Selection and Monte Carlo Optimization of Telescope Array Radar Remote Receiver Stations

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Ultra-High Energy Messengers Parallel Session

TeVPA 2013

August 27th, 2013

Outline

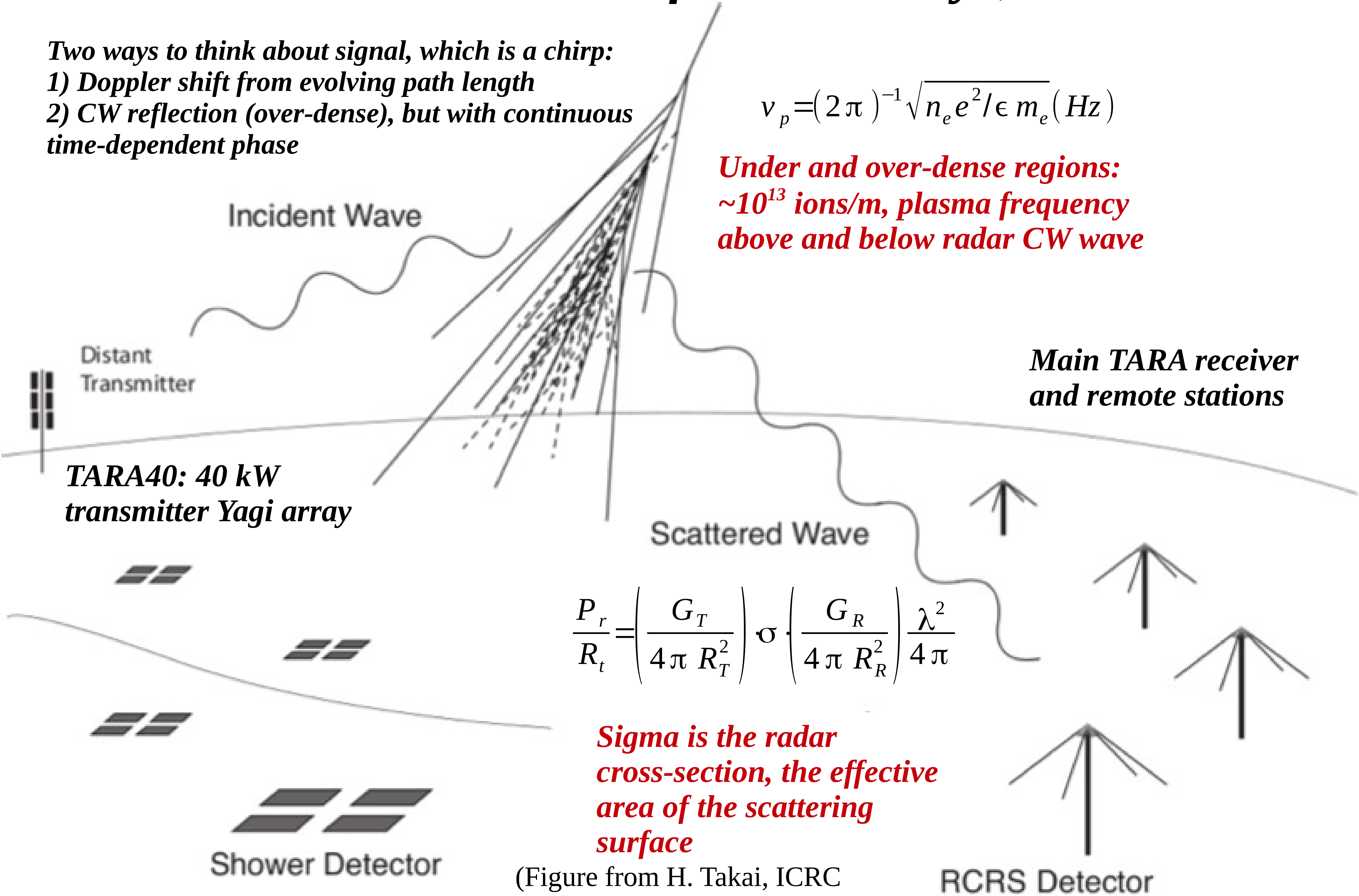
- *Cosmic ray physics, and a new way to detect cosmic rays at energies of 10^{18} eV*
- *Concept of bi-static radar detection, plasma frequencies, and other atmospheric radar detections*
- *Remote station noise backgrounds*
  - *Coincidence formation and anthropogenic noise minimization*
  - *Background studies*
- *Deployment of prototype remote station*
  - *Hardware design, data collection*
  - *Environmental data analysis and power consumption – *QuarkNet student*
- *Monte Carlo analysis*
  - *Basic signal dependencies, beginning to reconstruct primary information*
- *Conclusion*

Bi-static Radar Detection of Cosmic Rays, I

Two ways to think about signal, which is a chirp:
1) Doppler shift from evolving path length
2) CW reflection (over-dense), but with continuous time-dependent phase

$$\nu_p = (2\pi)^{-1}\sqrt{n_e e^2/\epsilon\, m_e}\,(Hz)$$

Under and over-dense regions: ~10^{13} ions/m, plasma frequency above and below radar CW wave



Main TARA receiver and remote stations

TARA40: 40 kW transmitter Yagi array

$$\frac{P_r}{R_t} = \left(\frac{G_T}{4\pi R_T^2}\right)\cdot\sigma\cdot\left(\frac{G_R}{4\pi R_R^2}\right)\frac{\lambda^2}{4\pi}$$

Sigma is the radar cross-section, the effective area of the scattering surface

(Figure from H. Takai, ICRC Proceedings, 2013)

Bi-static Radar Detection of Cosmic Rays, II

Four regimes to consider:

Regime #1: plasma frequency exceeds transmitter (over-dense), and transmitter wavelength exceeds critical radius of shower (Rayleigh)

Regime #2: plasma frequency exceeds transmitter (over-dense), and transmitter wavelength is less than the critical radius (optical) … less likely, lambda = 6 m (see below)

Regime #3: plasma frequency is lower than transmitter (under-dense), and Rayleigh regime … requires coherent scattering before electron thermalization, need ~30 m wavelengths

Regime #4: plasma frequency is lower (under-dense), and optical regime … requires coherent scattering before electron thermalization, diffusion, and recombination

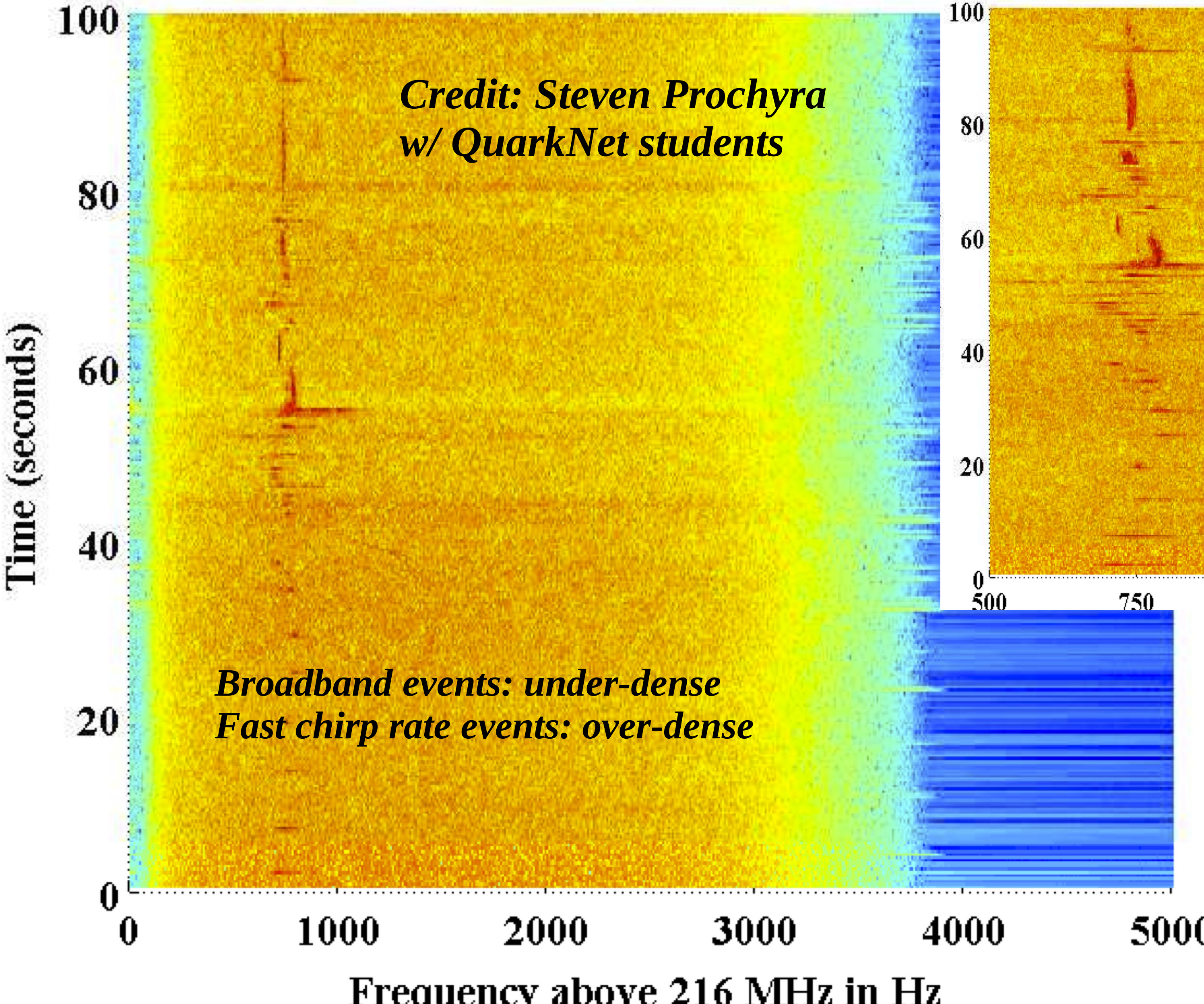
Radar cross-section for regime #1 as a thin wire approximation (main source of signal) (Gorham 2001):

