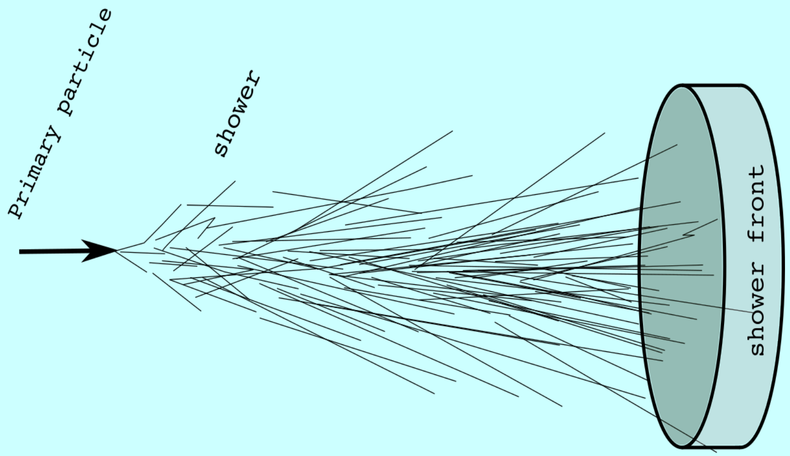
- primary particle will create a cascade of secondaries in a medium



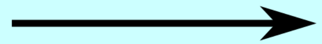
propagation direction

examples:
-neutrinos in ice
-UHECR in air
-collider beam-dump

particle-shower plasmas (PSP)



- primary particle will create a cascade of secondaries in a medium
- secondaries form a shower front & ionize the medium by kicking out <u>cold</u> electrons



examples:
-neutrinos in ice
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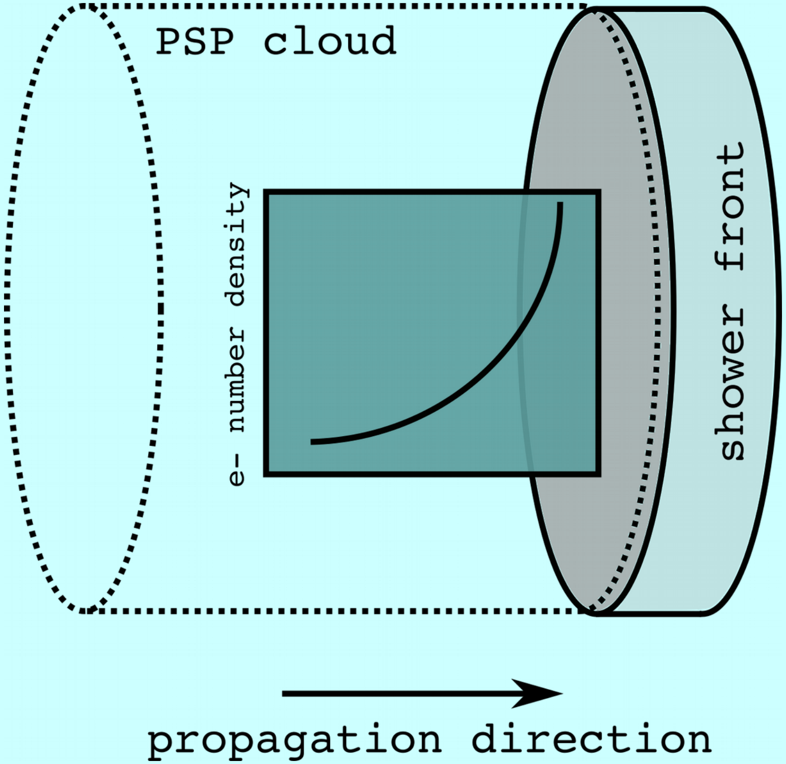
particle-shower plasmas (PSP)

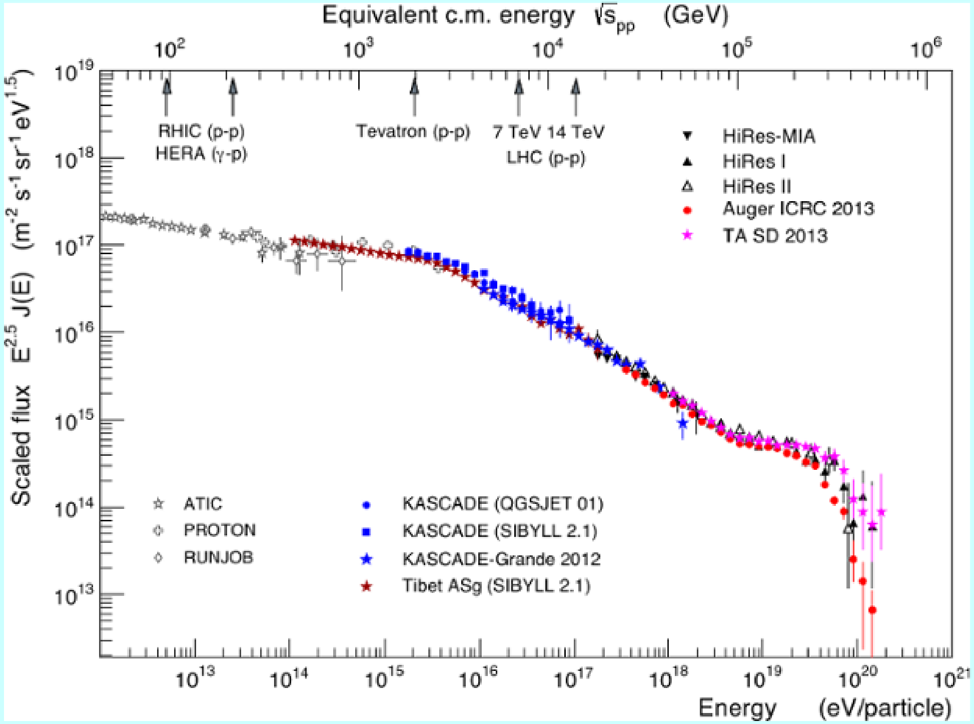


examples:
-neutrinos in ice
-UHECR in air
-collider beam-dump

- primary particle will create a cascade of secondaries in a medium
- secondaries form a shower front & ionize the medium by kicking out cold electrons
- PSP plasma cloud is formed:
  - is cold, quasi-stationary, and short lived with evolving number density
- for high primary energy, plasma can be quite dense
- "plasma"= "quasi-static plasma", read: number of electrons=number of ions
- **may reflect radio**

who cares?

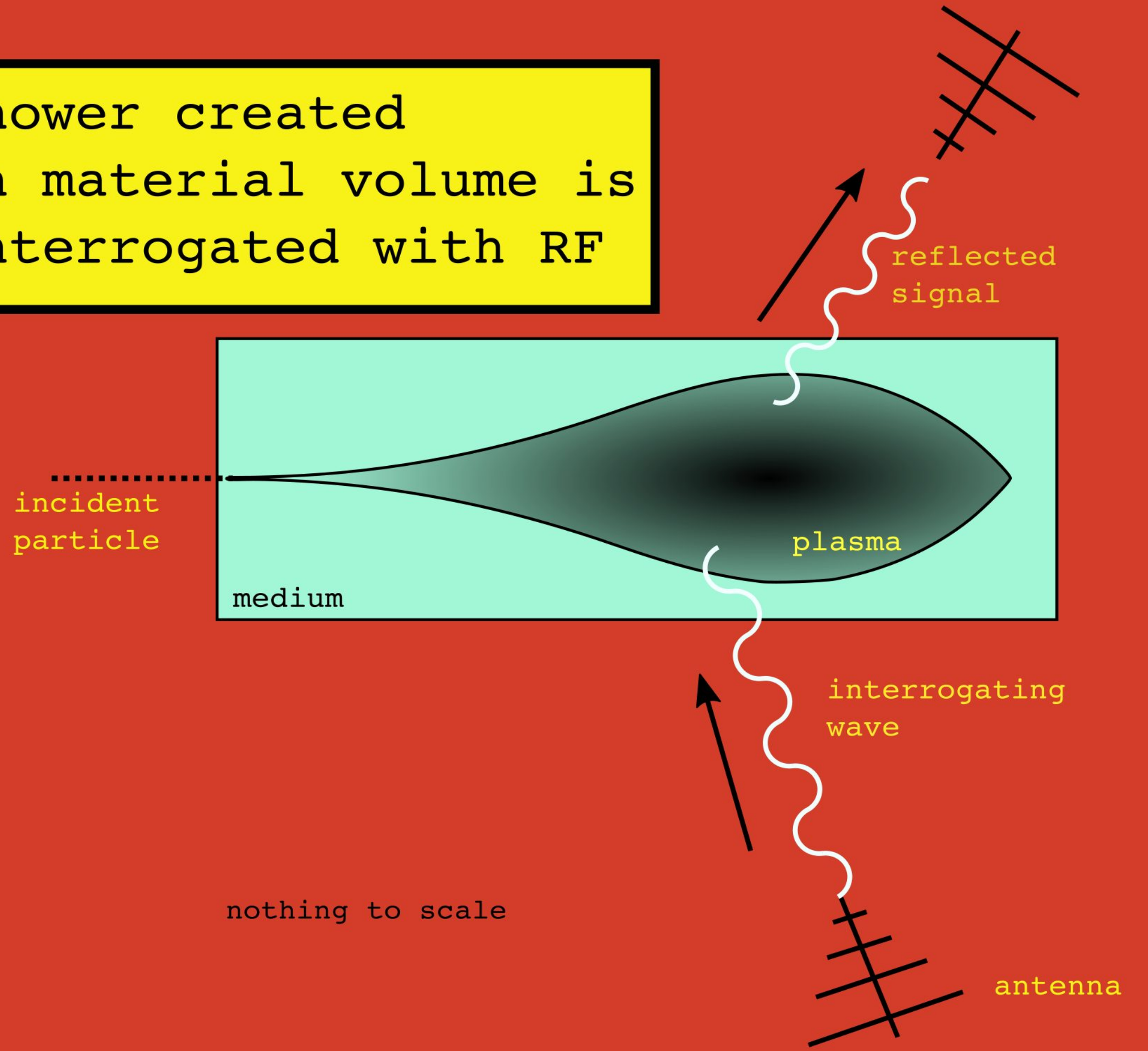
- A detection method for the highest energy particles!



- Flux of highest energy neutrinos is very low, interaction cross section very small.
- detection schemes (optical Cherenkov, Askaryan) high geometric dependence
- Flux of highest energy cosmic rays very low as well
- a way to cover more volume with less apparatus <u>with less geometrical dependence of the signal</u> (more on this later)

simple (useful) picture

Shower created in material volume is interrogated with RF



Scattered signal is coherent

part two:
RADAR detection of particle-shower plasmas

- history, meteors, TARA; key concepts

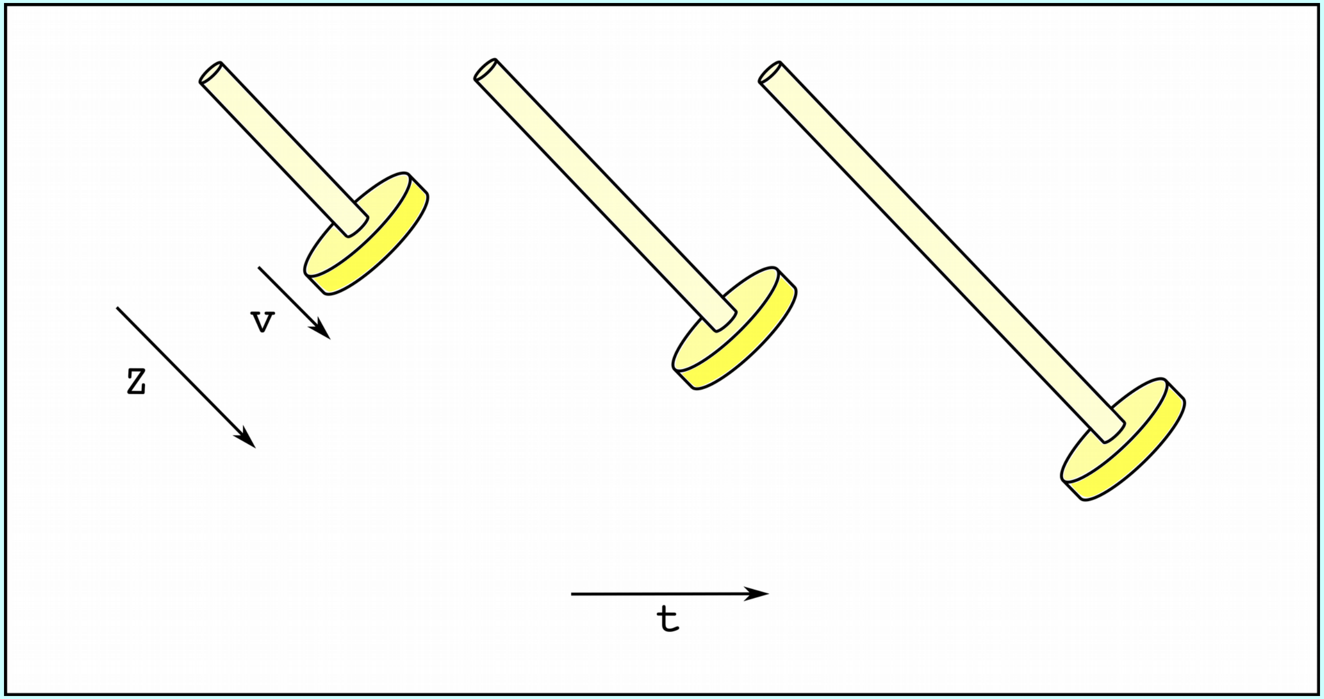
not new...

