

Bistatic Radar Detection of UHECR with TARA

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Abstract: The Telescope Array Radar (TARA) project will utilize a bistatic radar technique to detect radar echoes from the ionization trails of ultra-high energy cosmic rays as they pass through the Earth's atmosphere. This method of observing cosmic rays is unproven, and TARA is the largest and most ambitious attempt yet at detecting UHECR via their radar signature. TARA is co-located with the Telescope Array, the largest cosmic ray observatory in the Northern Hemisphere, which will provide confirmation of the radar detection of UHECRs via time coincidence. Since mid-2011, TARA has been field testing a low power version of the experiment to gain expertise and study techniques to better utilize the radar method on a much larger scale. In 2013 TARA will begin operations in high power mode using a 40 kW transmitter and a phased array of eight high-gain Yagi antennas with a gain of 23 dBi, broadcasting at 54.1 MHz with 100% duty cycle over the TA surface detector array. The effective radiated power will be over 8 MW, continuous. We will also be deploying an enhanced receiver system, making use of a 250 MHz receiver and on-board FPGA to allow smart triggering on signals with a signal-to-noise ratio of -10 to -20 dB. TARA will be the first experiment to attempt to utilize this detection technique at such high power in conjunction with a large cosmic ray detector. If this technique is proven successful, it will allow very large cosmic ray observatories, which are required to fully probe the ultra high energy regime, to be built much more cheaply and on larger scales than the current generation of fluorescence detectors and surface arrays. We will discuss the TARA observatory and present results obtained from our most recent analyses.

Keywords: cosmic rays, extensive air showers, radar

1 Motivation

Modern cosmic ray observatories primarily employ two techniques: arrays of particle detectors deployed on the ground and fluorescence telescopes.

With ground arrays, air shower particles are observed directly. Presently, ground arrays typically cover areas comparable to a large city. For example, the Telescope Array surface detector covers roughly the same area as New York City. The costs of the equipment required to instrument such a large area are enormous, and the available land can only be found in fairly remote areas.

A partial solution to the difficulties and expense involved in ground arrays is found in the fluorescence technique. Here, the atmosphere itself is part of the detection system, and air shower properties may be determined at distances as remote as 40 km. Unfortunately fluorescence observatories are typically limited to a ten percent duty cycle by the sun, moon and weather. Other cosmic-ray detection techniques currently under study make use of geomagnetic synchrotron radiation (LOFAR [1]), the

Askaryan effect in solids (ANITA [2]), and molecular bremsstrahlung [3].

Here we describe studies of air shower detection using the *bistatic radar* technique by the *Telescope Array Radar* (TARA) project in western Utah, U.S.A. Bistatic radar shows promise as a remote sensing technique with a 24 hour duty cycle, an advance which — if successful — will allow the next generation of cosmic ray observatories to be built at a fraction of the cost required by current technologies.

2 The Bistatic Radar Technique

Radar detection of air showers is feasible because of the large ionization densities, approaching 10^{13} particles per cubic meter, at the core of a few-EeV air shower. The corresponding plasma frequency [4] is of order 50 MHz. This is in the low-VHF range. Thus, cosmic-ray induced air showers will reflect television transmissions.

Radar observation of cosmic rays is actually a 70 year-old idea. In the 1940's, Blackett and Lovell [5] proposed

cosmic rays as an explanation of anomalies observed in atmospheric radar data. A facility was built at Jodrell Bank, but no results were ever reported. Gorham [6] reignited interest in radar in a 2001 paper, and updated several critical calculations.

Recent experimental efforts utilizing atmospheric radar systems were conducted at Jicamarca [7] and at the MU-Radar [8]. Both observed a few signals of short duration indicating a relativistic target. However in neither case were the measurements made synchronously with a conventional cosmic ray detector.

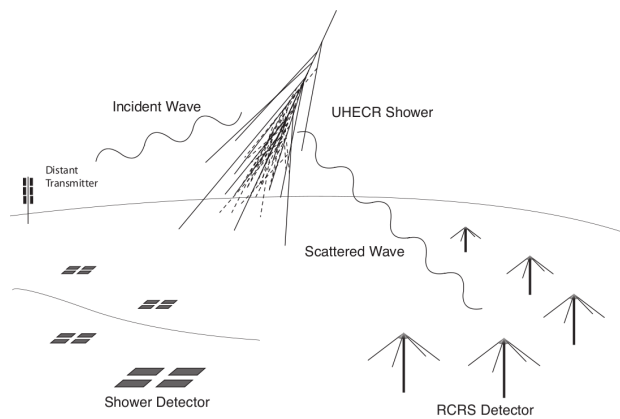


Fig. 1: The bistatic radar technique, as pioneered by the MARIACHI experiment. Conventional surface detectors are used to tag the presence of air showers while radar receiver stations detect the forward scattered echo.

A new approach, first considered by the MARIACHI [9] project, is to utilize *bistatic* or two-station radar in conjunction with a conventional set of cosmic ray detectors. This idea is illustrated in Figure 1. Such an arrangement will minimize the large doppler shift in frequency of the reflected signal. Also, depending on the size of the radar cross section relative to the sounding radiation, scattering in the forward direction might be enhanced relative to backscatter [10], thus providing an advantage in detecting the faintest echoes in comparison to monostatic or ranging radar.