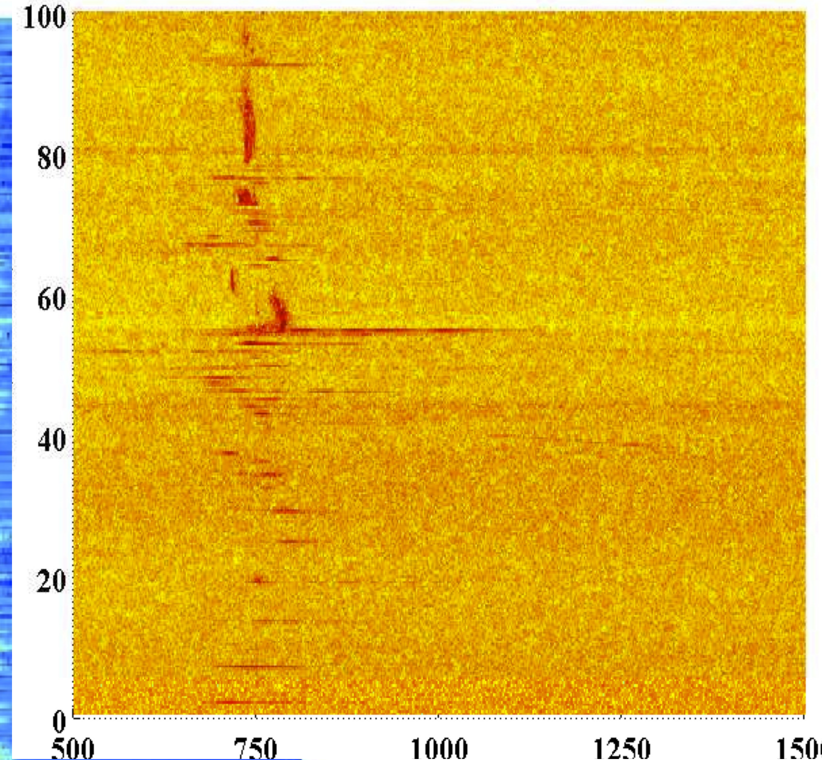
$$\sigma_{max}^{od} = \frac{\pi L^2 \cos^4(\varphi)}{\pi^2/4 + (\ln(\lambda/(1.78\pi r_c)))^2} \qquad \sigma^{od}(\theta) = \frac{\lambda^2 \tan^2(\theta)\cos^4(\varphi)}{(\pi^2/4 + (\ln(\lambda/(1.78\pi r_c \sin\theta)))^2)16\pi}$$

Critical radius r_c, Shower segment length L

Polarization angle phi, Radar wavelength lambda

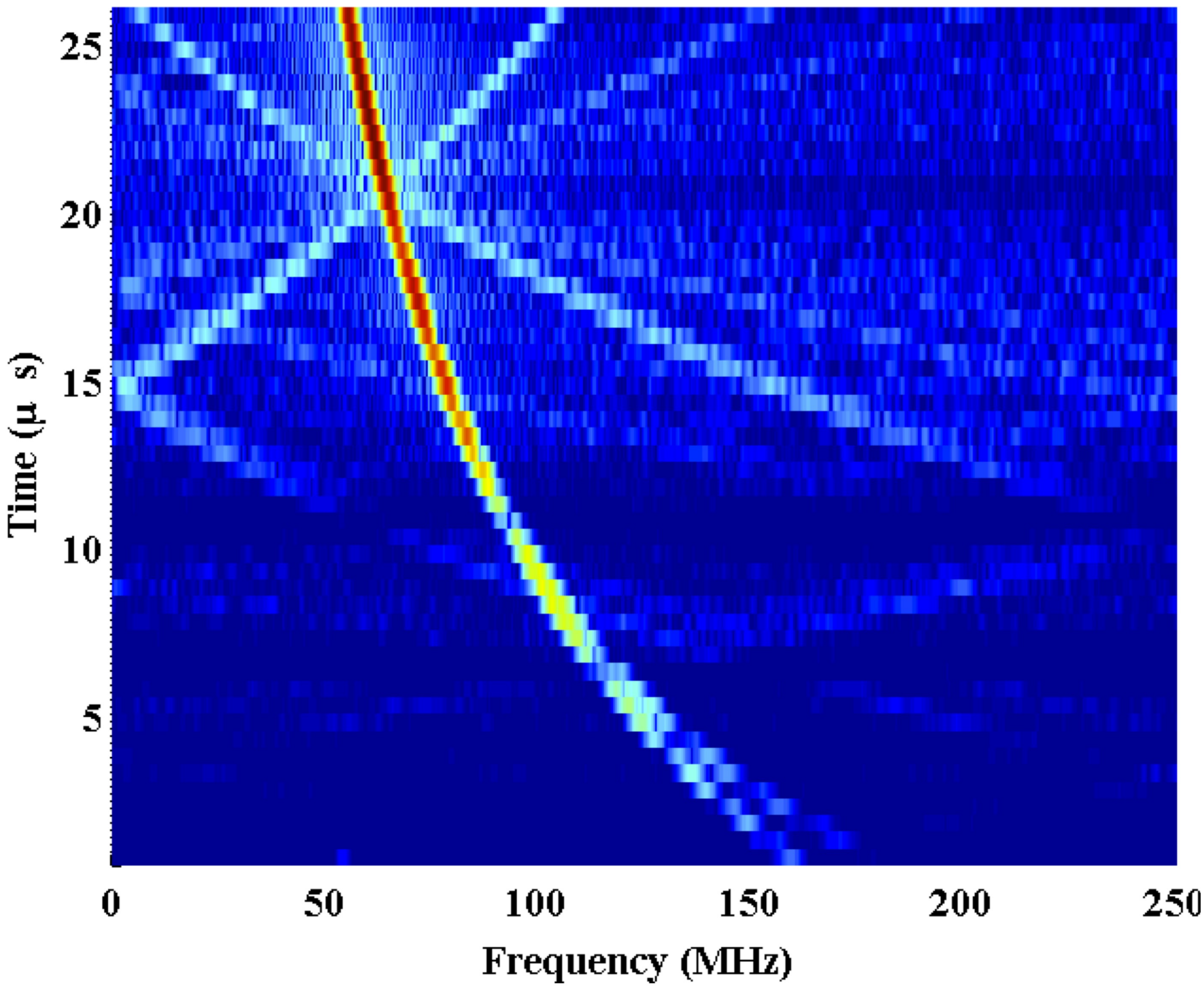
Meteorites – Similar to detection to cosmic rays





Energy of a typical meteorite ~ 3 x 10^{17} eV (Gorham 2001)

Example of a simulated signal – 50 EeV cosmic ray



Chirp rate: ~ 2 MHz/μs (typical)