1945:

Lovell @ Jordrell Bank observatory, UK set up a radio receiver to study ‘anomalous reflections’ from upper atmosphere, which they attributed to cosmic rays. (no signal)

...but there are some useful analogues...

transient atmospheric plasmas: meteors



- the "head" of the meteor, here shown as a disk, though it may be more of a hemisphere, moves with the velocity of the meteor
- the shower tail, here shown as a thin uniform cylinder, is stationary and persistent

'thin wire' model, first published 1947:

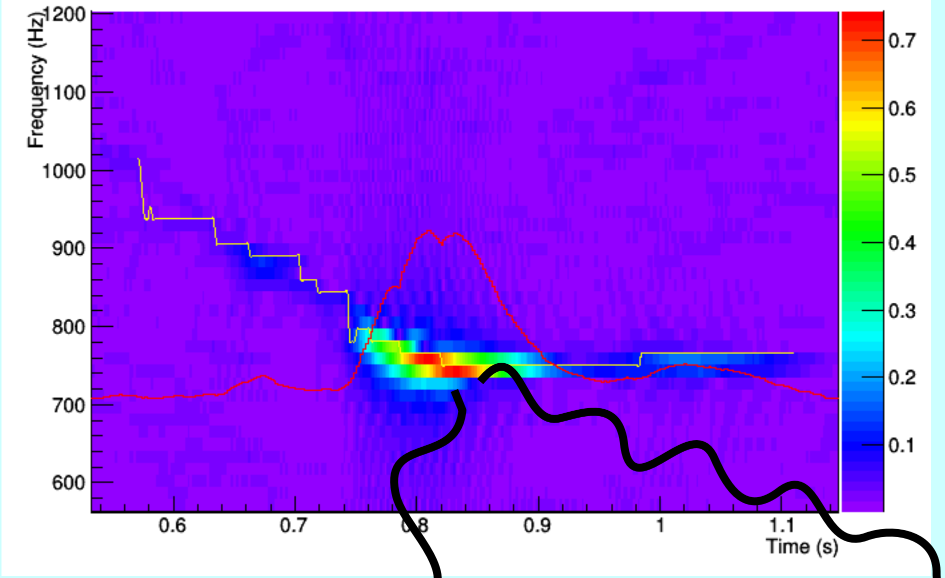
$$\sigma = \frac{4\pi l^2 \sin^2\theta (\sin x/x)^2}{(\pi/2)^2 + (\log\{\lambda/\gamma\pi a \sin\theta\})^2} \cos^4\varphi, \quad (5)$$

****valid for 'long wires'****

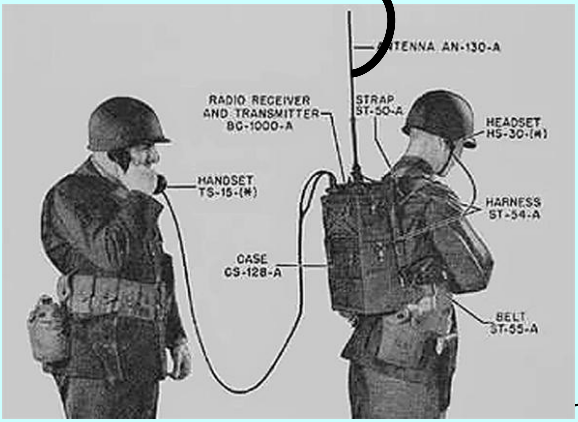
used as basis for UHECR model. . .

transient atmospheric plasmas: meteors

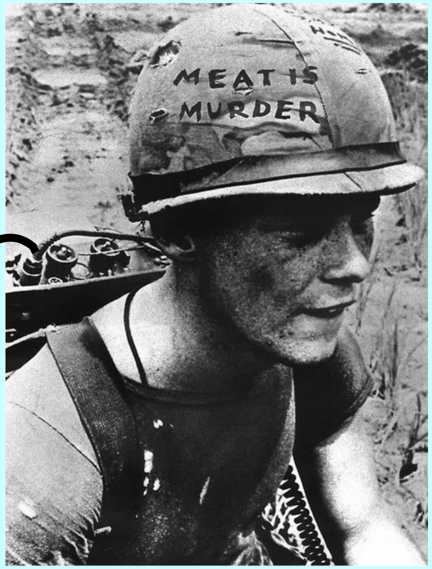
perseid meteor, captured Aug 2013.



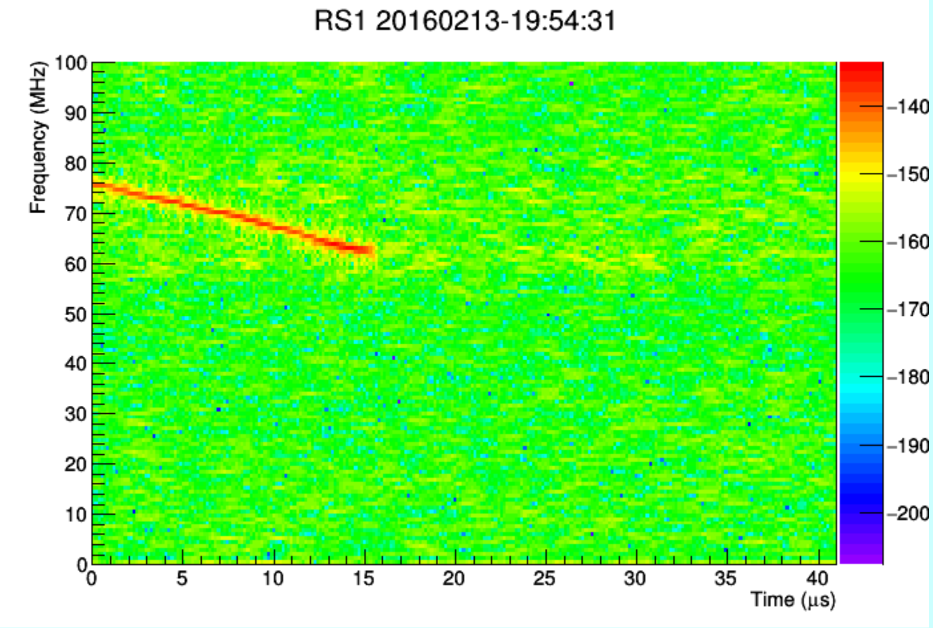
- meteors will ionize a trail through the atmosphere
- a large, mostly stationary plasma stays in the wake of a moving ball of plasma (as-yet, not fully understood)
- interrogate the atmosphere with RF, ←----get signals like this
- military used this for long-range comms back in the day



1000's km



transient atmospheric plasmas: UHECR

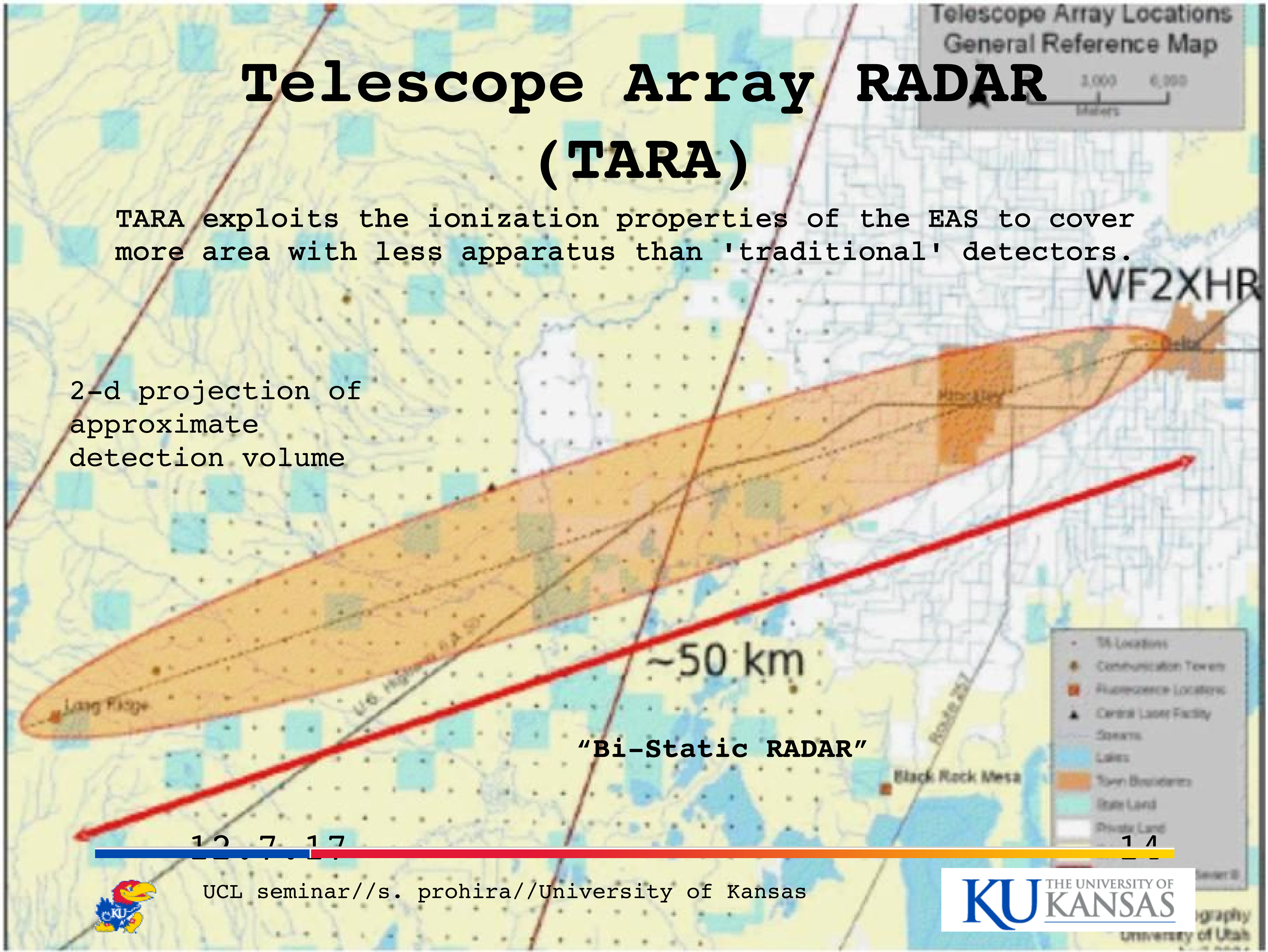


calibration signal based upon theoretical UHECR signal

- **ultra-high-energy cosmic rays-like meteors, but UHECR move relativistically**
- **plasma lifetime is shorter, $\tau_p \sim 1 - 10ns$**
- **plasma is stationary in 3-space but moves in 4-space!**
- **relativistic shower front leaves behind stationary, short-lived plasma**
- **originally modeled as meteors using "thin-wire" model [Gorham, Astropart. phys, 2001]**
  - **(now disfavored...)**

Telescope Array RADAR (TARA)

TARA exploits the ionization properties of the EAS to cover more area with less apparatus than 'traditional' detectors.



TARA

Telescope Array Radar (TARA) Observatory for Ultra-High Energy Cosmic Rays

R. Abbasi[a], M. Abou Bakr Othman[a], C. Allen[b], L. Beard[c], J. Belz[a], D. Besson[b,g], M. Byrne[a], B. Farhang-Boroujeny[a], A. Gardner[a], W.H. Gillman[d], W. Hanlon[a], J. Hanson[b], C. Jayanthmurthy[a], S. Kunwar[b], S.L. Larson[e], I. Myers[a,*], S. Prohira[b], K. Ratzlaff[b], P. Sokolsky[a], H. Takai[f], G.B. Thomson[a], D. Von Maluski[a]

http://dx.doi.org/10.1016/j.nima.2014.08.015

Design, Construction and Operation of a Low-Power, Autonomous Radio-Frequency Data-Acquisition Station for the TARA Experiment

S. Kunwar[b,*], R. Abbasi[a], C. Allen[b], J. Belz[a], D. Besson[b,f], M. Byrne[a], B. Farhang-Boroujeny[a], W.H. Gillman[c], W. Hanlon[a], J. Hanson[b], I. Myers[a], A. Novikov[f], S. Prohira[b], K. Ratzlaff[b], A. Rezazadeh[a], V. Sanivarapu[a], D. Schurig[a], A. Shustov[f], M. Smirnova[f], H. Takai[e], G.B. Thomson[a], R. Young[b]

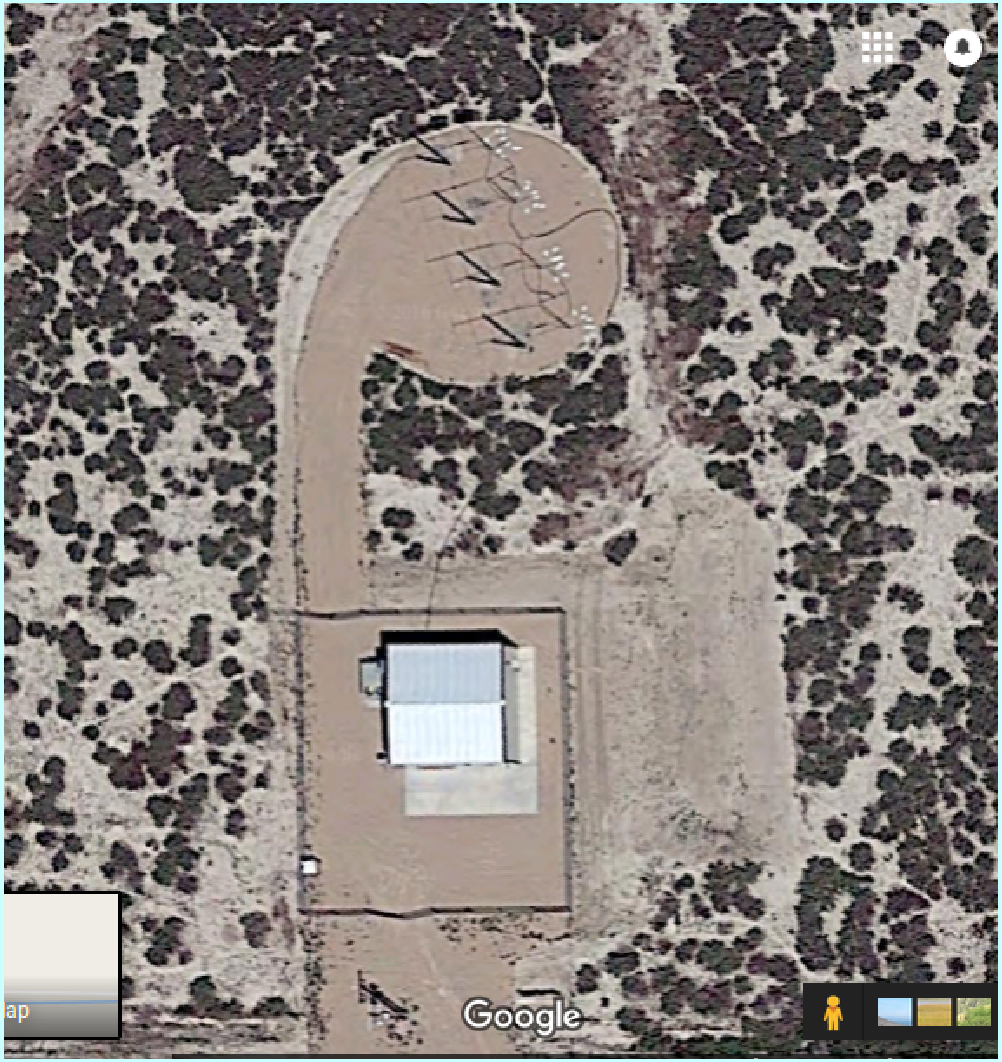
10.1016/j.nima.2015.05.072

First Measurement of the Cosmic Ray Extensive Air Shower Radar Cross-section Upper Limit with Telescope Array Radar (TARA)

R.U. Abbasi[a], M. Abe[m], M. Abou Bakr Othman[ah], T.Abu-Zayyad[a], M. Allen[a], R. Anderson[a], R. Azuma[b],

http://dx.doi.org/10.1016/j.astropartphys.2016.11.006

TARA



Phased array 8xYagi-Uda antennas @12-20kW: effective power 8MW

The TARA transmitter array.

- Extensive Air Showers (EAS) from UHECR may form ionized column dense enough to reflect sounded RF.
- Co-located with the Telescope Array (TA) surface detector, TARA attempts to detect these echoes.
- Bi-Static RADAR configuration

TARA main detector (U of Utah)

- Two techniques:
  - Florescence Detector(FD) triggers
    - Analysis by I.Meyers et.al. Reports <u>no signal</u>

http://dx.doi.org/10.1016/j.astropartphys.2016.11.006

  - Match Filter trigger
    - Analysis ongoing.
- Theory Question: what is the actual Radar Cross Section (RCS)?
    - I.Meyers, et. al. (above) places first RCS upper limit at ~10 cm^2 (optimal geometry, 100EeV)
    - O(10^-4) P.Gorham prediction

Canned formula:

$$P_r = P_t \frac{G_r}{4\pi R_r^2} \sigma_{eas} \frac{G_t \lambda^2}{16\pi^2 R_t^2}$$

The Remote Stations

-Desired a more isolated, noise-free location

-Initially located 4 km from main detector on Long Ridge.