MARIACHI is a high school cosmic ray outreach project based in Long Island, New York. MARIACHI makes use of “parasitic” bistatic radar, in which emanations from ambient commercial television stations are used as a source of radio frequency electromagnetic waves. Over the course of several weeks’ observation, coincidences in time were observed between radio antenna activity and ground array detectors located at several high schools [11].

The next logical step in the development of the bistatic radar technique is to observe air shower echoes using a single transmitter under experimental control in coincidence with a state-of-the-art “conventional” cosmic ray detector in a low-noise environment. This is the goal of the TARA project.

3 Expectation for Bistatic Radar Signal

The magnitude of the power received in a bistatic radar arrangement is given by the *bistatic radar equation*:

$$P_R = P_T \cdot \left(\frac{G_T}{4\pi R_T^2} \right) \cdot \sigma \cdot \left(\frac{G_R}{4\pi R_R^2} \right) \cdot \left(\frac{\lambda^2}{4\pi} \right) \quad (1)$$

where P_R (P_T), G_R (G_T), R_R (R_T) are the receiver (transmitter) power, antenna gain, and distance to target respectively. The factor $\lambda^2/4\pi$ (where λ is wavelength of the sounding radiation) relates the receiving antenna’s gain to effective area.

The radar cross section σ is the least well understood contribution to the received power, and in some sense determining σ is the most immediate objective of TARA. For the purposes of understanding σ , it is useful to divide the shower into two regions:

(1) The “underdense” region, which comprises most of the ionization induced by the shower (for VHF sounding frequencies), for which the plasma frequency

$$v_e = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{m_e \epsilon_0}} \quad (2)$$

(where n_e is the ionization electron density, e is the electron charge, m_e the mass of the electron and ϵ_0 is the permittivity of free space) is less than the frequency of the sounding radiation. In the underdense region, the scattering cross section is just the classical Thomson cross section multiplied by the number of ionization electrons present. However the energy reradiated by electrons in the underdense region will be attenuated by the effects of collisional damping caused by collisions with neutral nitrogen molecules. This effect may reduce the effective underdense cross section by several orders of magnitude.

(2) The “overdense” region, for which the plasma frequency is greater than the frequency of the sounding radiation. Here, the shower acts like a macroscopic conductor. However there are uncertainties in air shower models as to the size of this region. In particular, if it is too small skin depth effects may limit the contributions to σ from this region of the air shower.

As noticed by Underwood [12] and Bakunov *et al.* [13], one feature of the radar echo that should be nearly independent of the free electron lifetime and the exact nature of the scattering cross section is the Doppler-like frequency shift that results from the relativistic movement of the shower front (Figure 2). The shape of this curve is mostly due to air shower geometry. Because the free electron lifetime is short (10-100 ns), the duration will be dominated by the lifetime of the air shower and the fraction of the time that the air shower cross section is above the detectable threshold. This feature simultaneously places a high bandwidth/sampling rate demand on the receiver data acquisition, and creates a unique signature for air shower echoes. This signature will be exploited fully in TARA data acquisition schemes.

4 Bistatic Radar Studies with TARA

Radio-quiet western Utah is an ideal location in which to pursue this next step. Not only is the dearth of radio

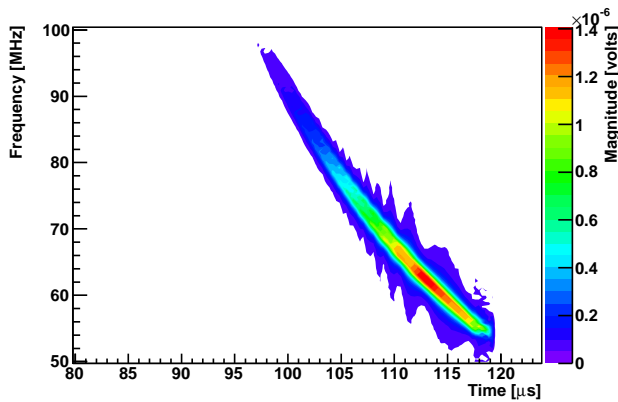


Fig. 2: Spectrogram of “chirp” for simulated air shower, initiated by 10^{19} eV cosmic ray midway between 54.1 MHz transmitter (TX) and receiver (RX), located 50 km apart. The shower is inclined at a zenith angle of 30° in a plane perpendicular to a line connecting transmitter and receiver.

noise exceptional among potential sites in the U.S., but it is within reasonable driving distance of the Salt Lake City area and University of Utah. Further, it is the site of the Telescope Array cosmic ray observatory, the largest UHECR research facility in the Northern Hemisphere.

The TARA project has developed in two stages, which we will refer to as TARA1.5 and TARA40. From April 2011 to July 2012 the first stage utilized a 1.5 kW transmitter, donated by a local television station, to broadcast a 54.1 MHz continuous wave signal over the Telescope Array surface detector (SD) by means of a fairly low-gain (8.5 dBi) Yagi antenna. Signals were received on the far side of the SD by an array of dual polarization log-periodic VHF antennas (Figure 3) located at the Telescope Array Long Ridge fluorescence detector (FD) site.