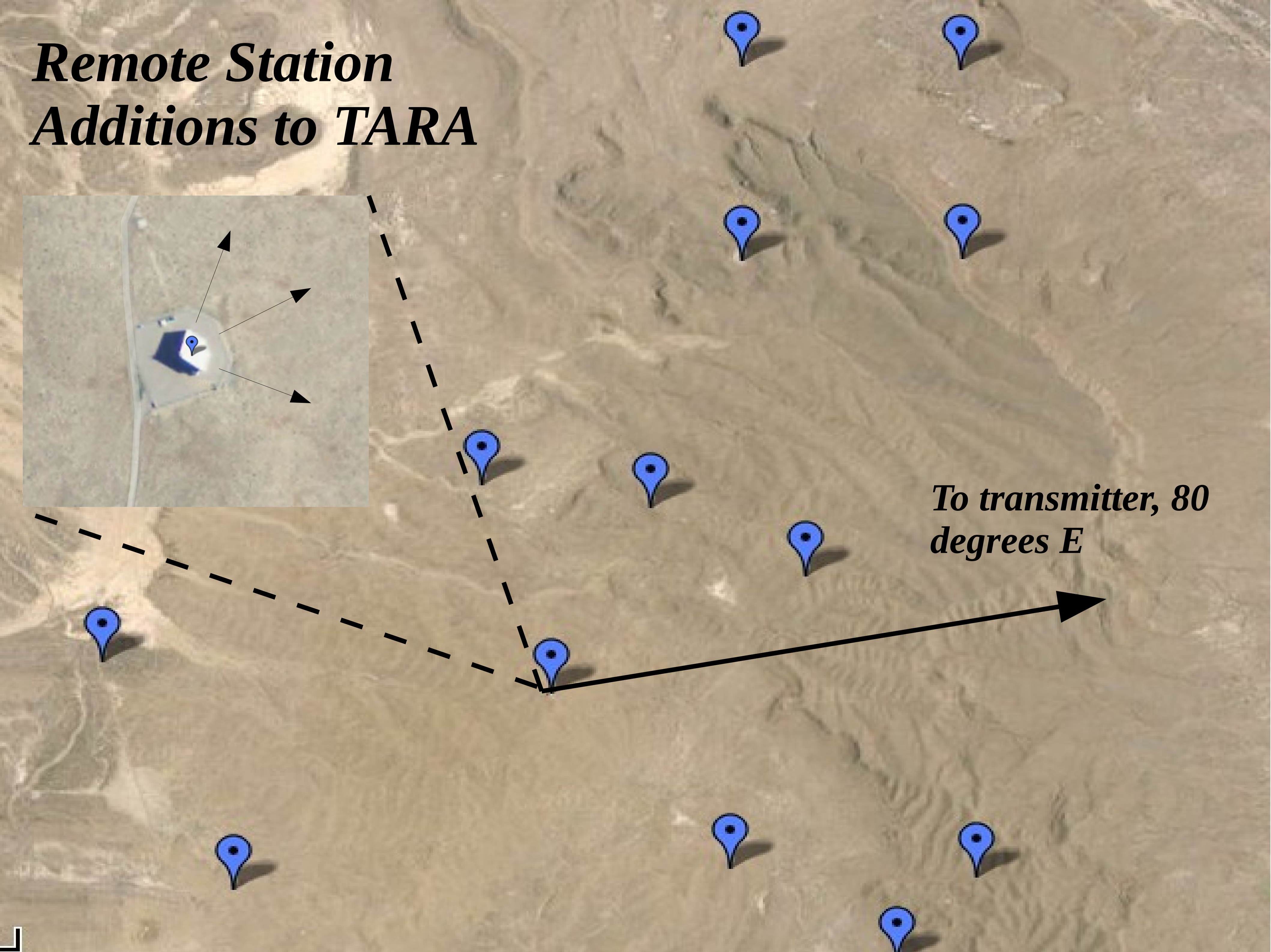
Energy: 50 EeV

Zenith: 45 degrees

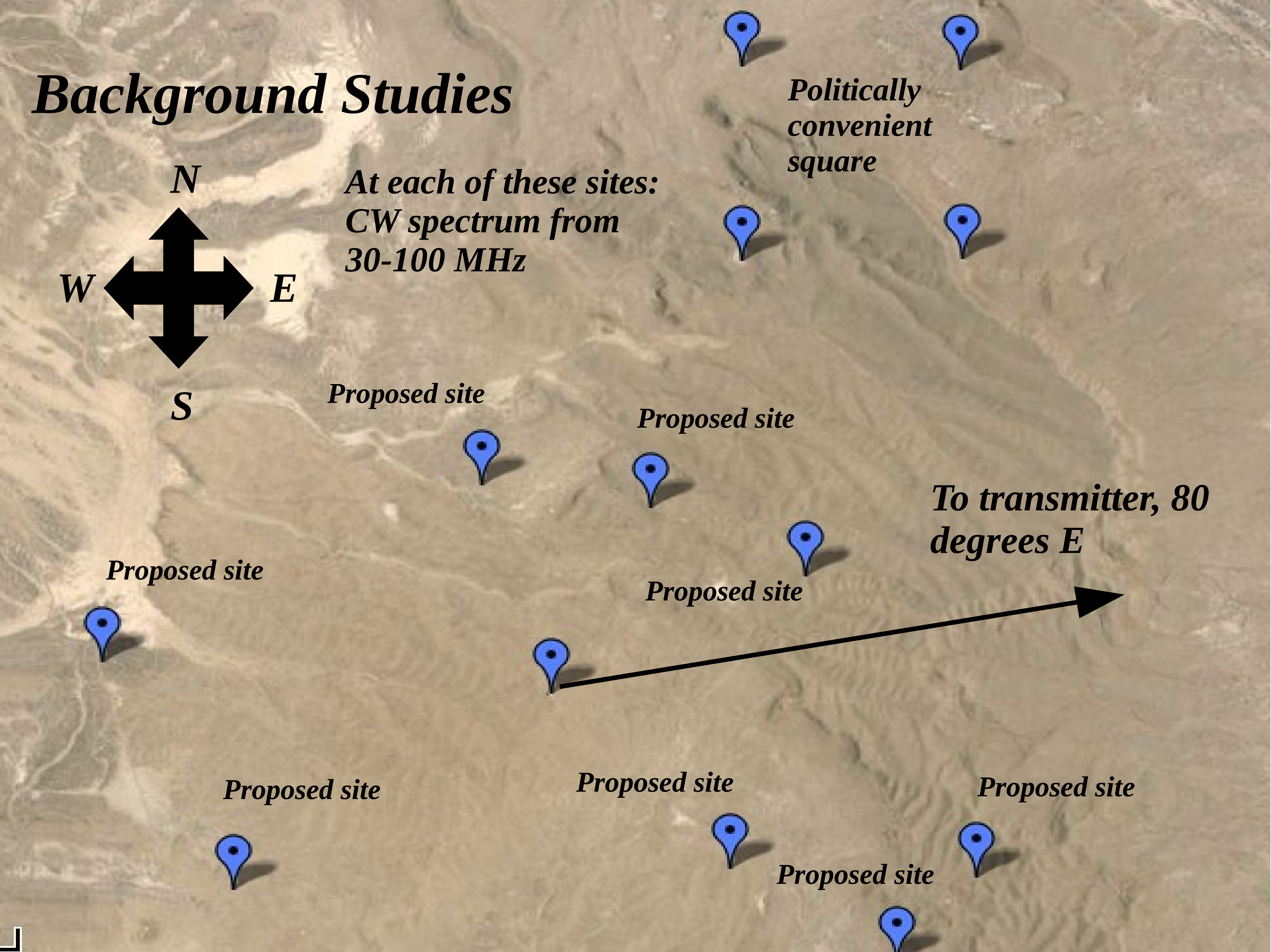
Chirps down to the transmitter CW frequency of 54.1 MHz