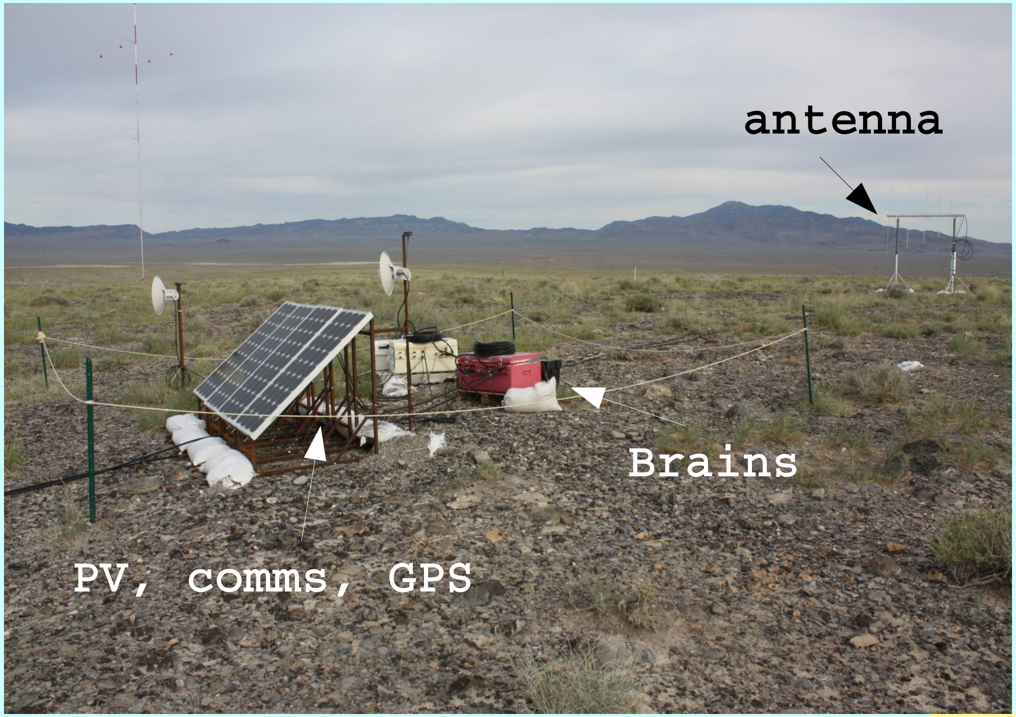
-Fully autonomous

-Different trigger scheme.

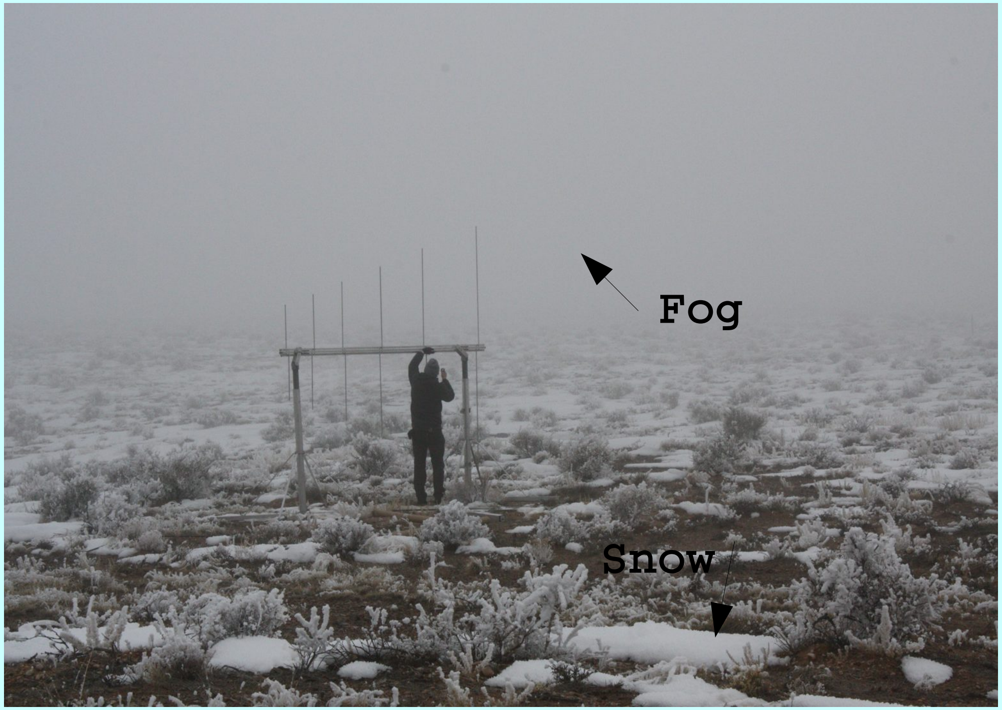
-Custom hardware and firmware

RS deployment/decomission/redeployment

Deployment 1:
Summer 2014-Summer 2015



Deployment 2:
Feb 2016-June (Dec) 2016



talk-PHOTON2015 Novosibirsk

First Deployment had hardware issues.

Second deployment had new firmware trigger, but poorer location. lots of data.
Thanks to A.Novikov for deployment, U.Latif and J.Macy for retrieval

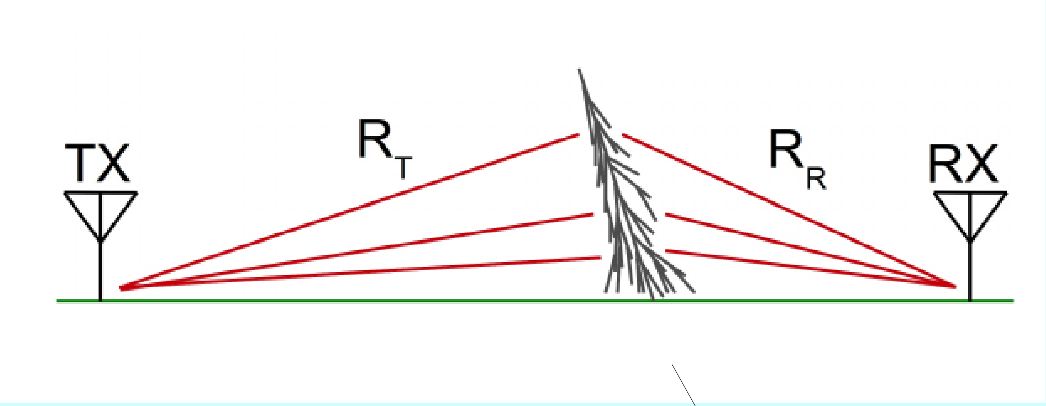
Remote Station trigger-Chirps

return signal from a CW sounding signal results in a frequency-shifted signal, O(10μs) in duration.

"chirp"

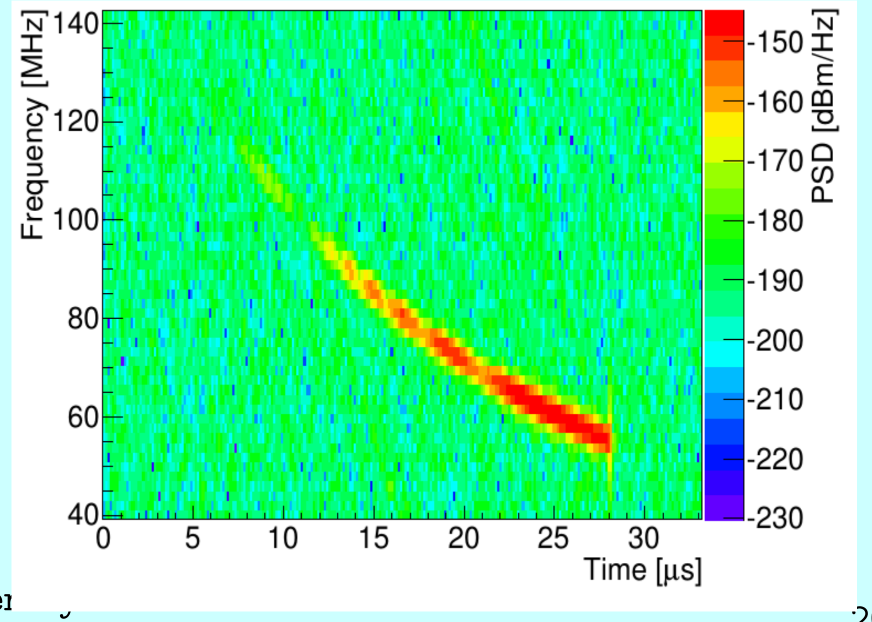
not a Doppler shift, but an artifact of sum of return phases from sounding wave

We exploit the chirp in our trigger scheme.



sum of rays from different <u>stationary</u> plasma at different locations in 4-space results in frequency shift!

(fig. I Meyers)

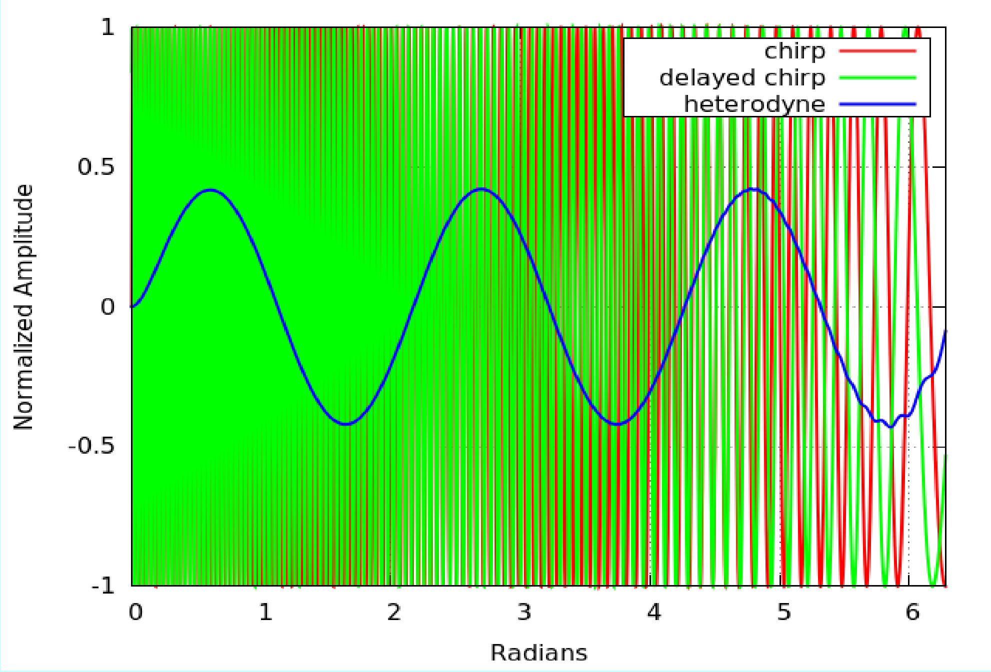


Remote Station Trigger

Custom Firmware trigger
Xilinx Spartan 6 FPGA, Nexys 3 dev bd.

Heterodyne method:

-Generally: extract a modulation by mixing two signals
-Here: the two signals are the same, but one is offset in time.

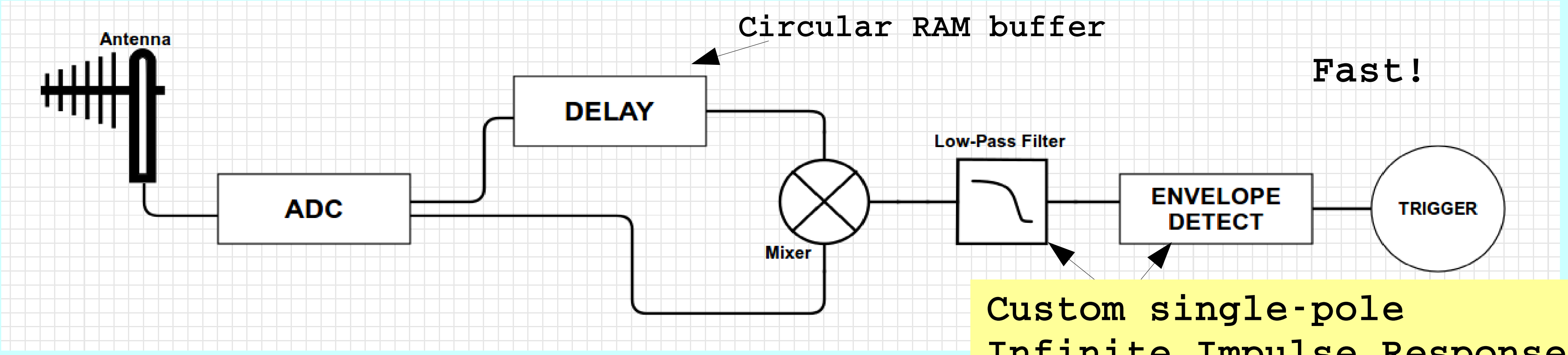


2 signals:

$$\theta = \omega t + \kappa t^2 \quad and \quad \phi = \omega\tau + \kappa\tau^2$$

$$\tau = t + \delta t$$

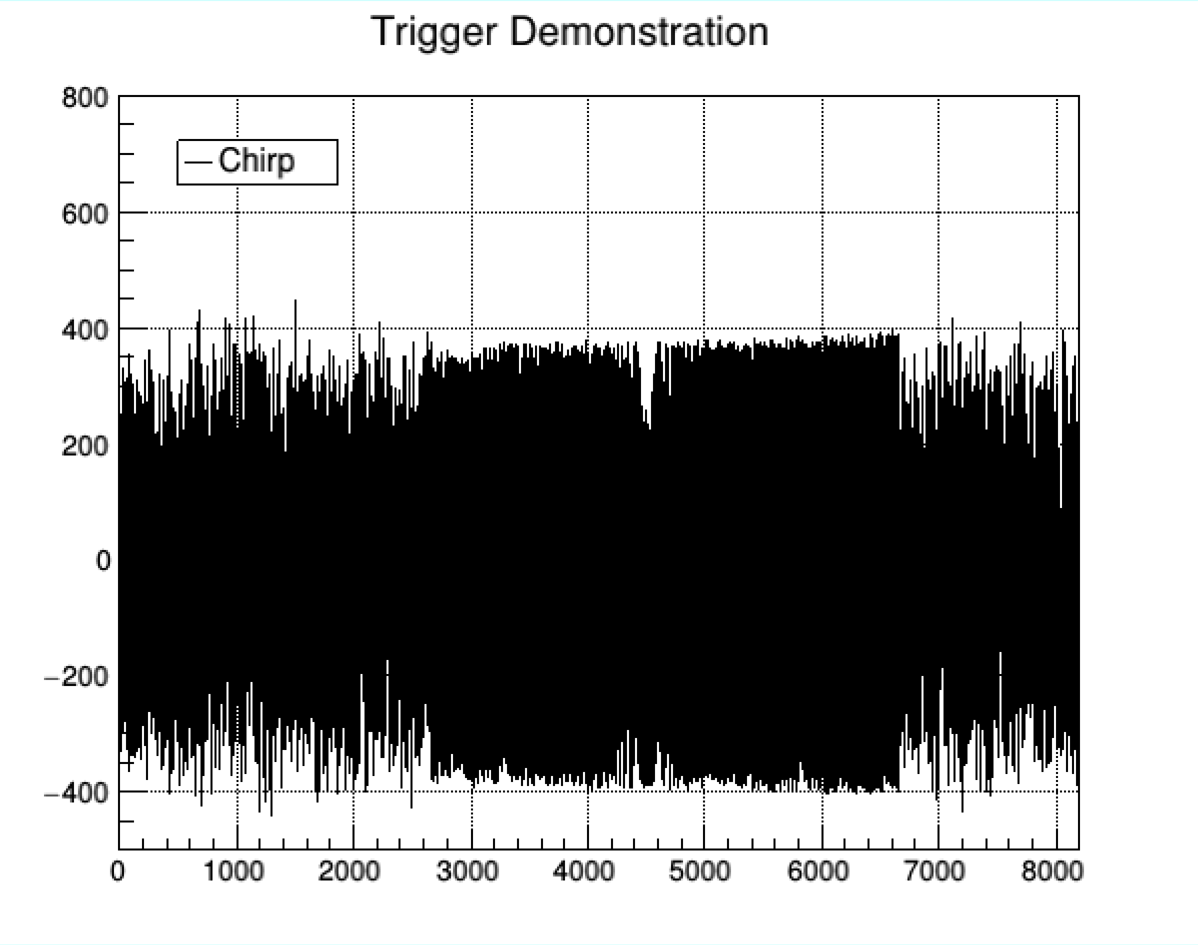
$$2sin\theta sin\phi = cos(\theta - \phi) + cos(\theta + \phi) \quad \rightarrow f_{mono} = 2|\kappa|\delta t$$



