Radio-Based Detection of Ultra-High Energy Cosmic Rays with the Telescope Array Radar (TARA) Observatory Remote Stations

Photon 2015
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Primary interaction in upper atmosphere results in cascade of charged particles

Cascade may be detected at surface (Auger, TA) or through florescence (Fly's Eye, TA)

Why another method?

FLUX of $\sim 10^{19}$ eV events approximately $1/\text{km}^2/\text{century}$!

Not enough time-need more area-need a cost-effective solution.

TARA

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

Dense enough shower core will re-radiate RF at sounding frequency if resonant with frequency of plasma in dense shower core:

$$\omega^2_p = \frac{n_e e^2}{\varepsilon_0 m_e}$$

Function of number of electrons-at critical density, shower will be resonant to our frequency, 54.1 MHz.
Bi-Static Radar

- Separation of Transmitter (tx) and Receiver (rx) along some baseline

- At critical ionization density, rx will receive signal from tx sounded off core of EAS

Doppler shift is minimized

\[ f = \frac{1}{\lambda} \frac{d}{dt} [R_T + R_R] \]
Transmitter
Detection Scheme

Continuous wave (cw) VHF is transmitted at 54.1 Mhz

UHECR event initiates EAS in atmosphere with critical ionization density

Shower intersects area with mutual coverage by tx and rx

Shower core re-radiates the transmitted signal to rx in characteristic way...
Chirps

Our bi-static approach minimizes Doppler shift, allowing for detection at VHF.

As subtended angle tx-->shower core-->rx increases, Doppler shift decreases.

Result is an approximately linear downgoing chirp

This chirp is differentiated from the CW carrier and background through system hardware/firmware

Field-captured calibration chirp.

Courtesy S. Kunwar
Meteors-a Lab for cosmic rays

Only other thing to regularly bombard earth’s atmosphere, and establish an ionized trail.

Similar energy!
TARA Remote Stations
TARA Remote Stations

Fully autonomous UHECR detectors

- Comms, GPS
- PV panels
- Station 1
- Station 2
- Cow filter
- Antenna
Station structure

- Broadband antenna
  - Filtration, amplification
    - Triggering Scheme, Data capture
  - Chirp Calibration Unit (CCU)
Antenna

Log Periodic Dipole Antenna gives broadband response to broadband chirps with roughly flat response.
Station structure

- Broadband antenna
- Filtration, amplification
- Chirp Calibration Unit (CCU)
- Triggering Scheme, Data capture
Removal of carrier = no amp saturation.

Crystal notch filter.
Amplify-Galaxy check

RMS voltage of forced trigger data fit to the bore-sight track of the galactic center-excellent agreement=galactic floor visible

Courtesy s.kunwar
Station structure

- Broadband antenna
- Filtration, amplification
- Triggering Scheme, Data capture
- Chirp Calibration Unit (CCU)
De-Chirp

We take the input signal and mix it with a delayed copy of itself, using the Heterodyne method:

\[ \sin(\theta)\sin(\phi) = \frac{1}{2}\cos(\theta - \phi) + \frac{1}{2}\cos(\theta + \phi) \]

Neglect-out of band

For a linear chirp,

\[ \theta = \omega t - \frac{k}{2}t^2 \]
\[ \phi = \omega(t + \tau) - \frac{k}{2}(t + \tau)^2 \]

Where \( k \) is the chirp rate, and \( \tau \) is the amount of delay. Solving gives a monotone at frequency

\[ f_m = k\tau \]

As illustrated on the next slide.
De-chirp

Chirp (blue) mixed with a delayed copy of itself (green) and the resultant monotone (red).
De-Chirp

Signal embedded in noise

Post-heterodyne monotone

Power detection in bands of choice (chirp rate selectivity)
Triggers record of high-speed (250Ms/s) data.
Detect

Trigger logic ensures that no two adjacent bands may trigger simultaneously—rejection of time transients like lightning.
Brains

Nexsys 3 Spartan-6 FPGA.

- 200 MS/s ADC for data channels into FPGA with in-house custom firmware
- Trigger logic
  - 4 channels with different bandpass filters
  - Logic rejects broadband time transients

Raspberry Pi

- Data is transferred to Single Board Computer (SBC)
- Ethernet link allows for total control of threshold parameters and station control
- Low power consumption
Station structure

- Broadband antenna
- Filtration, amplification
- Triggering Scheme, Data capture

Chirp Calibration Unit (CCU)
Chirp Calibration Unit (CCU)

“fat” dipole

PV, brains
CCU

Field Captured Calibration Signal

Fires once a second for ten seconds
Every hour, to keep an eye on
Backgrounds and trigger performance
Upgrades-June 2015

- Improved station timing accuracy
- Firmware update-more control
Timing

Timing:
- 2 stations with 65 meter baseline

- GPS unit provides 100 pps output with ~10 ns resolution
- each FPGA runs local 200 MHz clock - drives counter with ~5 ns resolution
- counter is reset every 10ms

- triggered event reads counter value for precision timing = angular resolution.
Firmware

Spartan-6 firmware has several parameters:

- Trigger board
  - 4 channels each varying in width-offsets provide more stable triggering capabilities

- Threshold
  - total trigger threshold may be set based on current ambient noise level (in the works)

- Time-Over-Threshold
  - TOT width and thresh allows for greater reject of short time transients
Current Status

- Currently taking data-hope for an uninterrupted capture from now until September

- Station Upgrade happening right now! Implementation of new firmware revision.