Current form of the receiver samples at 250 MS/s to capture full profile

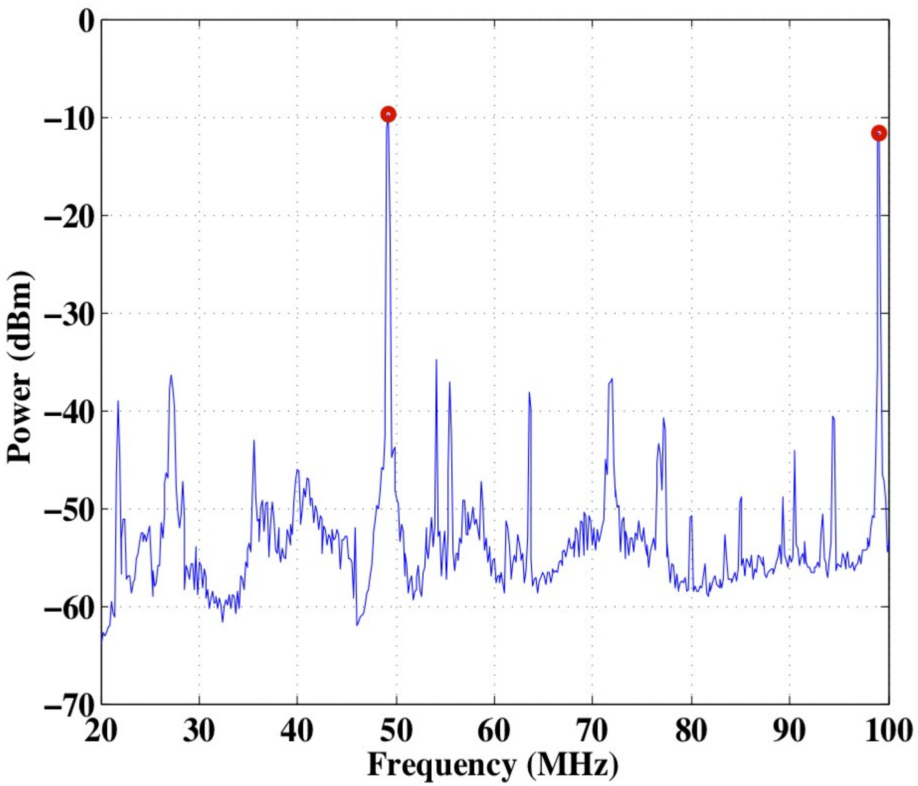
Remote Station Additions to TARA

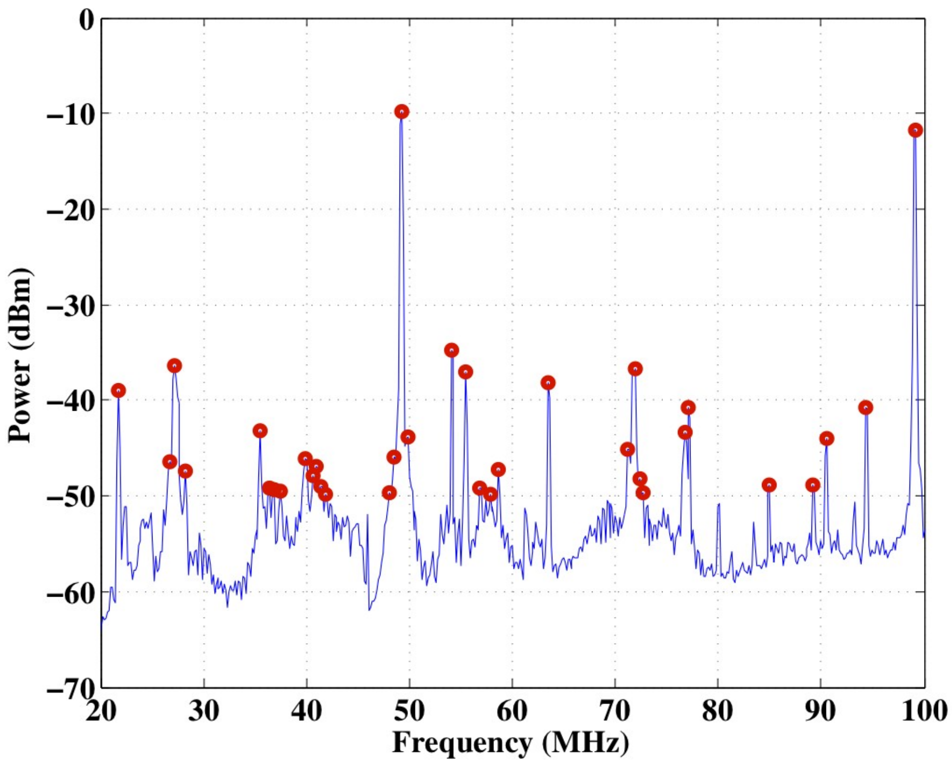


Background Studies



Peak Finding



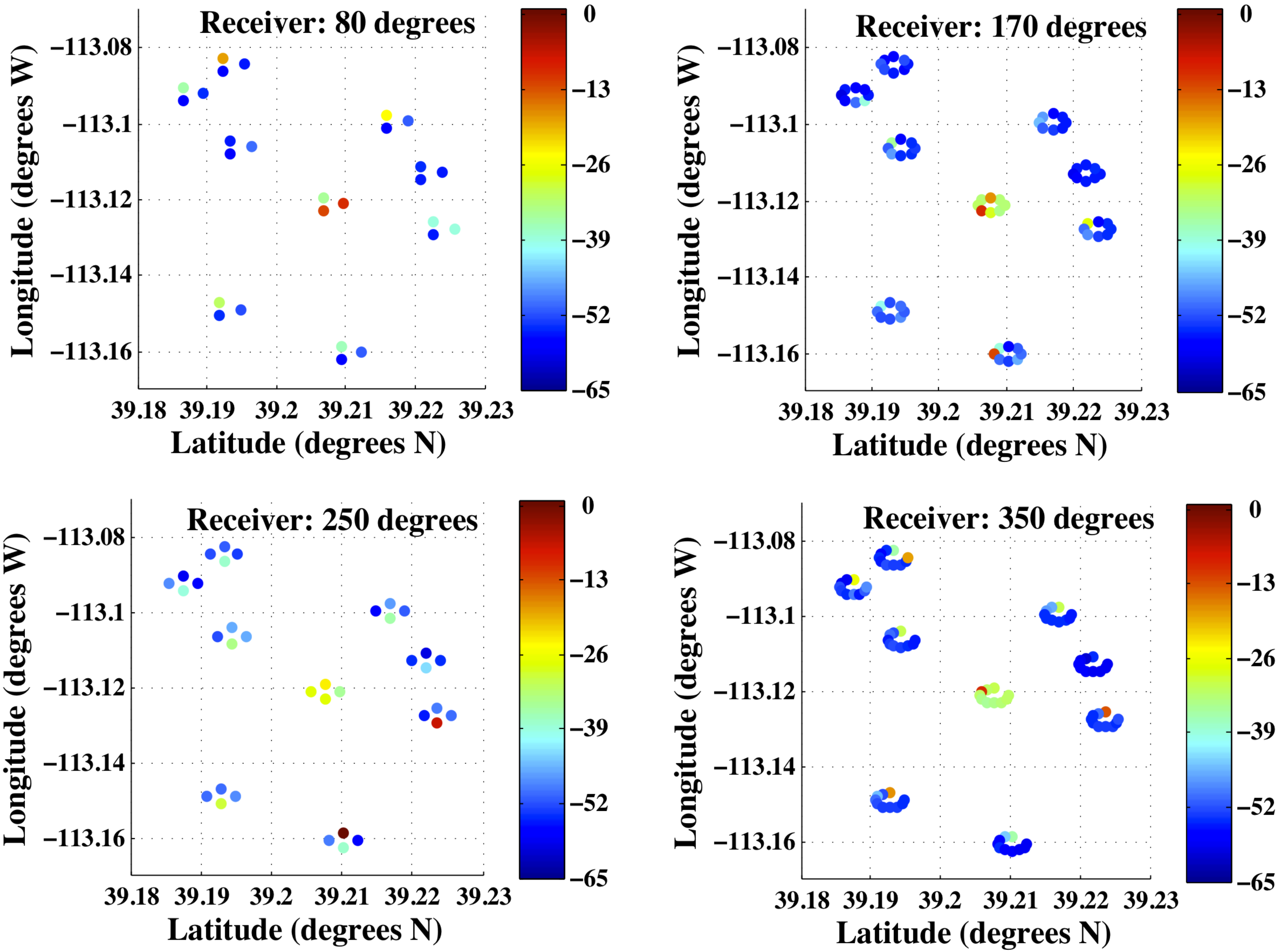


Fluorescence detector site, Eastward heading, -30 dBm threshold on peak finding algorithm

Fluorescence detector site, Eastward heading, -50 dBm threshold on peak finding algorithm

Peak finding algorithm: findpeaks in matlab (compares adjacent frequency bins to search for local maxima)

Power in dBm

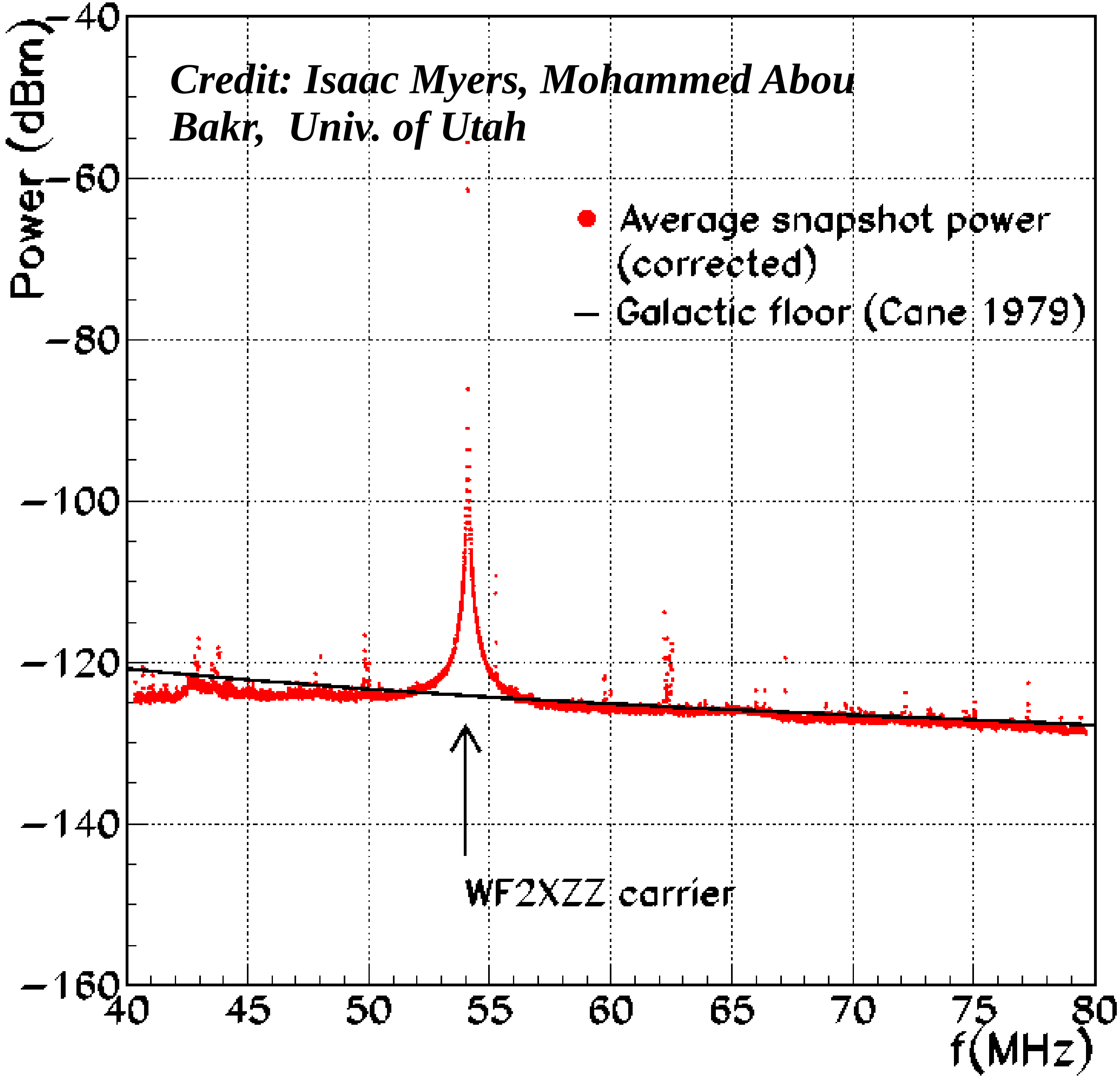


Receiver: 80 degrees
Receiver: 170 degrees
Receiver: 250 degrees
Receiver: 350 degrees
Longitude (degrees W)
Latitude (degrees N)
−113.08
−113.1
−113.12
−113.14
−113.16
39.18
39.19
39.2
39.21
39.22
39.23
0
−13
−26
−39
−52
−65

Conclusions drawn from the background study

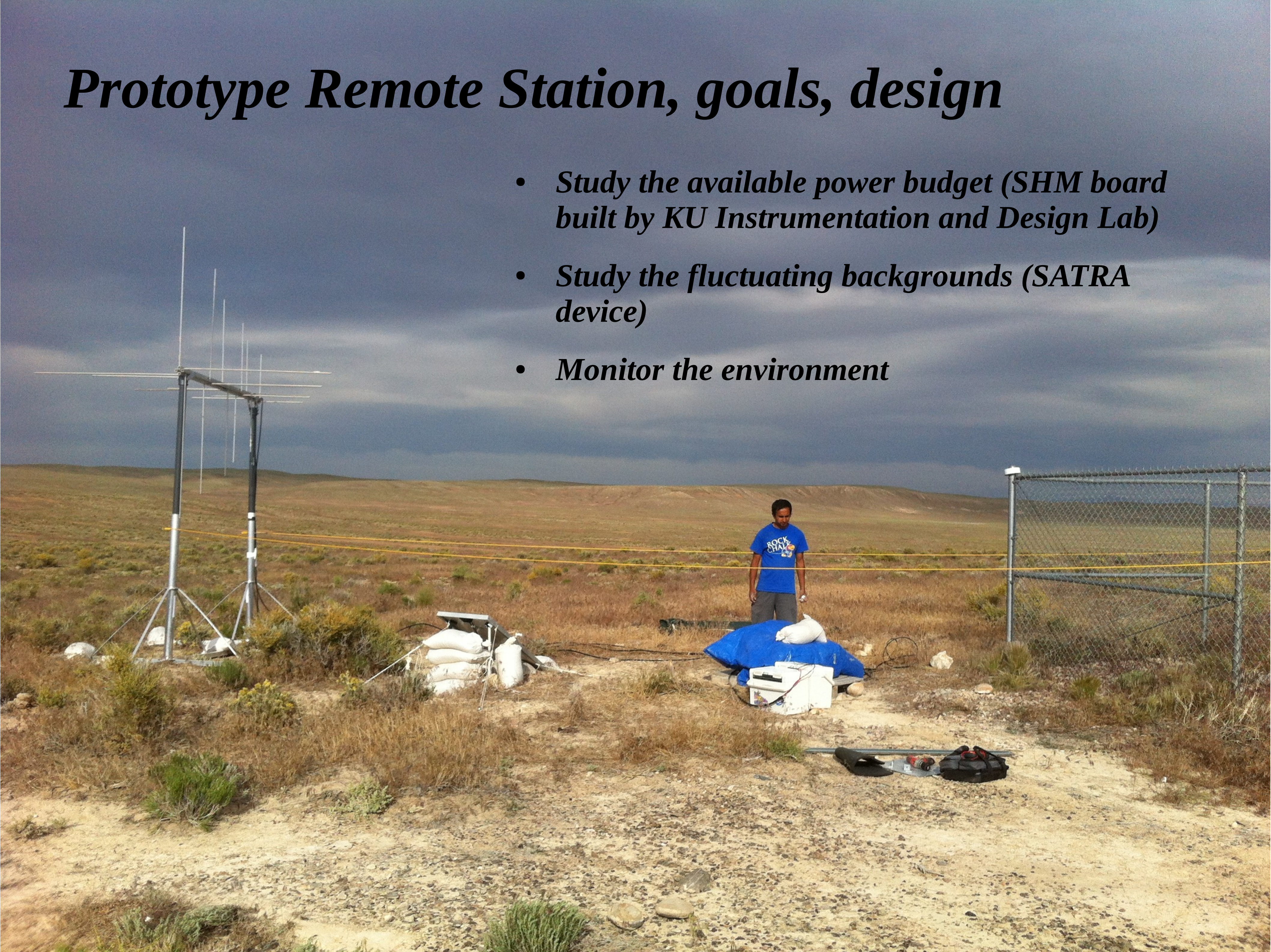
- ***Far more noise spikes are found when observing North or South (airline traffic, HAM radio)***
- ***East and West produce fewer spikes (good because transmitter is East of FD site)***
- ***The remote sites investigated are much quieter (~40 dB...green to blue) at the frequencies which are loud at the FD site***
- ***There are several sites that are "all blue," allowing for future coincidence studies with TARA at FD***