Custom single-pole Infinite Impulse Response time-domain filter

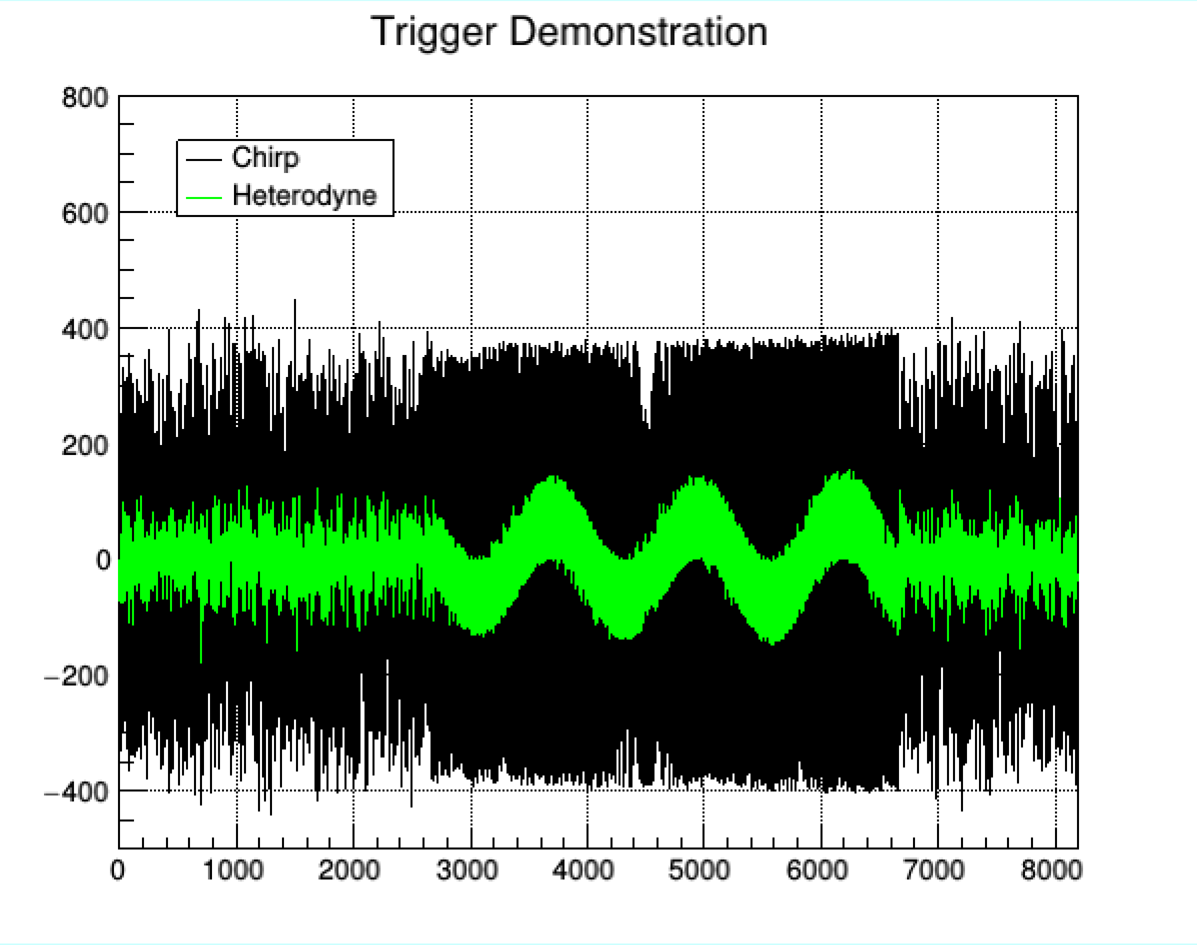
http://hdl.handle.net/1808/21885

Trigger



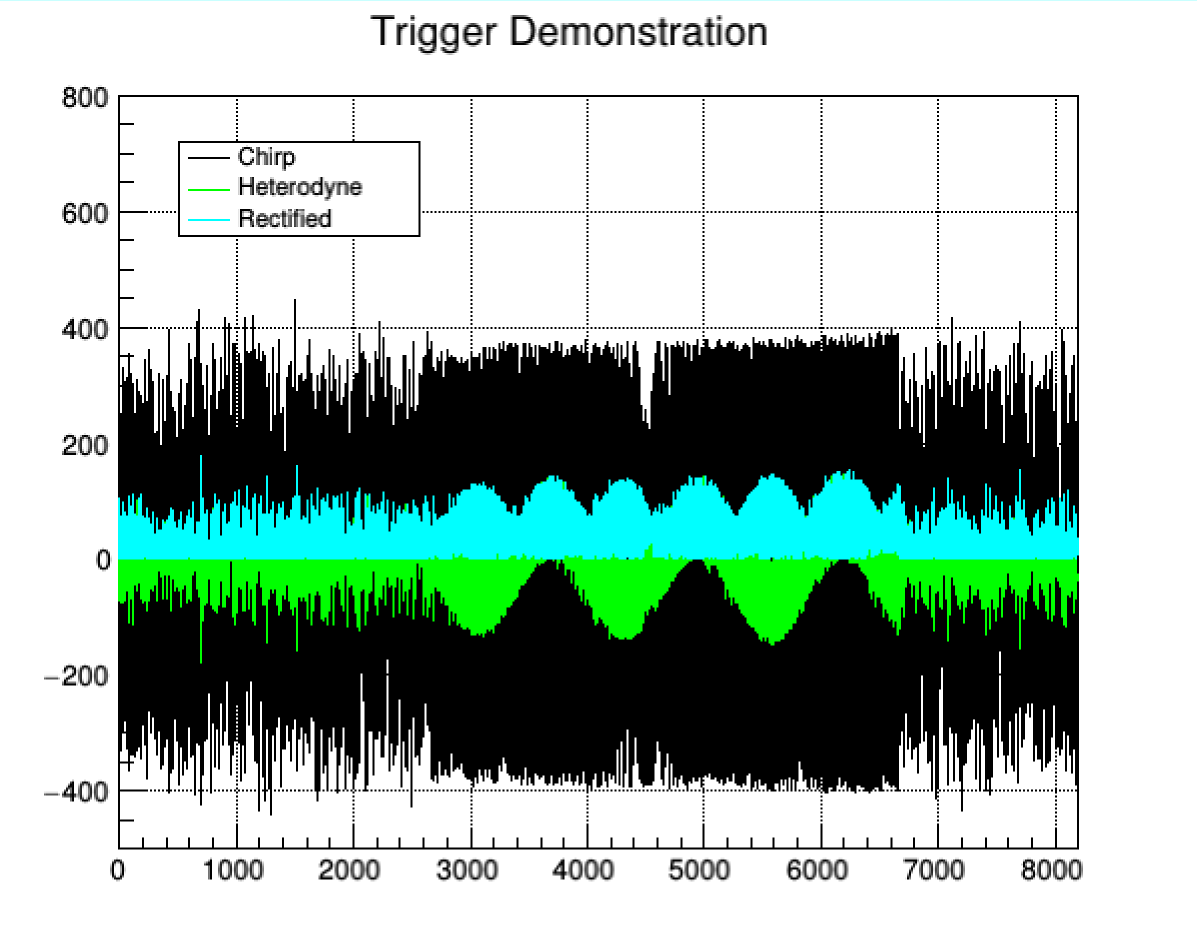
~0dB SNR linear chirp embedded in noise

Trigger



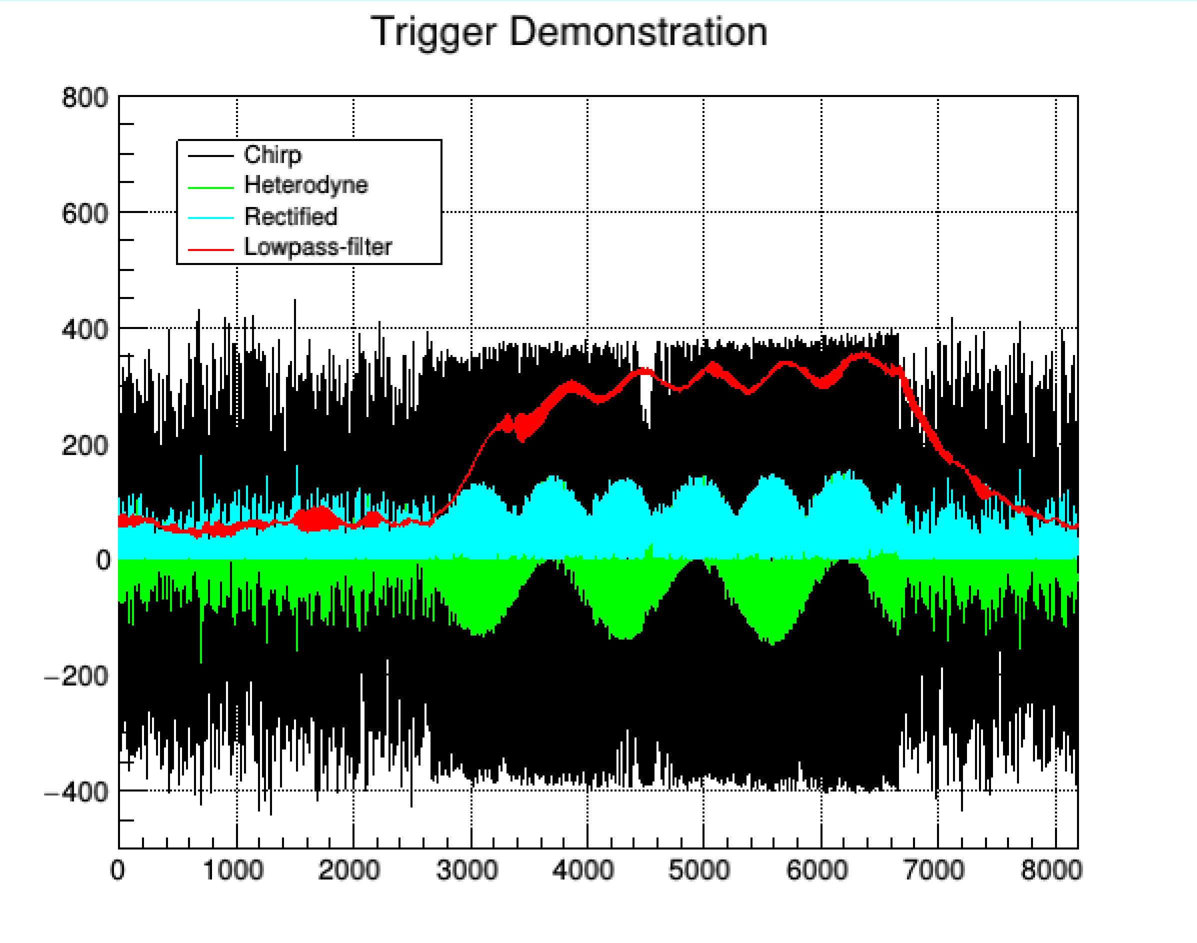
Heterodyne leaves a monotone

Trigger



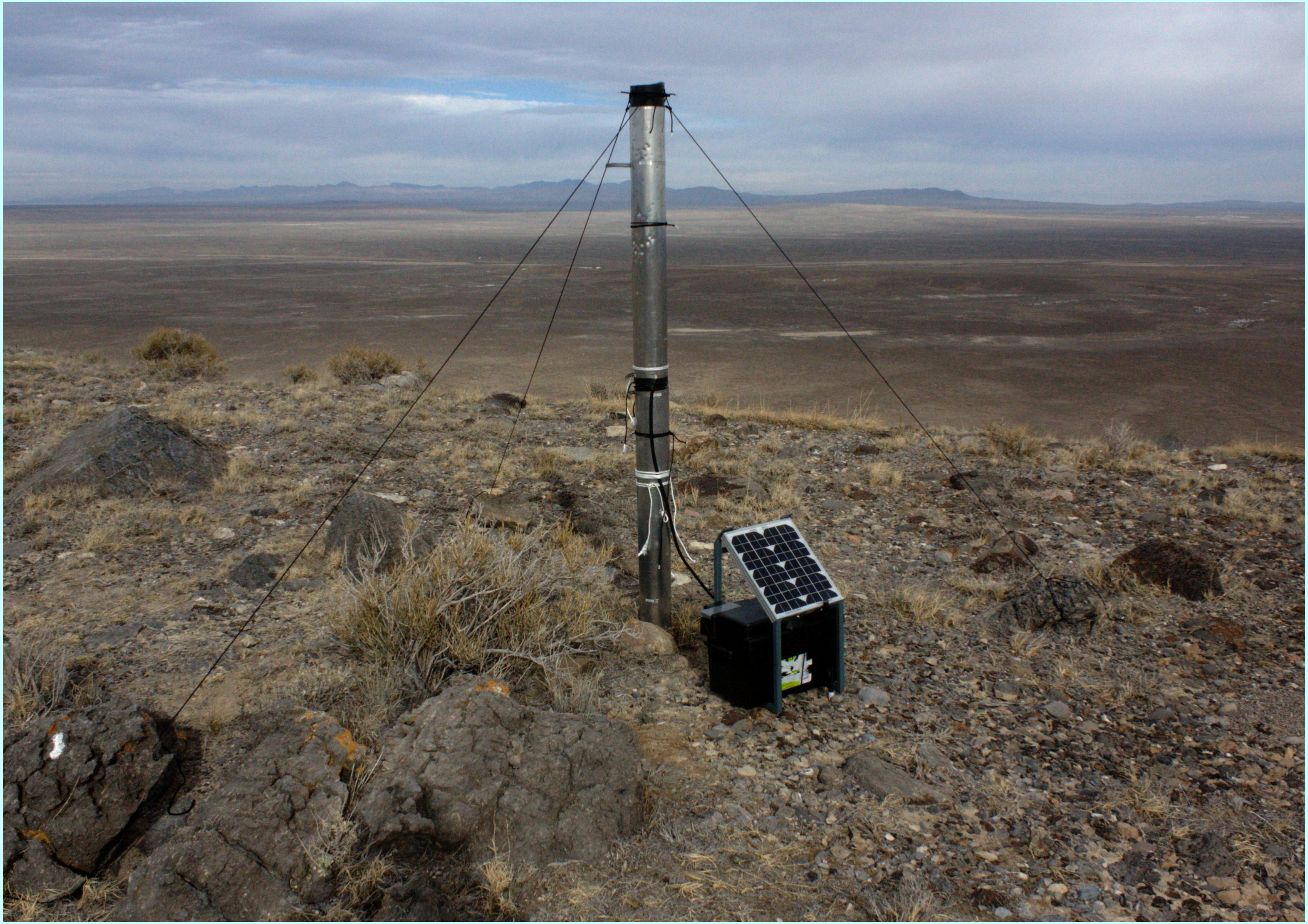
Envelope detection step 1: rectify

Trigger



Envelope detection step 2: lowpass-filter, amplify: SNR~1 → SNR ~6

Chirp Calibration Unit(CCU)

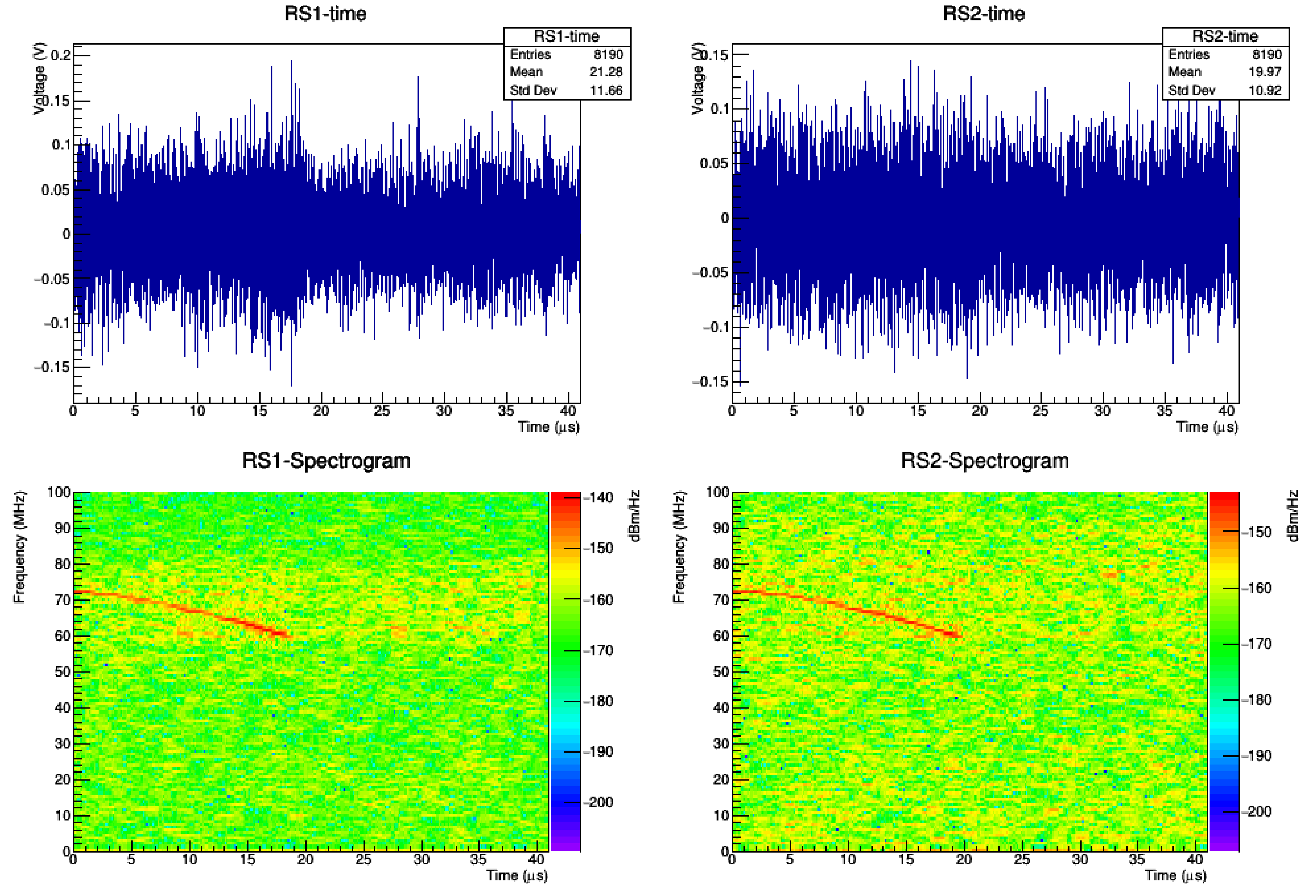


Chirp Calibration Unit(CCU)

CCU sends out a chirp every minute.

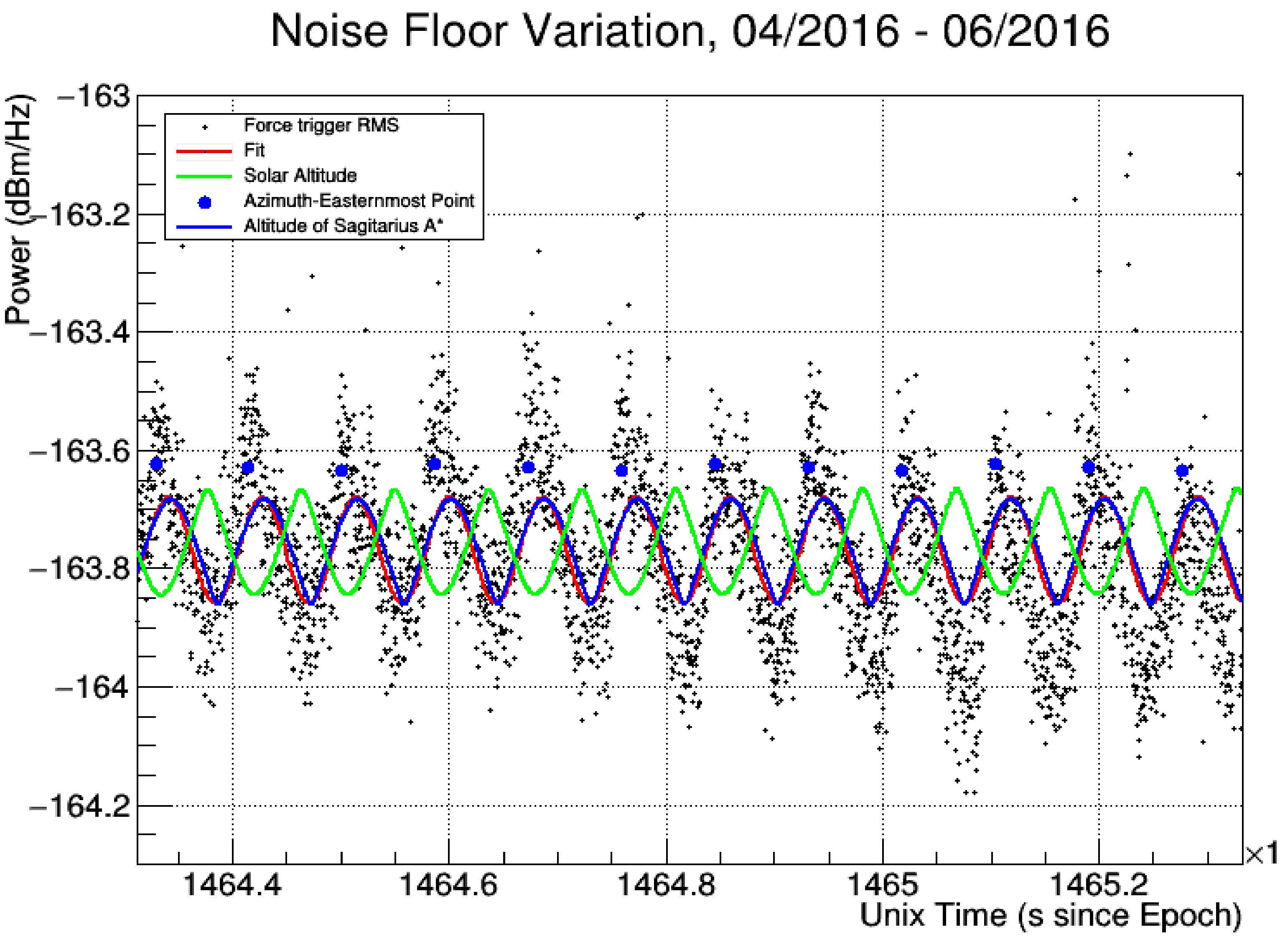
Attenuated output to level of noise.

Here captured in both stations in the field. 2016-02-17-12:26 UTC



stations sensitive to 'in-field' signals at 0db SNR.

System Sensitivity- Galaxy Check



plot forced triggers from april through june

Fit agrees with altitude of galactic center (Sagittarius A*)

Blue dots indicate easternmost point of galactic center while above the horizon

Also shown for comparison is the altitude of the Sun, indicating our fluctuation is not solar-thermal.

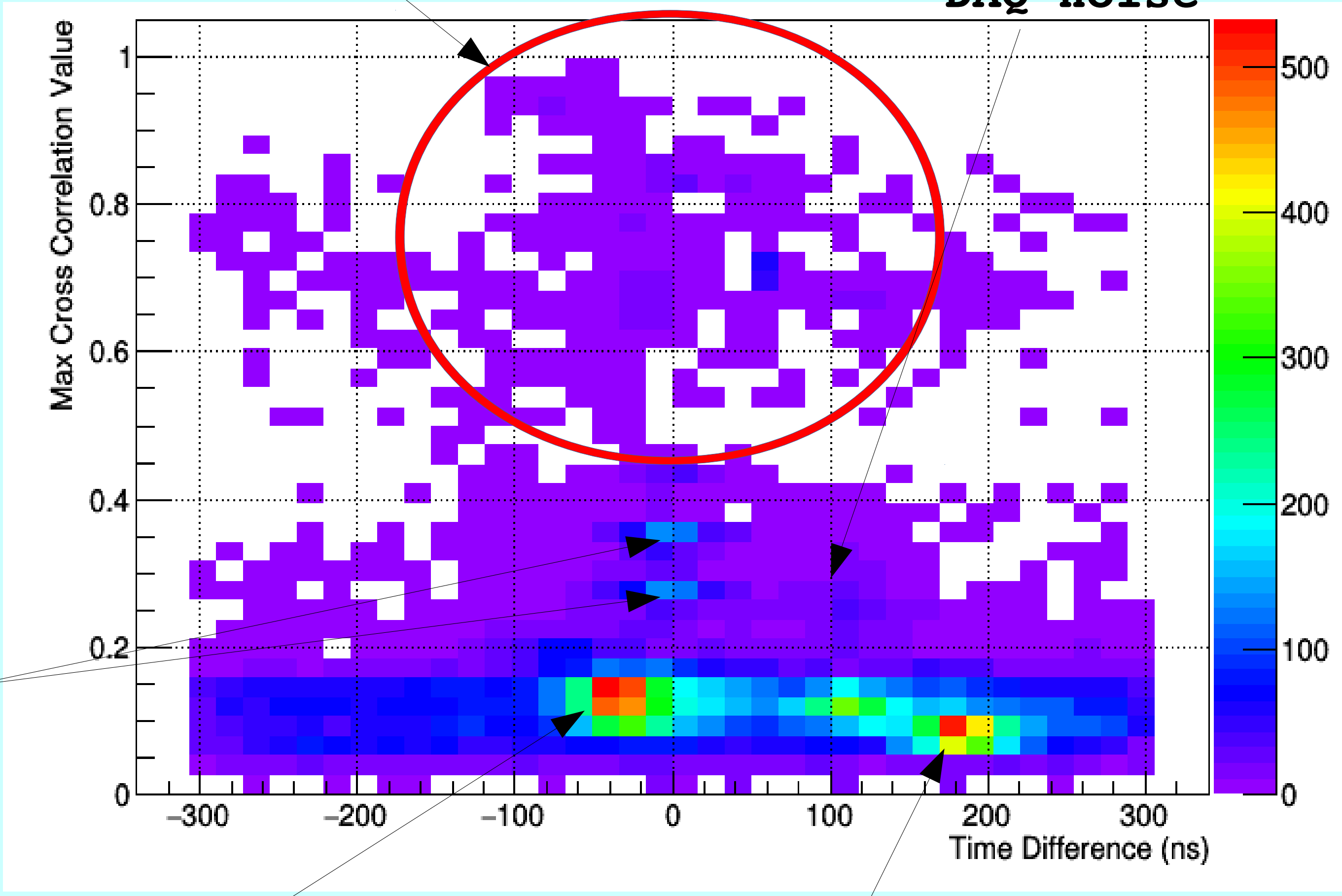
Initial Results- Self-coindiences

Possible Events (TODO)

DAQ noise

- With two stations we can “point” to noise sources, in part because they are restricted to the ground plane (at least the hot ones)

Pointing:
+200ns->270° in φ
-200ns->90° in φ



CCU

Cross correlation finds highly similar events

Electronics enclosure

FD building

Initial Results- TA coincidences

- Preliminary timestamp comparison between TARA and TA events yields <u>no direct coincident events.</u>

- SAD!!

- <u>However</u>:
  - During our 6 week run time, TA was off-line for 1 week.
  - No events in the TA data set over 60EeV.
  - Our detection volume is larger-possible events not detected by TA (unlikely)

part three:
Theory/upcoming experiments

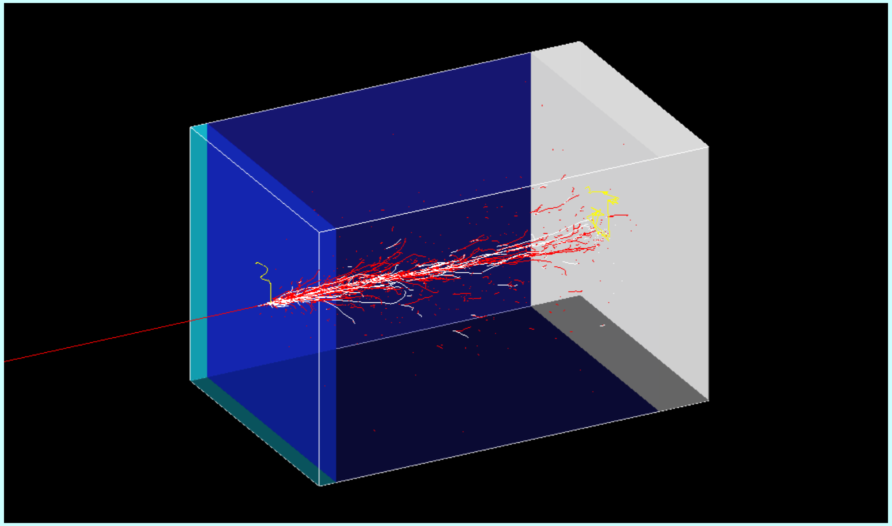
- particle-level sims; GEANT4; beam-test

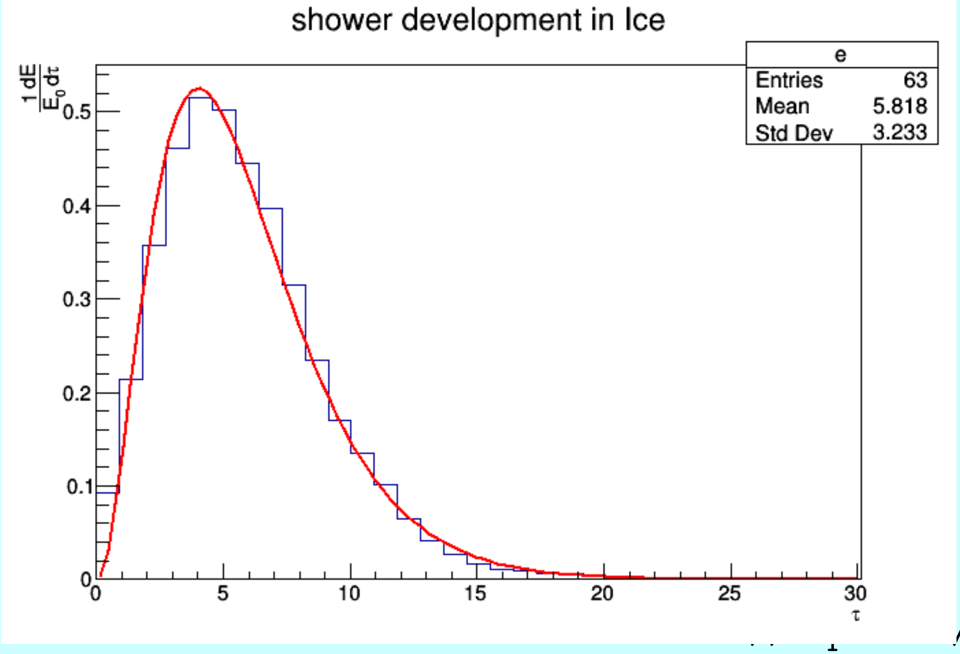
signal?