Galactic noise floor – observationally confirmed

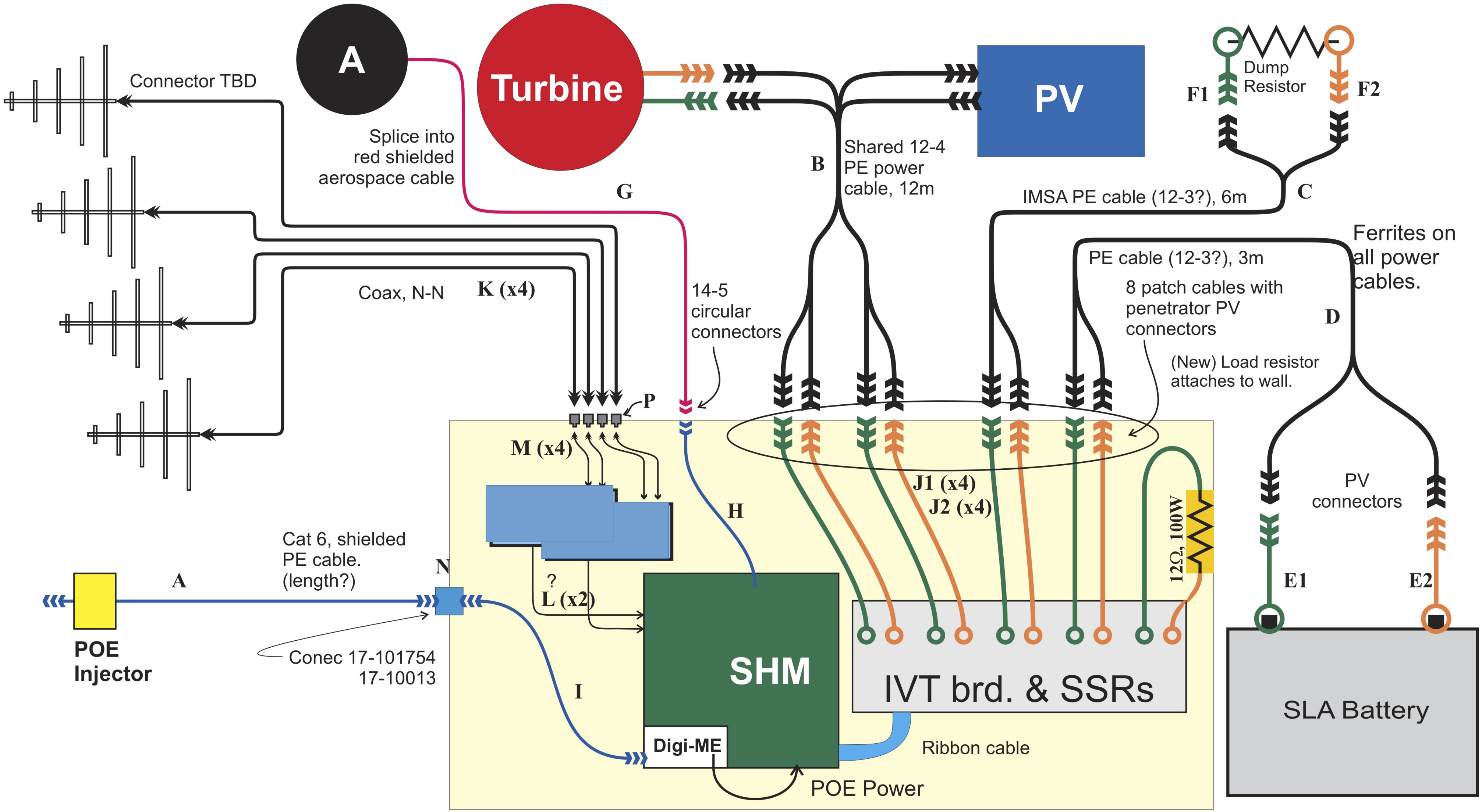


Prototype Remote Station, goals, design

- ***Study the available power budget (SHM board built by KU Instrumentation and Design Lab)***
- ***Study the fluctuating backgrounds (SATRA device)***
- ***Monitor the environment***

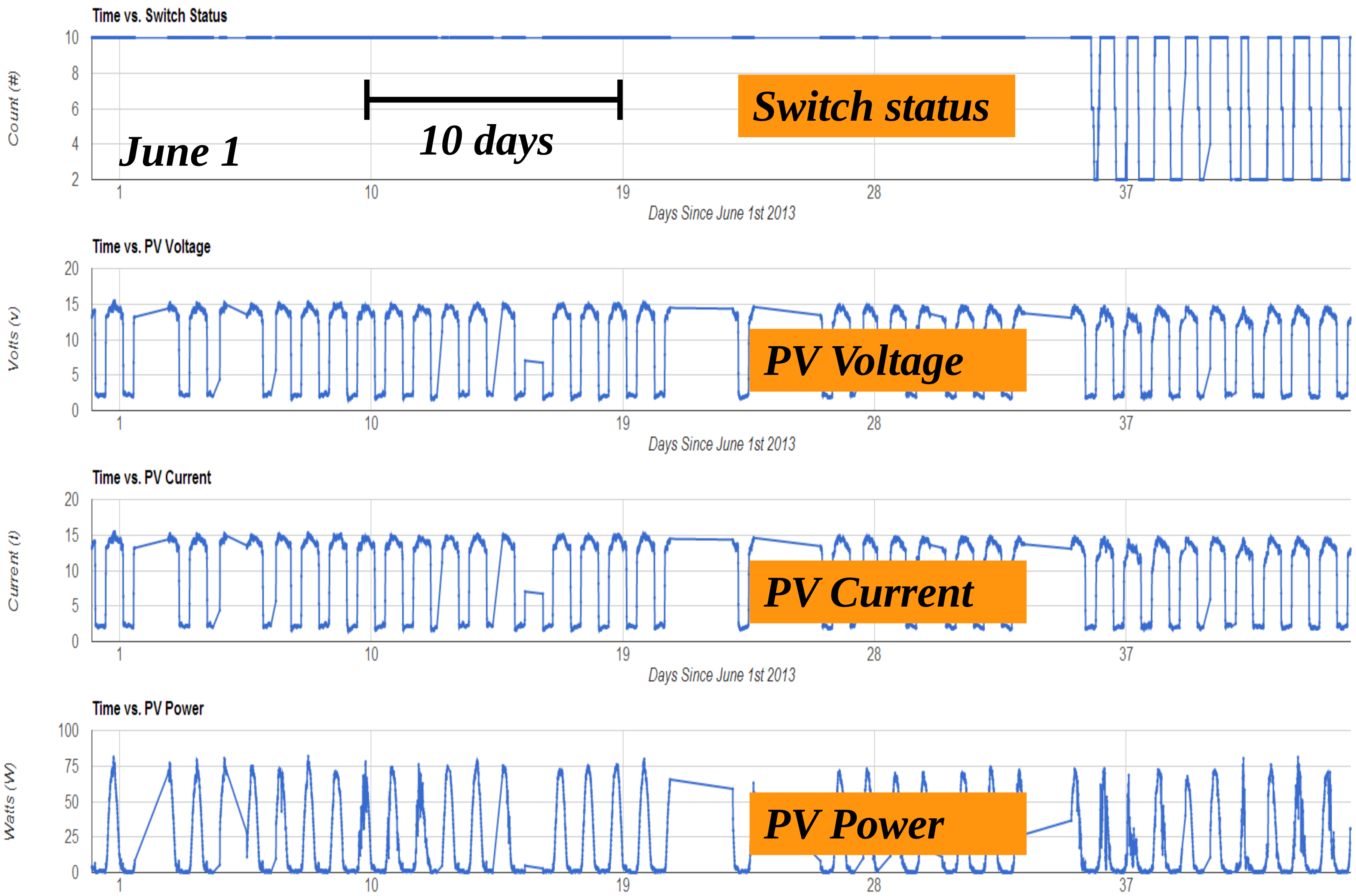


Prototype Remote Station, design

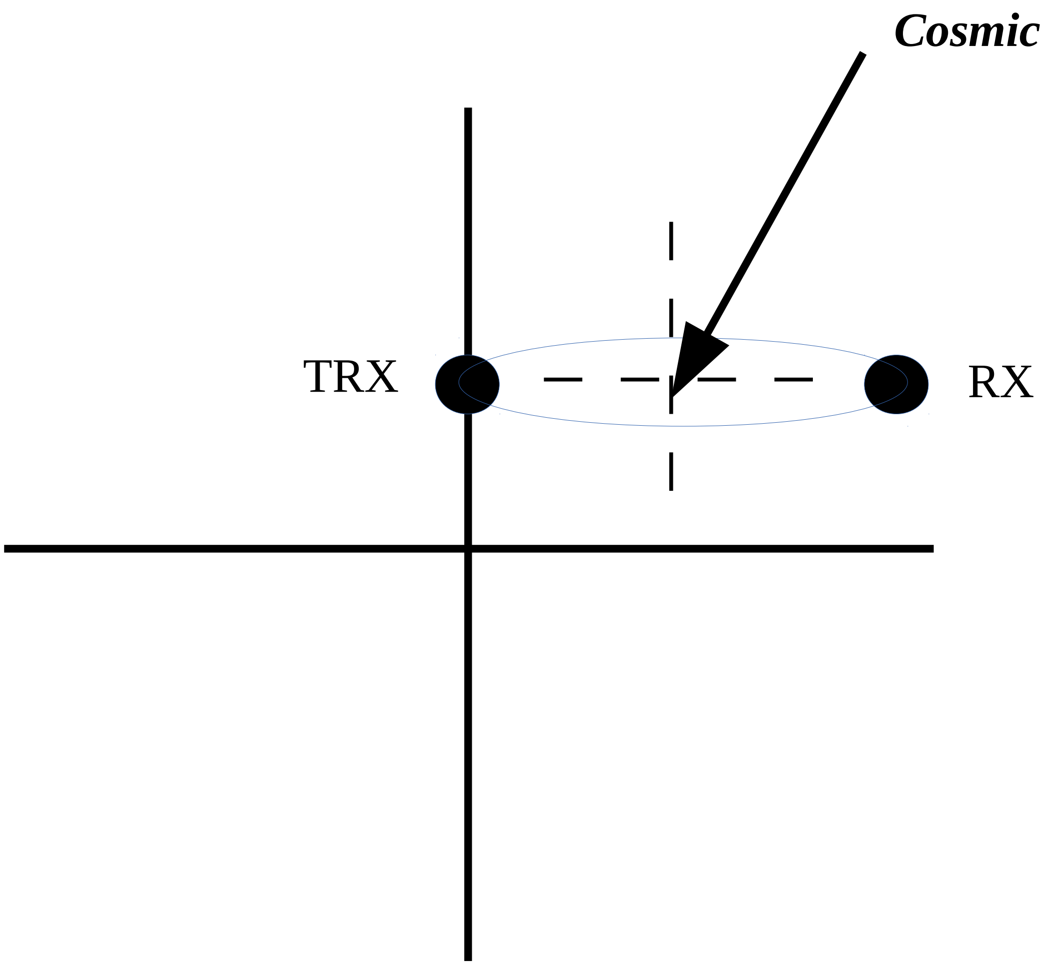


TARA Power Station Connection Diagram
KLR
Last update: 5/14/2013

Prototype Remote Station, data, I



Monte Carlo Analysis



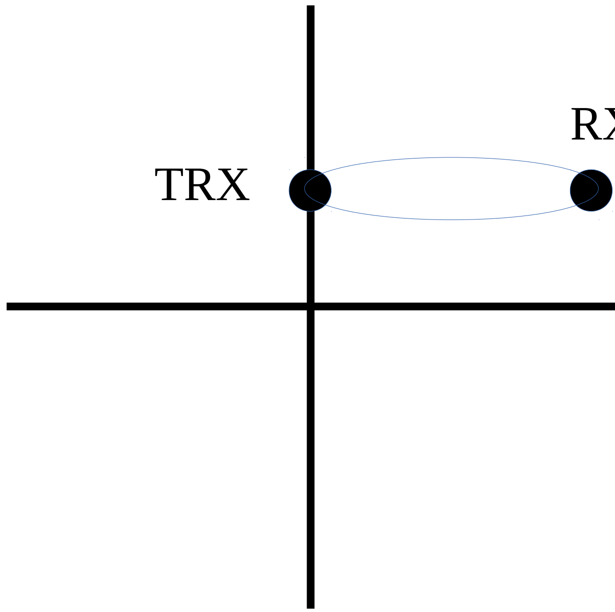
***Azimuthal angle* is measured from positive x-axis**

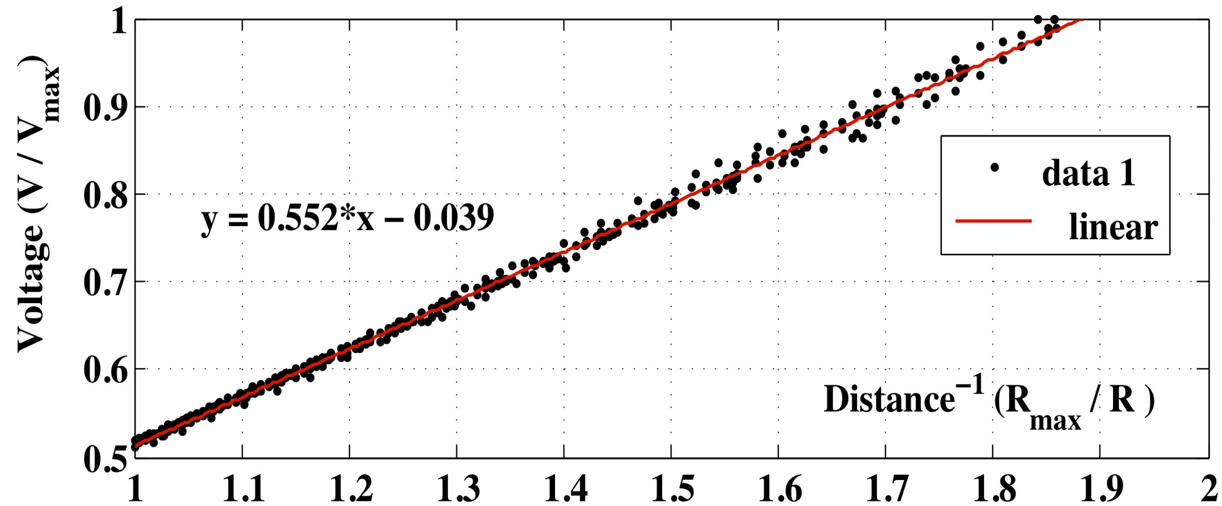
***Zenith angle* is measured from 0 to pi**

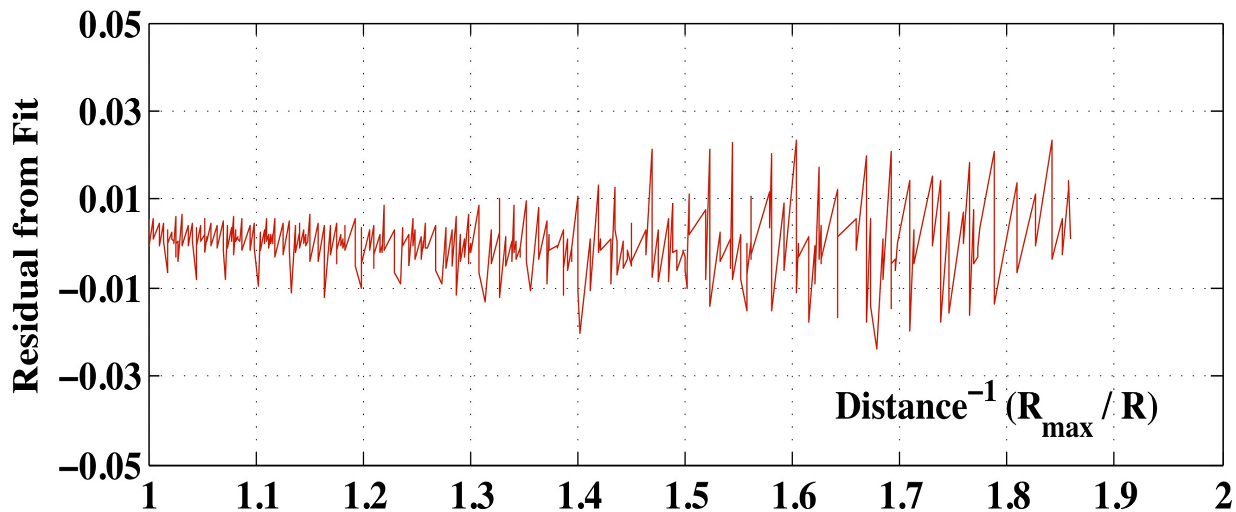
***Core hit locations* are measured in global (x,y) coordinate system**

Tests: move receiver to test signal dependency for remote stations, effect of dipole modulation (over-dense calculation), receiver and transmitter beam-widths, process for determining theta and phi, energy

Early Reconstruction Efforts, I (All Monte Carlo)





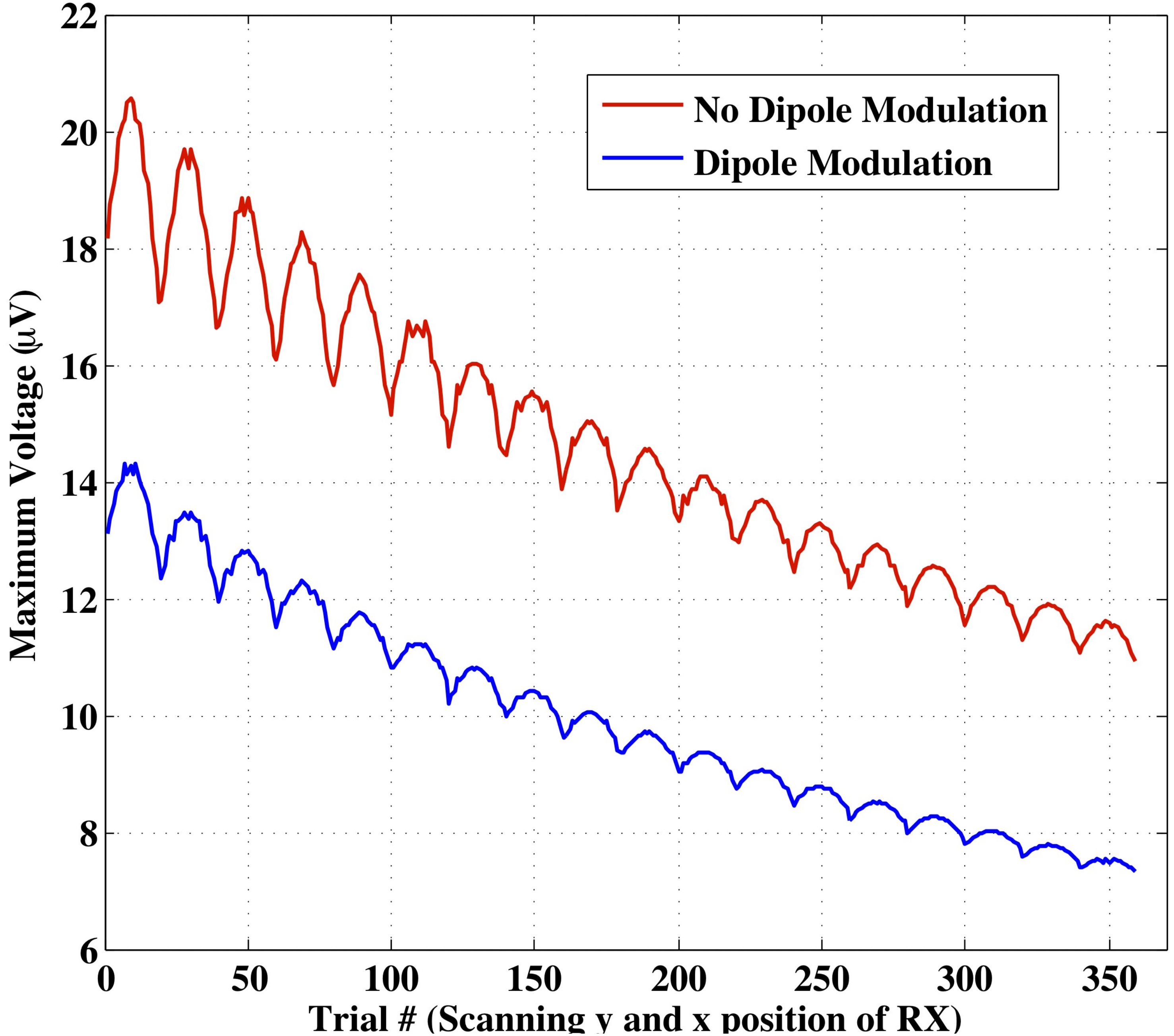


Chirp Simulation:

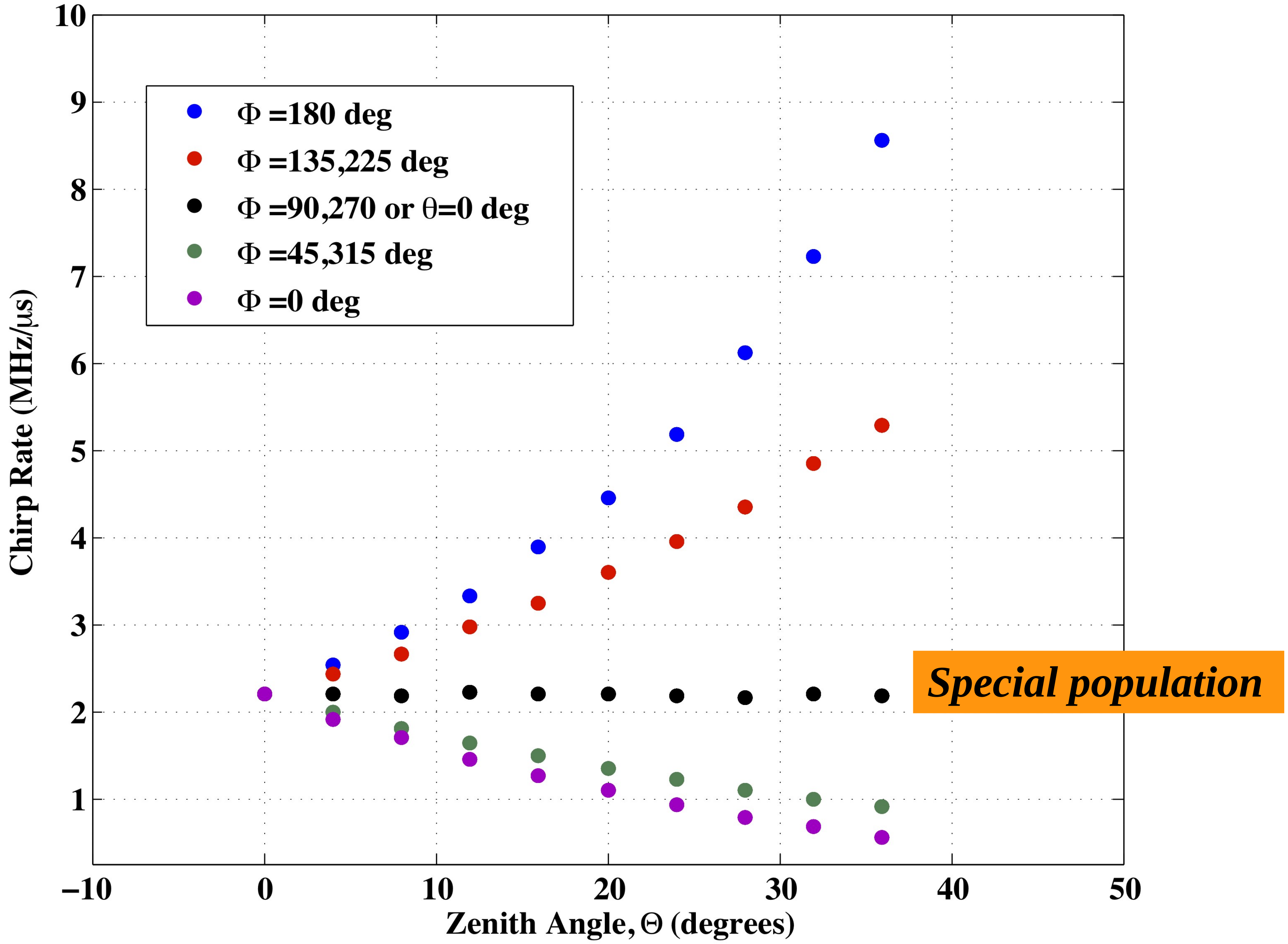
TRX: gain/beam-width/ polarization of the physical transmitter (phased Yagi array) at (0,25k)

RX: gain/beam-width polarization of the receivers (dual-pol LPDA) at (39.5k,25k)