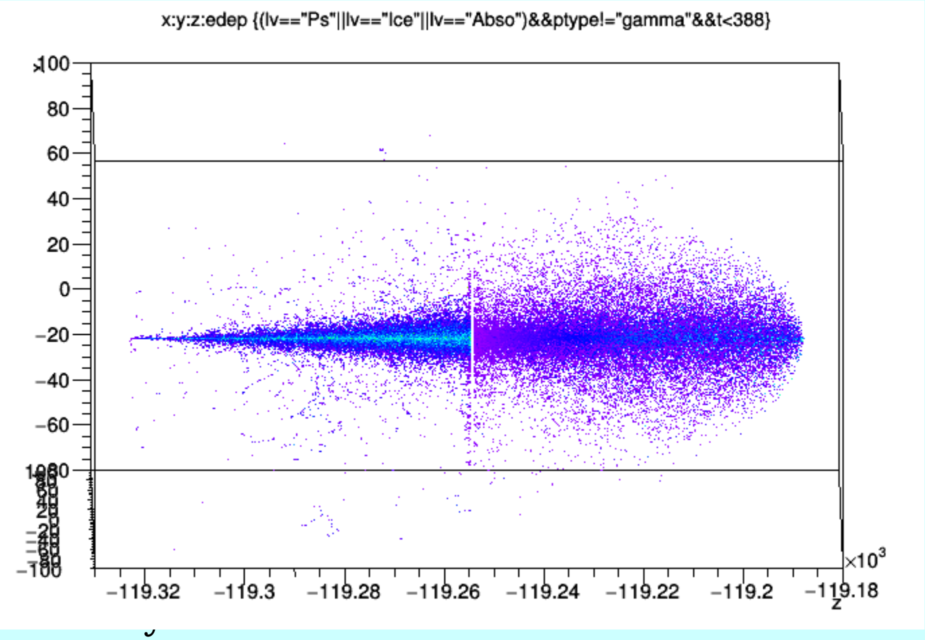
- ok so, why didn't TARA see anything? (probably)
  - basing UHECR physics on meteor model ("thin wire") likely incorrect
- limit set at 10^{-4} of the "thin-wire" cross-section. that's a big discrepancy
- several possible explanations
  - plasma lifetime much shorter than predicted
  - density lower than expected (Stasielak et. al)
  - collision rate far higher than expected (Meyers et. al)
  - other???
- need more data for air showers (redeploy stations!)
  - first run was only 6 weeks long
  - redeploy in remote location-run parasitically of FM
- need a lab test
  - interrogating a controlled shower will help to classify/quantify the above
- but first, simulation.

GEANT4

- massive, elegant, fully-customizable simulation suite for particle interactions with matter
- allows users to specify any geometry of any material (down to the atomic level) and blast it all with any particle of (almost) any energy, with full access to all particle-level parameters and data. wow!



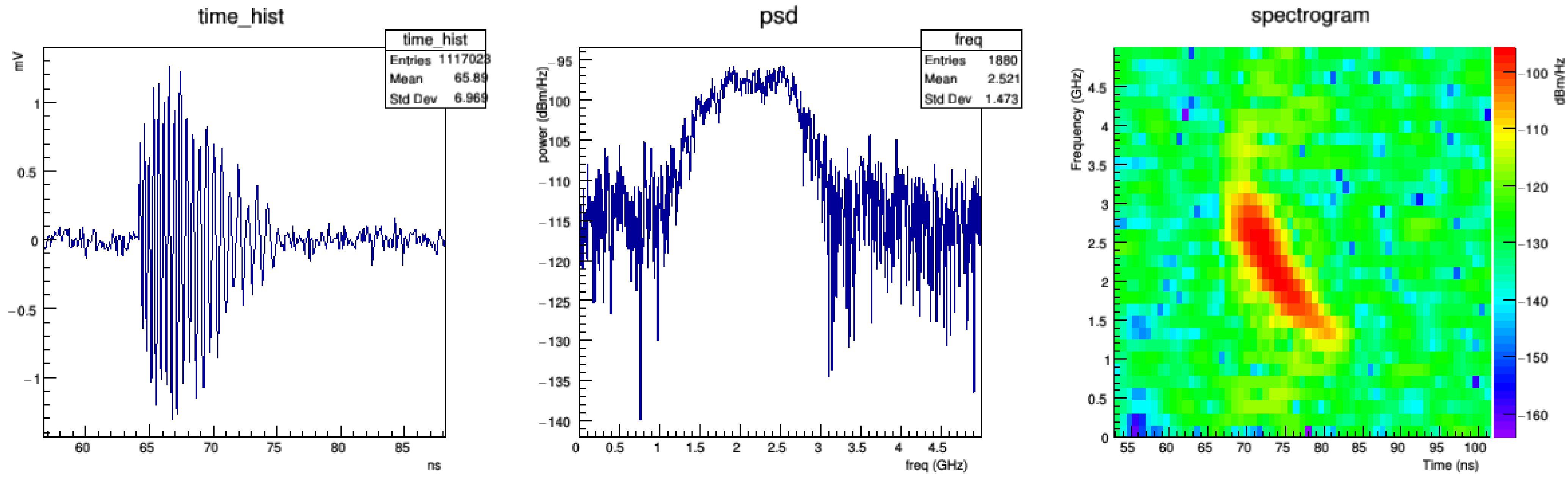




GEANT4 + RadioScatter

custom module for G4 to simulate radio scattering from shower.

- particle level
  - scattering amplitudes calculated using single particle <u>classical</u> EOM
- includes Compton effects (if any)
- includes inverse Compton effects (if any)
- includes collisions
- includes refraction/medium-specific RF propagation



RadioScatter

- scattering from the collection of single particles should reproduce results from the macroscopic, analytic plasma treatment of Stasielak, Bakunov, Raizer, etc.
- single particle EOM (classical regime), treated for generality as as a damped free particle in E field

  $$m_e(\ddot{\mathbf{x}} - \gamma\dot{\mathbf{x}}) = q\mathbf{E}$$

- Larmour formula for non-relativistic particles (assume ionization e are O(1-10)eV, low energy, low velocity)

  $$\mathbf{E}_a = \frac{q}{c}\left[\frac{\hat{n}\times(\hat{n}\times\dot{\beta})}{R}\right]_{ret} = \frac{q}{c^2}\frac{\ddot{x}}{R}\hat{\epsilon}sin\theta$$

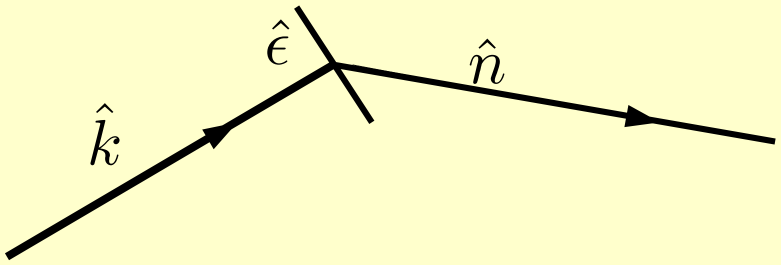
  where $\hat{\epsilon}$ is the direction of the acceleration of the individual electron, and θ is the angle between the acceleration vector and the outgoing direction $\hat{n}$
- solve EOM, assuming far-field

RadioScatter

- assuming $\vec{E}$ is a monochromatic plane wave,

$\mathbf{E} = E_0 e^{i(\mathbf{kx}-\omega t)}\hat{\epsilon}$

$$\boxed{\mathbf{E}_a = \frac{q^2}{c^2}\frac{\omega}{m}\frac{E_0}{R}\frac{e^{i(kx-\omega t)}}{(\omega + i\nu_c)}\hat{k}\cdot\hat{n}}$$

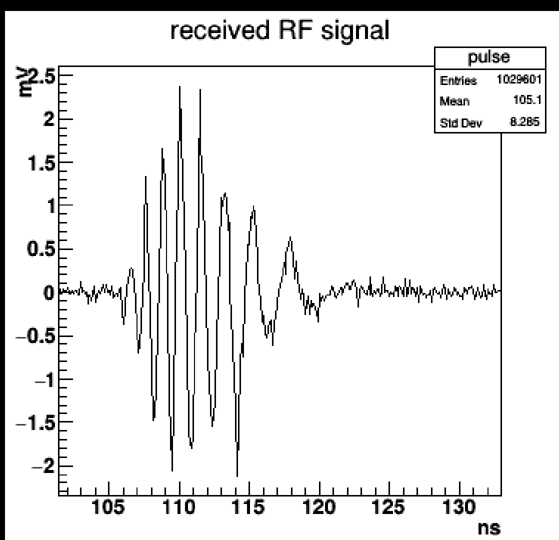


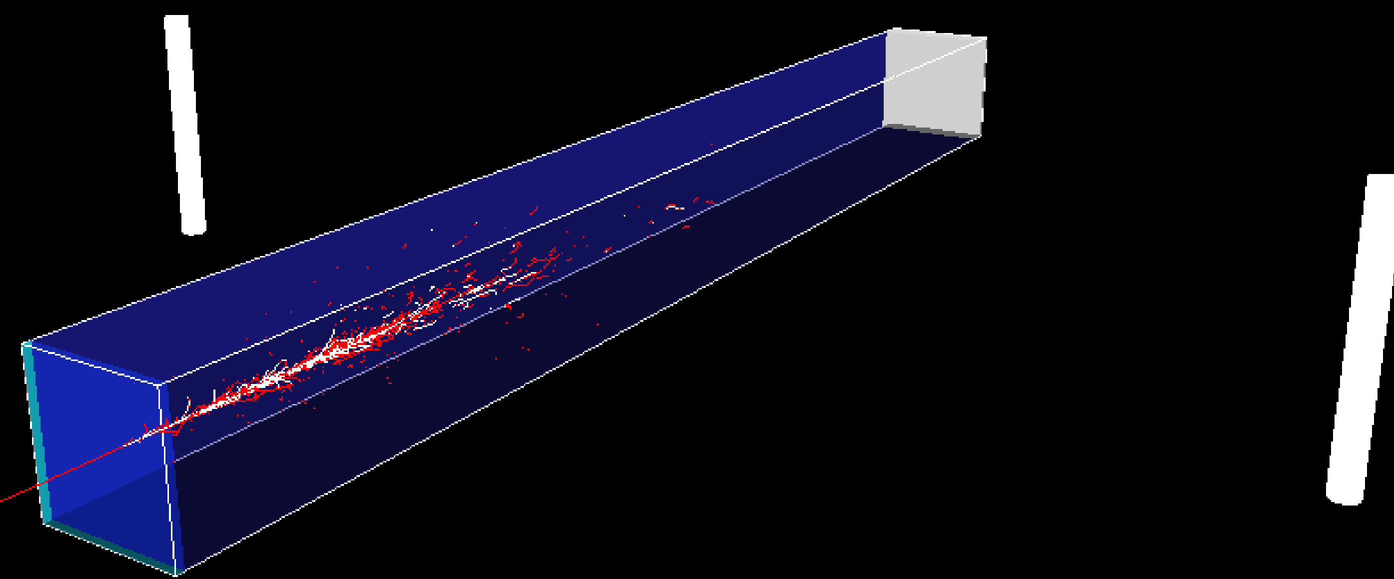
- the far-field Larmour equation for the acceleration field of an electron, with collisions, under influence of incoming RF wave
- $\hat{k}$ is the direction of incoming wave propagation, $\hat{n}$ is the direction of outgoing wave
- in module, use:

$$Re[\mathbf{E}_a] = \frac{q^2}{c^2}\frac{\omega}{m}\frac{E_0}{R}\left[\frac{\omega cos(kx-\omega t) + \nu_c sin(kx-\omega t)}{(\omega^2+\nu_c^2)}\right]\hat{k}\cdot\hat{n}$$

RadioScatter

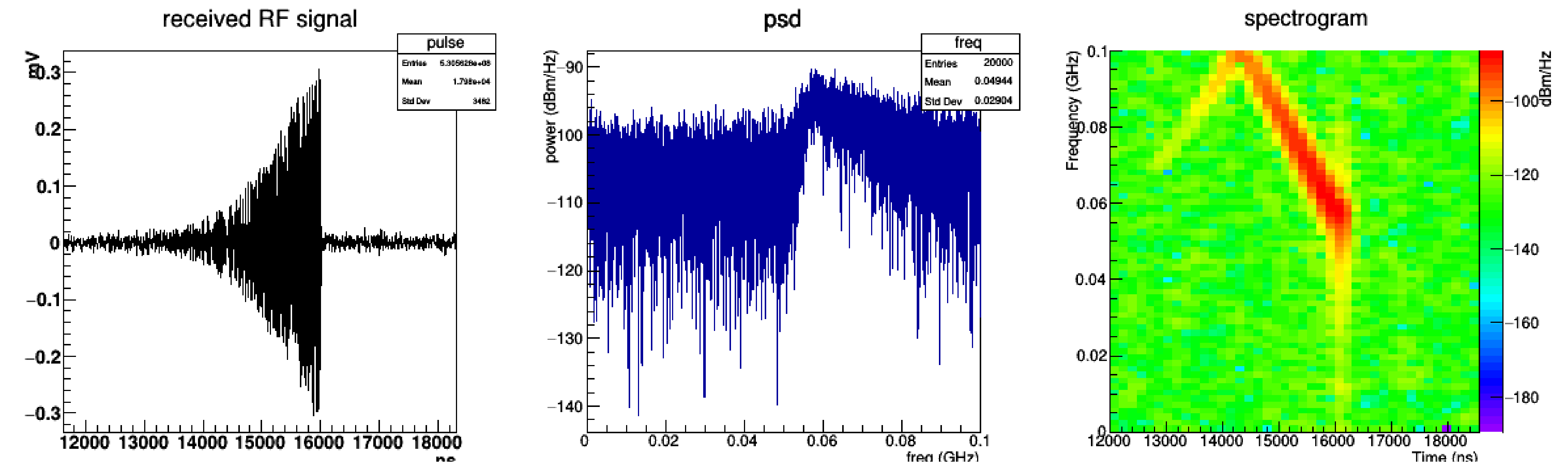
- how does it work?
  - -make 4-vectors of energy deposits (ionization e number densities) in G4
  - -set a given tx/rx geometry, frequency, and receiver sampling rate
  - -calculate retarded fields and propagation fields for each 4-vector
  - -sum fields at receiver at a given sample rate (bin size)