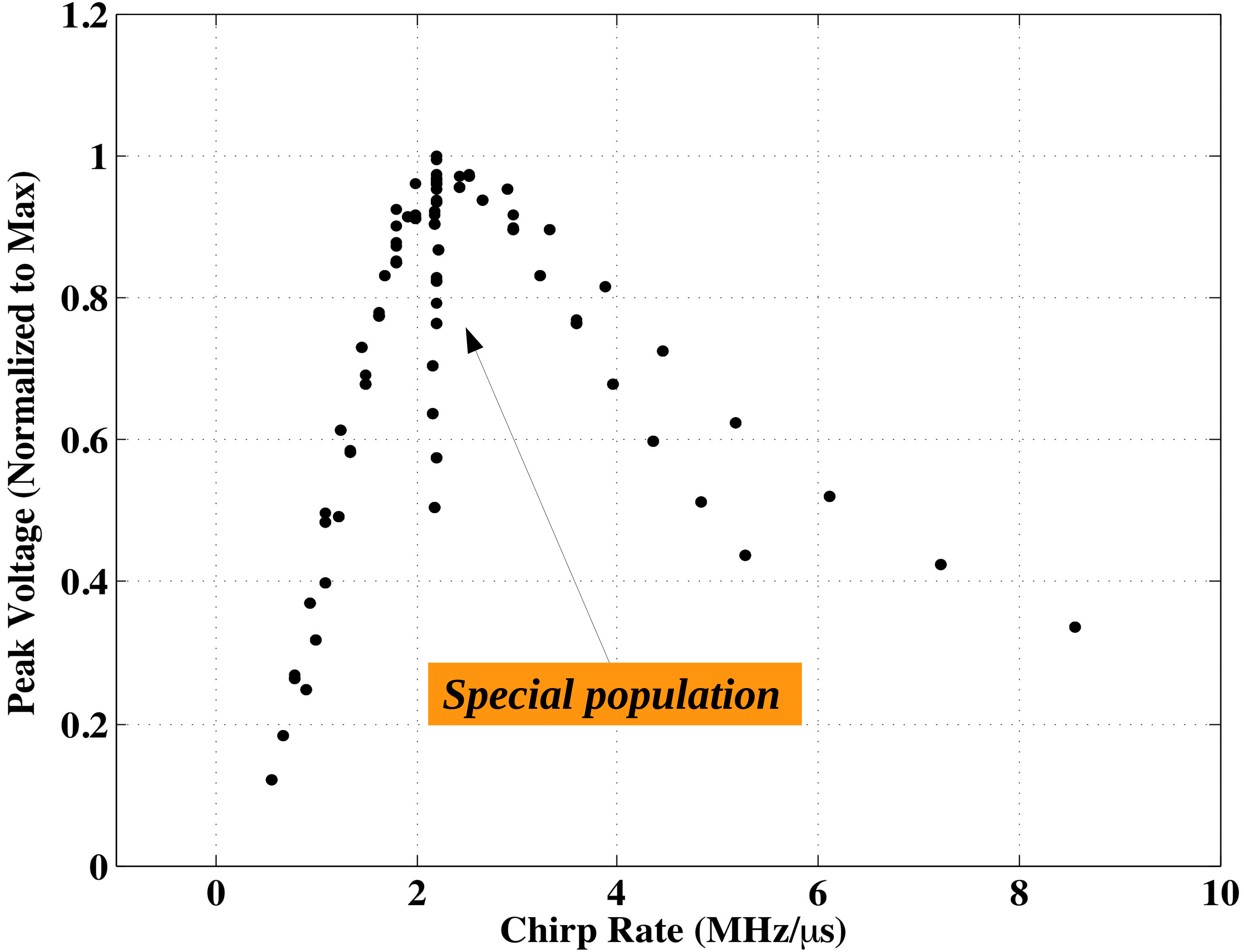
Early Reconstruction Efforts, II



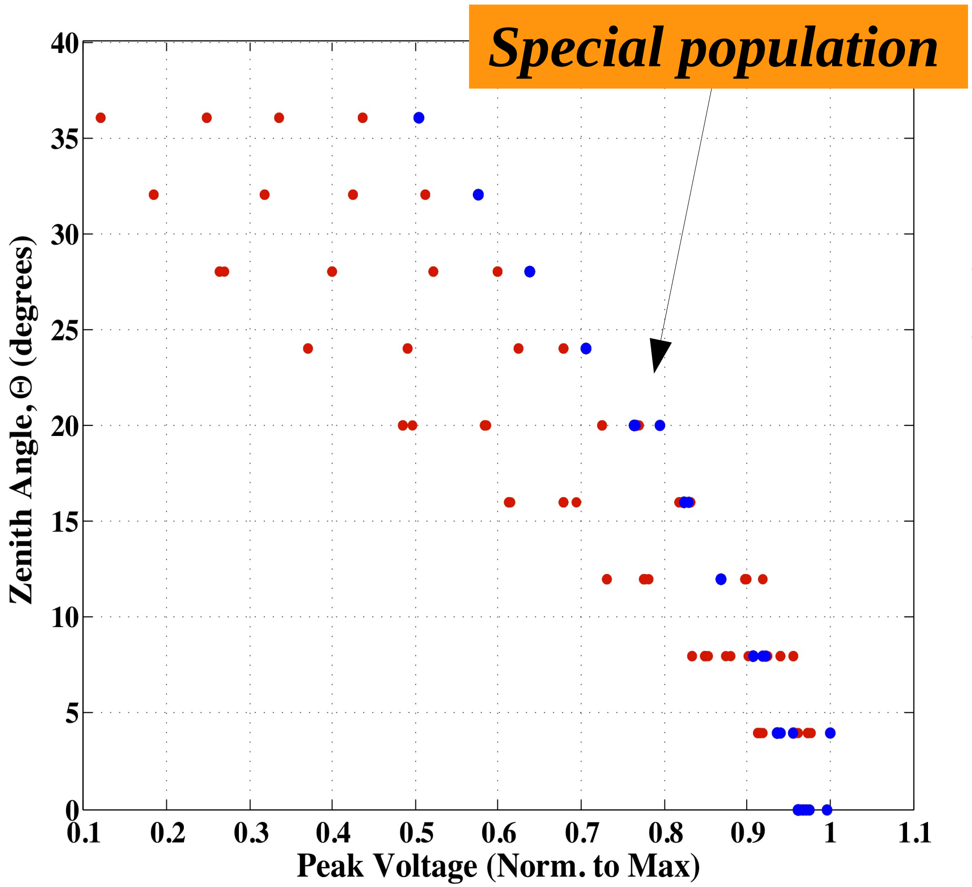
Early Reconstruction Efforts, IV

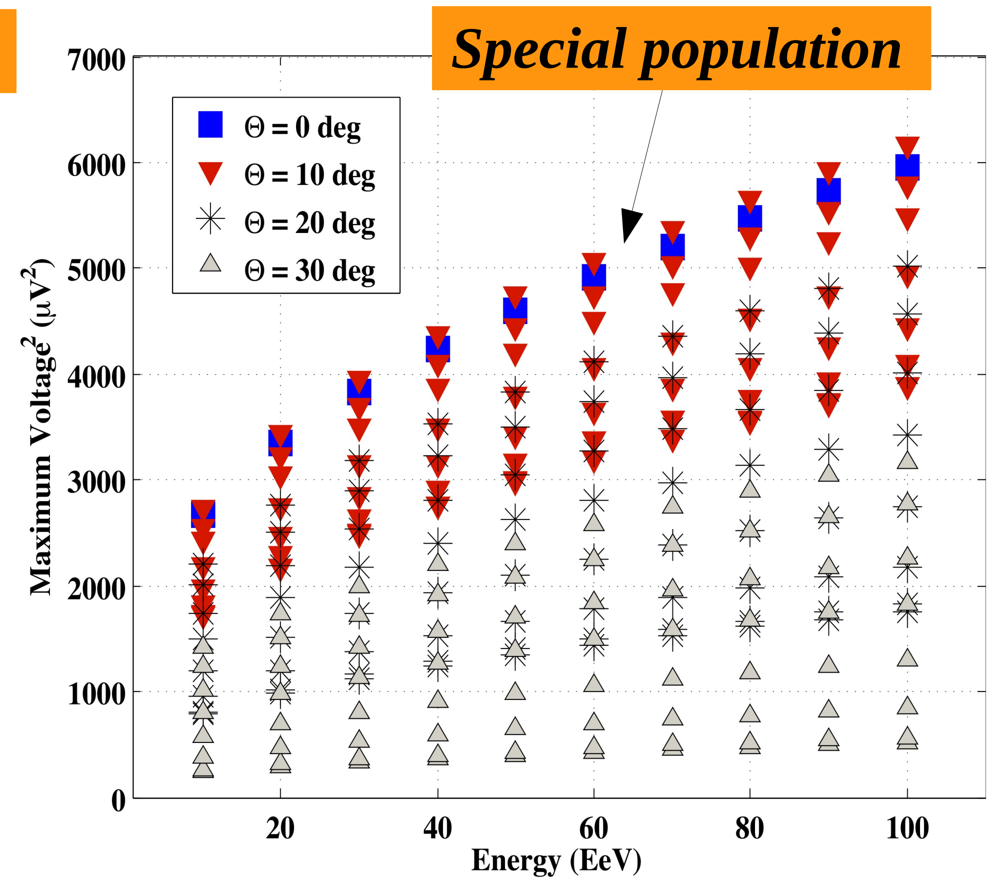


Early Reconstruction Efforts, III



Early Reconstruction Efforts, IV





Attempting to obtain the zenith angle independently, and beginning to understand how to derive the energy.

Blue events are the special geometric population

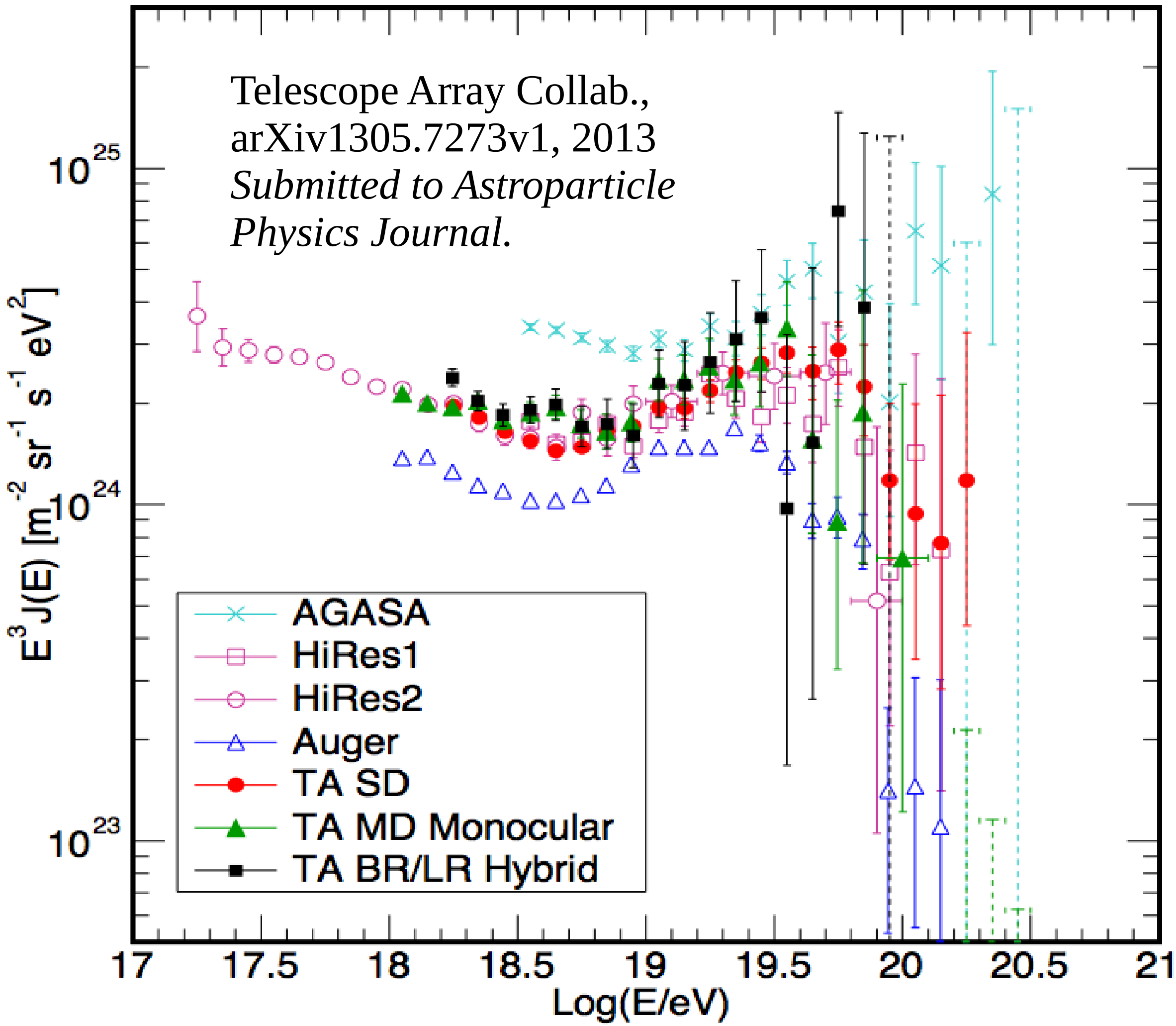
Conclusion

- ***TARA is a new way to detect cosmic rays***
- ***Remote stations are being designed, built for quiet environments discovered***
- ***There are several handles on event geometry leading to information on the primary cosmic ray***
- ***Future work: multi-remote station studies to derive geometry from signal timing***

References

- ***Gorham, P. "On the possibility of radar echo detection of ultra-high energy cosmic ray-and neutrino-induced extensive air showers." Astroparticle Physics 15, 2001***
- ***Isaac Myers, Mohammed Abou Bakr, private communication***
- ***Steven Prochyra, Samridha Kunwar, private communication***
- ***Ackermann et. al. "Detection of the Characteristic Pion Decay Signature in Supernova Remnants." Science, 339 (2013)***

Cosmic Ray Spectrum, and GZK effect



$$p^+_{CR} + \gamma \rightarrow \Delta^+ \rightarrow p^+ + \pi^0 \rightarrow p^+ + 2\gamma$$

$$p^+_{CR} + \gamma \rightarrow p^+ + e^- e^+ \quad \langle T_{\mathrm{CMB}} \rangle = 2.7\ K$$

Nucleon-photon threshold effect which produces secondary particles, including neutrinos

Fermi data: example of protonic supernova remnant-origin (≤10 TeV) (Ackermann et al., 2013)

How heavy are they (are they mostly protons, or heavier)?

Electron-positron production before cutoff

Concentration before cutoff suggests that maximum energy is higher than GZK energy

Prototype Remote Station, data, II (Kerry Thomas via QuarkNet)