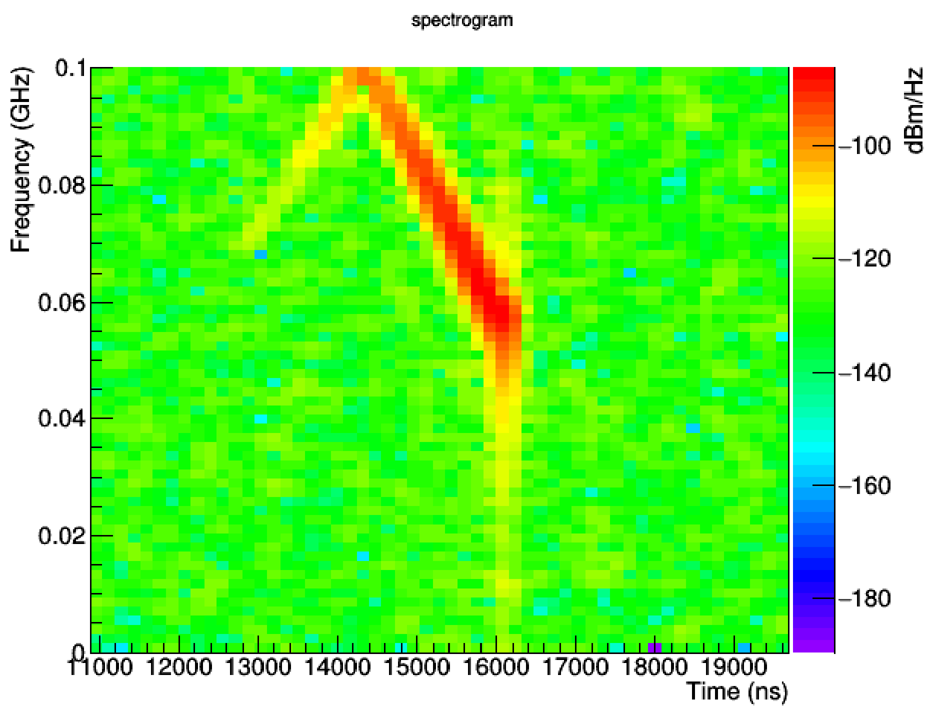
RadioScatter

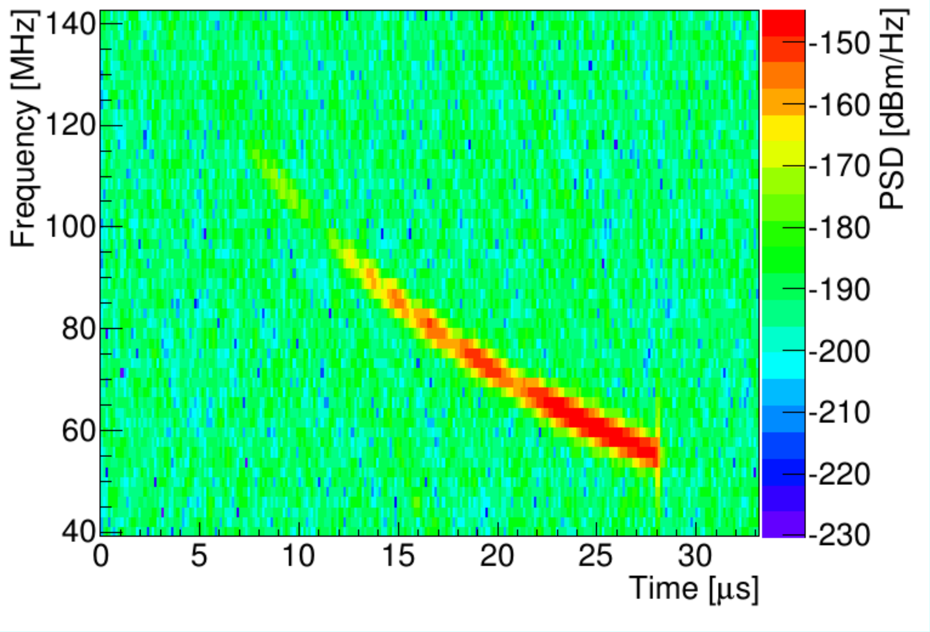
- Scattering is <u>coherent</u>
- predicted frequency shift from shower is observed here, with <u>no consideration for macroscopic effects</u>.
- treat plasma lifetime τ_p as 0 - may we consider this a minimum signal amplitude?



Here: 5EeV primary proton, in air, 54.1 MhZ sounding frequency
ideas for improving trigger-signal may be used to reject transients...

RadioScatter





RadioScatter pulse
geometry predicts ~-20MHz/us

TARA simulation pulse
(I.Meyers et al.)
~-3MHz/us

so far so good...

RadioScatter-conclusions

- simulated signal matches analytic, macroscopic theory decently <u>qualitatively</u>. several things…
- TODO:
  - short range interactions??
  - plasma frequency discrepancy
    - $\omega_p > \omega_I$, necessary condition, seems to come from macroscopic effects

      -not present here
  - experimental verification, of course!
    - see next slides.

SLAC-ESTB

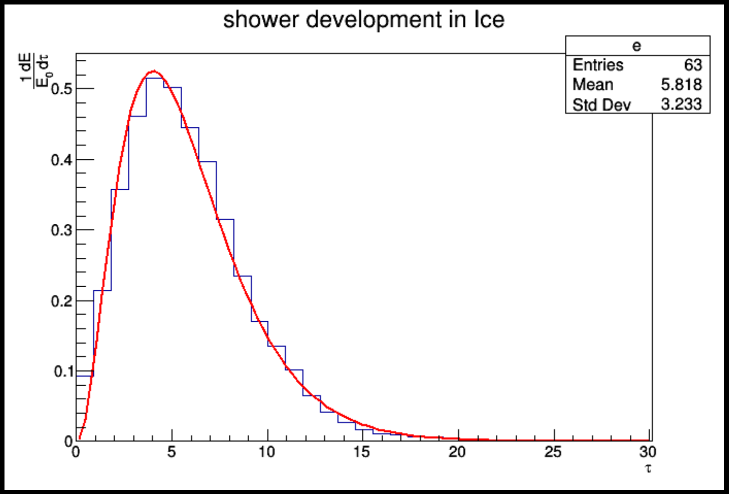
- The end-station test-beam at SLAC
  - users can install targets, detectors, etc, get 5Hz switched beam from main LCLS linac
  - rich history of facilitating discovery:
    - first evidence for quarks!
    - first detection of Askaryan radiation
- Install a target of high-density polyethylene (HDPE), produce particle-shower initiated plasma
  - empirically determine the number density/ plasma frequency, plasma lifetime
  - proposal has passed scientific merit review- awaits scheduling!!

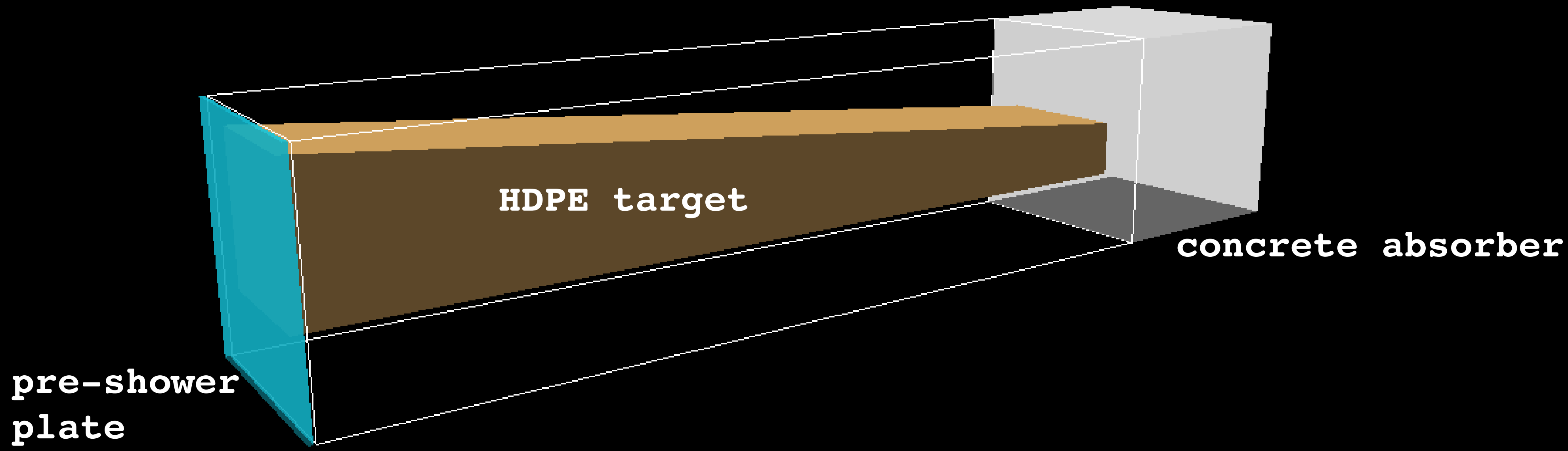
SLAC

plastic has low index of refraction (1.53) and similar density to ice.

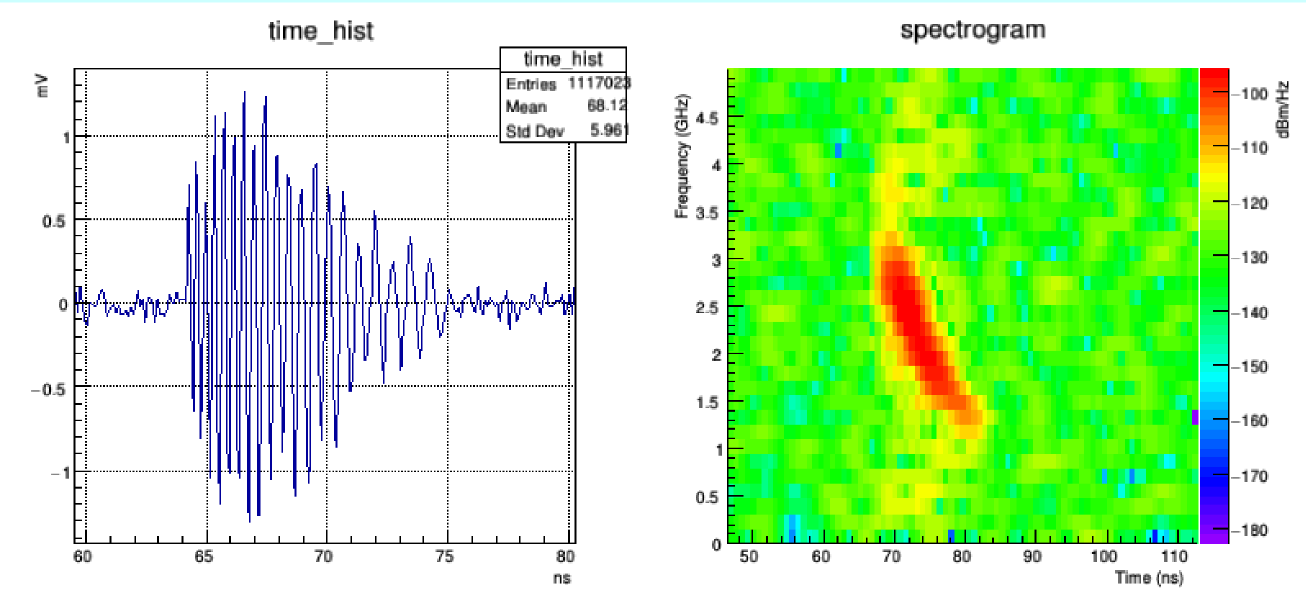
same target as SLAC T510

hope to extrapolate results to air, ice...other media





expected signal



with reasonable (28dBm) output power, simulation yields this rapidly frequency shifting pulse.

amplitude envelope is consistent with shower density profile.

well above thermal noise.

characteristic signal distinguishable from background.

plasma

- most simply, a gas of free charges
- in this talk, plasma = "quasi-static plasma"
  - $n_e = n_i$, number of electrons equals number of ions, overall
  - "plasma frequency" (useful!) measure of e- density

$$\omega_p = \left(\frac{4\pi q^2 n_e(t)}{m_e}\right)^{\frac{1}{2}} \rightarrow \omega_p \sim (n_e(t))^{\frac{1}{2}}$$

- radio interactions with plasma are well studied
  - Ionospheric scatter, meteor scatter (more on this), tokamak plasmas
- de-ionization rate of the plasma:

$$R(T) = \frac{dn_e}{dt} = \alpha n_e^2 + \beta n_e, \quad n_e = n_i$$

- coefficients α, β are temperature dependent. α is for e/i recombination, β is attachment to neutrals (dominant in air)

observables

- parameters of the PSP are observable in ways not accessible to passive measurements
- interrogate PSP with different RF
  - continuous wave
  - pulsed CW
  - broadband pulse
- quantify the plasma parameters
  - this is well understood. used to classify tokamak plasmas for decades.
    - recall: $\omega_p \propto \sqrt{n_e}$

    if $\omega < \omega_p$, reflection happens
  - elif $\omega > \omega_p$, nope!

observables

- 2 parameters of experiment can give us all the rest: $t_r, \omega_I \to \alpha, \beta, n_e$

we can monitor the signal duration as a function of interrogation frequency, and use the expression to figure out the dominant dissociation mechanism/coefficients.

$$\omega_p = \left(\frac{4\pi q^2 n_e(t)}{m}\right)^{\frac{1}{2}}$$

for example, if ? is negligible:

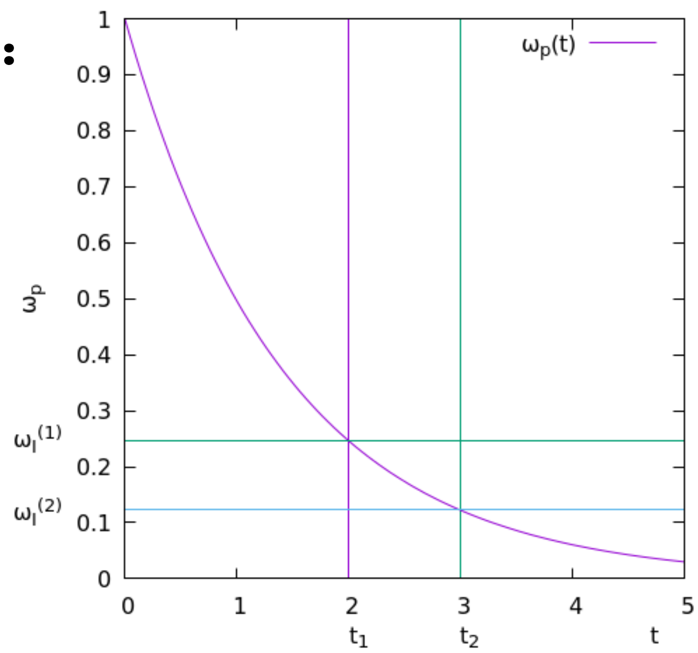
$$\frac{dn_e}{dt} = \alpha n_e^2 + \beta n_e \to \alpha << \beta \to n_e(t) = n_0 e^{\beta t}$$

$$\omega_p = 2\left(\frac{\pi q^2 n_0 e^{\beta t}}{m}\right)^{\frac{1}{2}}$$

$$t = \frac{ln[\omega_p^2/(4\eta)]}{\beta}, \eta = \frac{\pi q^2 n_0}{m}$$

$$t_r = \frac{ln[\omega_I^2/(4\eta)]}{\beta}$$

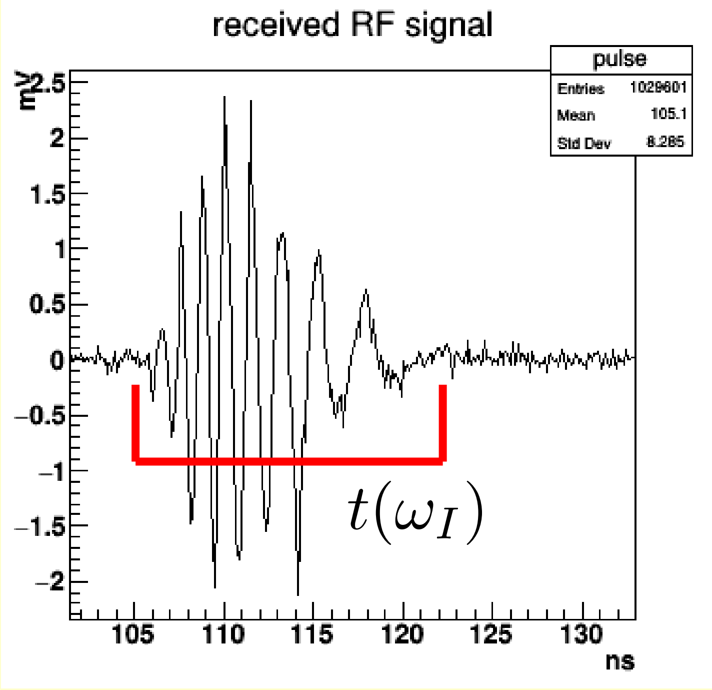
ex:



observables

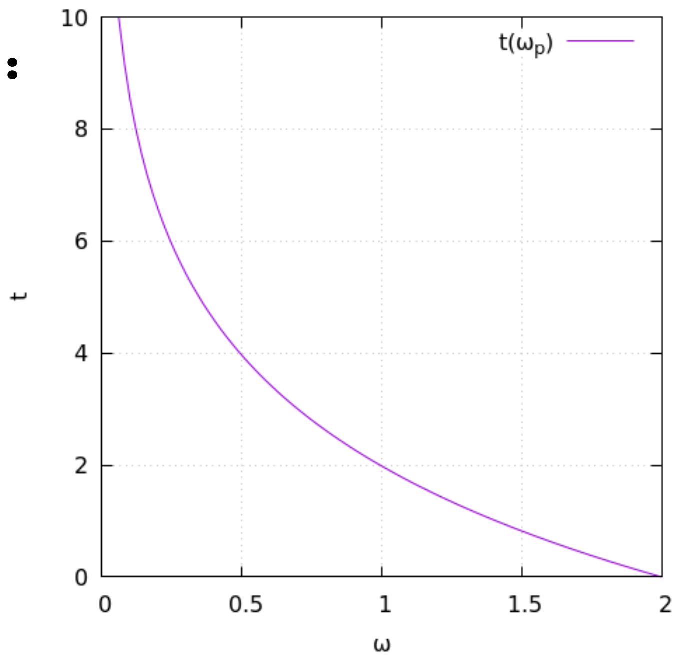
- signal duration is our primary observable, and our interrogation frequency is variable.

$$t = \frac{ln[\omega_p^2/(4\eta)]}{\beta}, \eta = \frac{\pi q^2 n_0}{m}$$



return signal duration as a function of interrogation frequency ω_I gives a curve to fit with parameters ω_p, α, β

ex:



summary

- RF scatter has been presented as a possible detection technology for high-energy particles
- previous experiments for UHECR have reported no signal, but only in air
- showers in a denser medium (read: neutrinos in ice) are better candidate for high density PSP
- simulations show appreciable signal with psp parameters as direct observables of the measurement.
- lab tests forthcoming

Thanks!

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backup

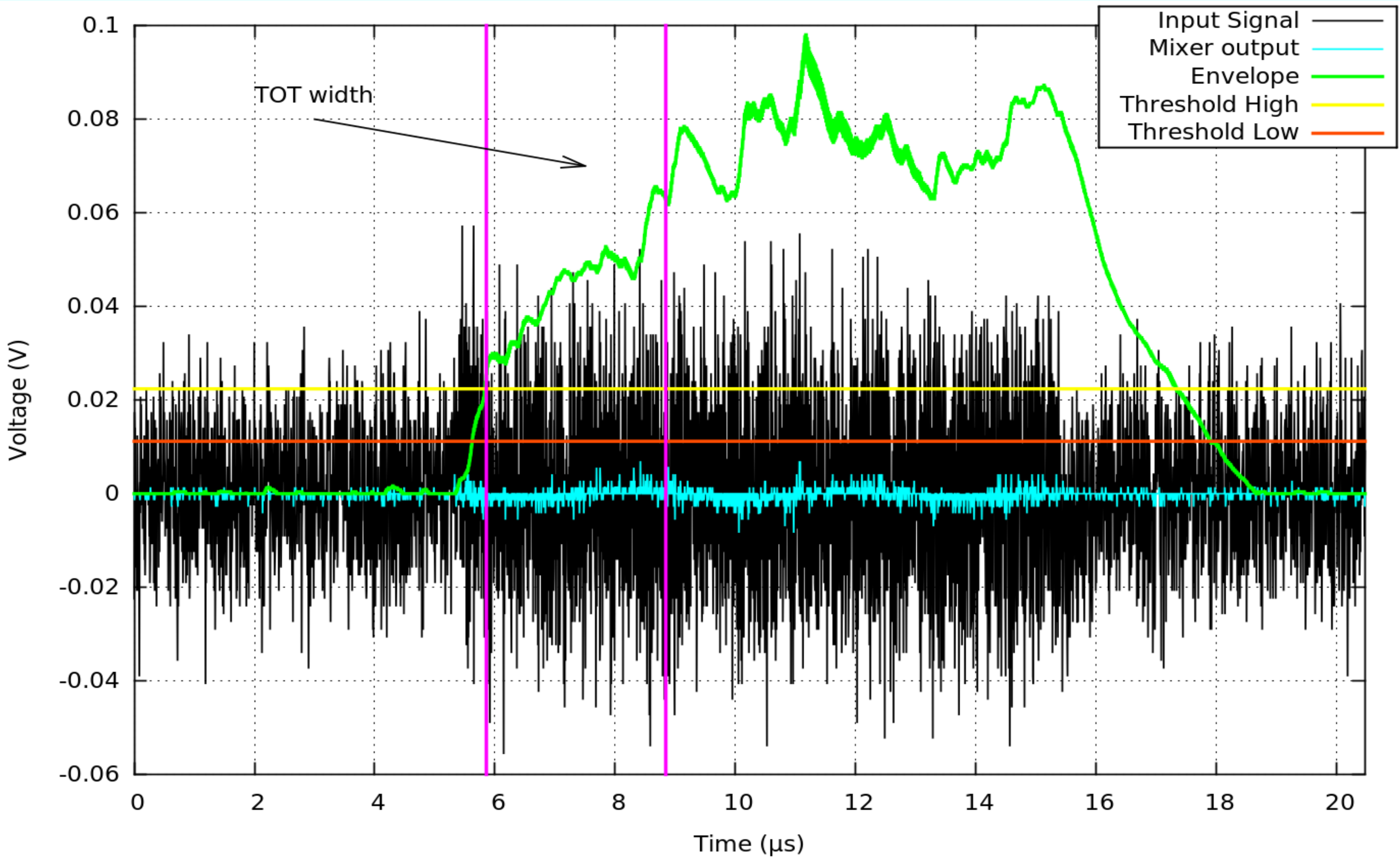
Trigger

Here a test chirp is embedded in Gaussian noise. (black)

The signal is heterodyned and filtered (blue)

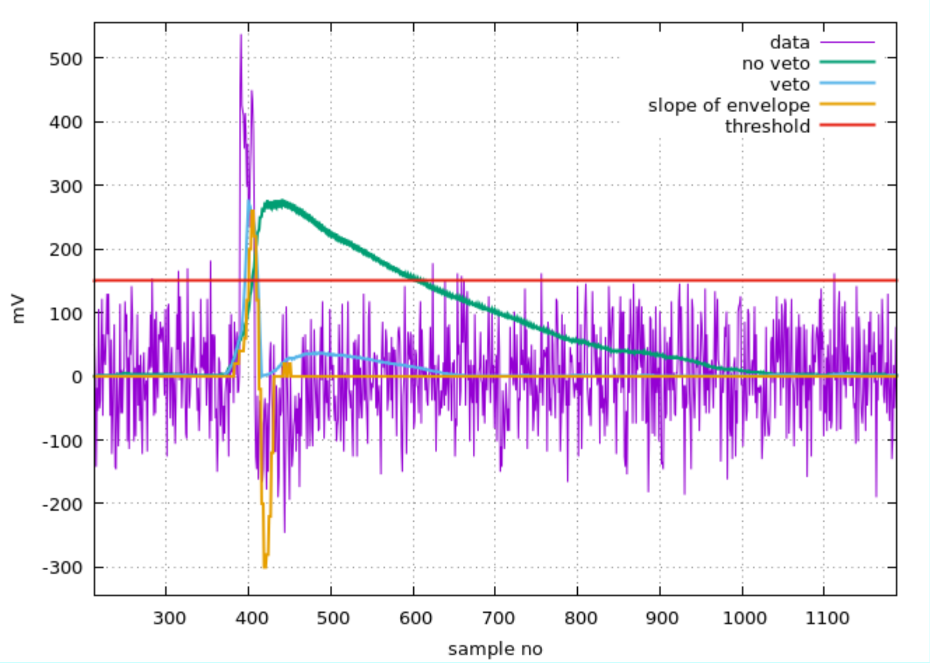
Envelope detection results in the green trace, which we trigger on.

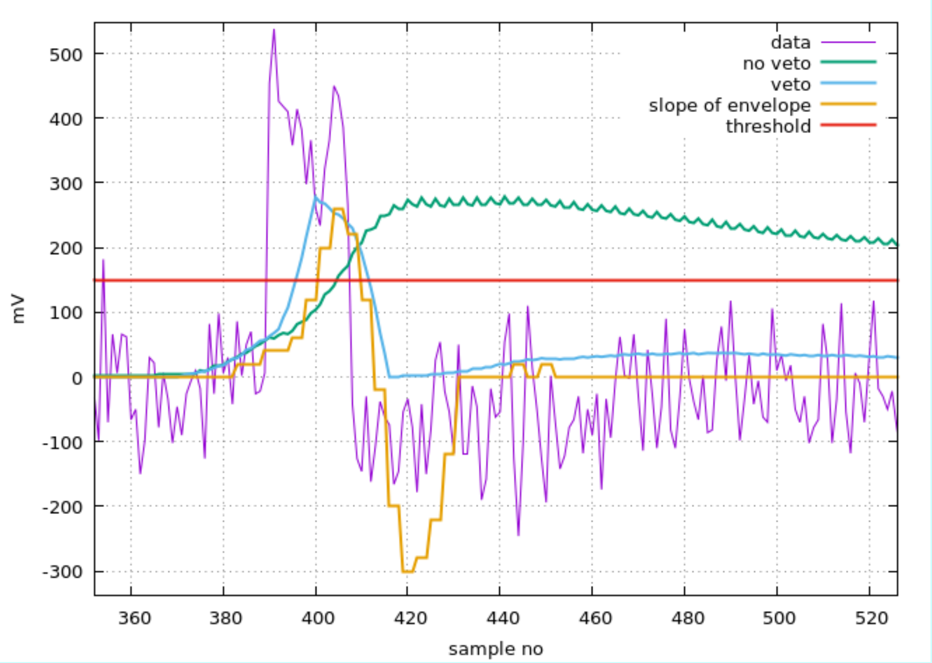
Must rise above high trigger and stay above low trigger for TOT duration.



All 'in firmware' traces

transient Veto





Anthropogenic backgrounds are usually spiky (read:broadband), and kill efficiency. Recently implemented a veto system: kills high-amplitude transients so they don't satisfy TOT trigger!

RadioScatter

- ask-what are the main interactions within the plasma?
  - Coulomb e/i interactions
    - only relevant within the Debye length
    - neglected in RadioScatter (for now)
  - e/e, e/n, e/i collisions
    - at EAS altitudes, as well as in a target media, neutral densities are very high, so the collision rate is significant
  - de-ionization processes
    - not discussed here atm
- identify terms in the EOM...

RadioScatter

- for free electrons there is no ‘friction’, but collisions prohibit free motion under influence of an external field (from Raizer).

$$\gamma \rightarrow \nu_c = \sum_s n_s \bar{v}_e \sigma_s$$

- identify γ as the collision frequency ν_c. n_s, σ_s are the number density of, and cross section of collision with, species s = n,e,i
- $\bar{v}_e$ is the mean thermal velocity of electrons, but G4 gives access to actual individual particle energies.
- n_0 for air is high, $\sim 10^{19} cm^{-3}$ so collisions are significant! (not included in original theory behind TARA)

physics questions

- what remains to be answered:

  1-what is the plasma lifetime?

  2-what is the evolving plasma density?

  3-what is the dominant scattering regime?

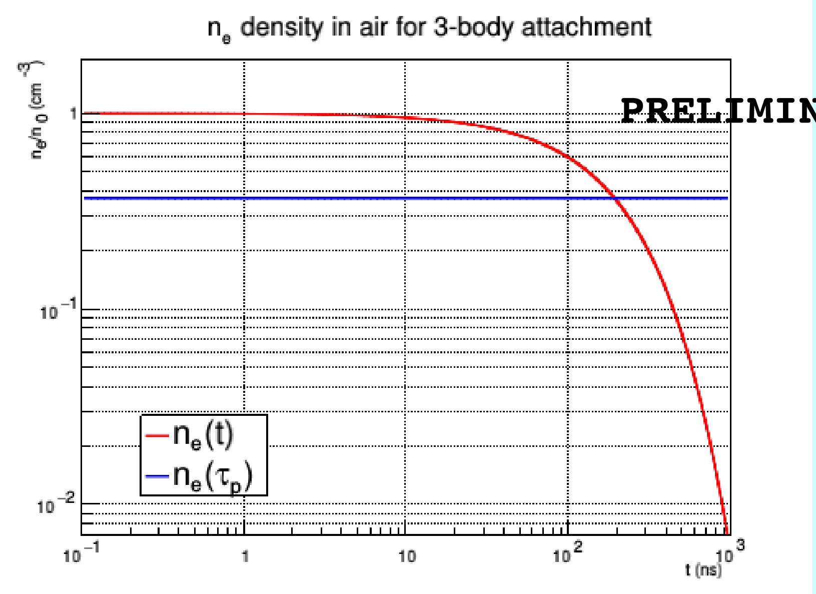
  4-what is the dominant dissociation regime?

  5-is there/what is a correct macroscopic model of the system?

'thin wire' model limitations

- Gorham 2001 says thin wire approximation is appropriate for modeling the UHECR PSP.
- cites Moliere radius of plasma disc at ~70m, but effective radius O(1m).
- VanVleck et all, 1947, in the paper cited by Crispin 1965, which is cited by Gorham, says:
  - "...under no conditions can the accuracy be monumental. For values of 2l/a of the order 10^3 it is doubtless quite good (say within a few percent) and for 2l/a >100 it is probably adequate, but for very "fat" wires of the order 2l/a = 10 the calculations can at most be relied on only for orders of magnitude. Even when l/a is very large, the theory may involve considerable percentage of error..."
- l=length of plasma, a is radius
- Alekandrov 1988 gives coeffs

- τ_p in air is O(10-100ns), l?O(10m), meaning the radius must be O(.1 m) for 2l/a>100
- so simply calculating the cross- sectional area of a cylinder of this sort is O(1 m^2), much lower than quoted maximum CS
  - maximum cross section if 'wire' is perfect, uniform conductor, no angular considerations, no change in number density
    - not the case in PSP!



PRELIMINARY