Fig. 3: Radar receiver antenna at Long Ridge fluorescence detector site.

For TARA1.5, data was recorded using the Ettus Research USRP-II software-defined radio receiver, in t-

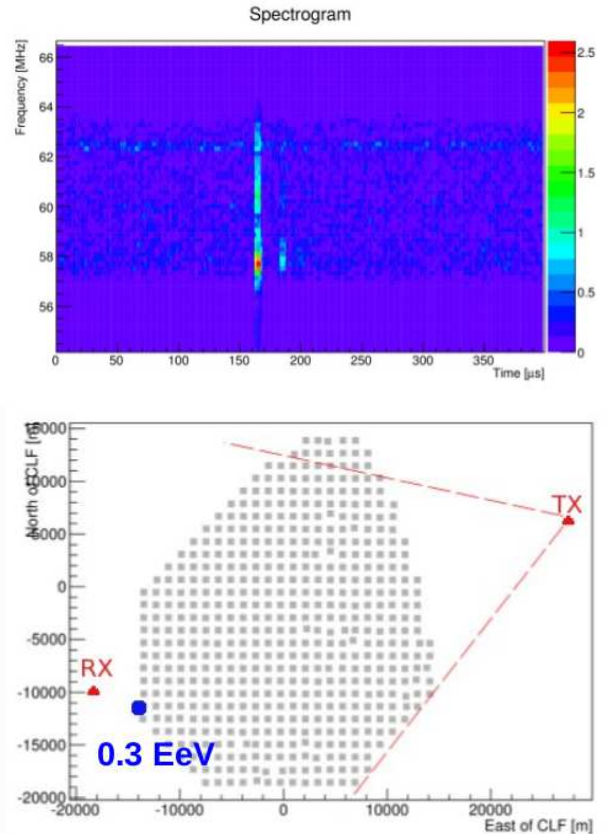


Fig. 4: Interesting waveform obtained in TARA1.5 FD-trigger stream. *Top:* Spectrogram. The sampling rate of the TARA1.5 receiver, 12.5 MS/s, was too slow to allow resolution of frequency changing with time. *Bottom:* Core location and energy of cosmic ray air shower which triggered the fluorescence detector.

wo modes: (1) triggered by the FD and read out at 12.5 Megasamples per second (after demodulation to a center frequency of 60 MHz), and (2) self-triggered by a 5σ threshold comparison and read out at 6.25 Megasamples per second. Although no conclusive evidence for cosmic ray radar echoes was found, several interesting waveforms were observed in temporal coincidence with air showers within the FD trigger stream (Figure 4).

The second stage of TARA, which we refer to as TARA40, will be completed during the summer of 2013. It will feature several enhancements over the TARA1.5 configuration:

- The transmitted RF power will be increased by a factor of 27, to 40 kW. This will be achieved by combining the output of a 20 kW transmitter donated to TARA by Salt Lake KUTV2 as well as an identical system purchased from another source.
- The antenna gain will be increased by a factor of 5 by using a phased array of 8 Yagi antennas (Figure 5), bringing the effective radiated power (ERP) of the system to over 8 MW, continuous. This new array will be capable of broadcasting in both horizontal and vertical polarizations.

- The transmitter-receiver baseline will be shortened, increasing the received power for a radar target centered over the ground array by a factor of 2.5.
- The receiver data acquisition system will be replaced with one based on the N.I. FlexRIO, featuring a 250 MS/s digitizer and fully programmable FPGA. This will allow real time smart-triggering on chirp-like waveforms, including signals below the noise floor and thereby decreasing the self-trigger threshold by up to two orders of magnitude in power.



Fig. 5: Phased array of 8 Yagi antennas, increasing transmitter gain to a factor of 21 dB over isotropic.

5 The Future of Radar Detection

TARA is only the first step in developing radar into a tool for doing particle astrophysics. Once a convincing echo signal has been seen, the two major questions which will need to be addressed are (1) Can the astrophysically interesting parameters of air showers be extracted from the radar echoes exclusively? (2) Can this be done at a cost which is significantly less than that of conventional air shower detection technologies?

Astrophysically interesting quantities of air showers include pointing direction (geometry), primary energy, and depth of shower maximum X_{max} . The first step in reconstructing these would be to determine the shower geometry, *e.g.* from stereo observation of the “chirp” (Figure 2). Currently, we are developing remote receiver stations, not tethered to the Long Ridge fluorescence site, to allow for stereo observation. To study energy and X_{max} , the next step would be to look at the received power versus slant depth, which will be proportional to the number of shower particles and dependent on the radar cross section.

At this point, there remain large uncertainties in the potential cost-effectiveness of this technique, until the detection thresholds and signal-to-noise ratios of the cosmic ray echoes are known. Ultimately it will come down to a question of the effective radiated power required to obtain a useful signal.

In conclusion, bistatic radar is a candidate remote-detection technique for the observation of the highest energy cosmic rays. TARA is the most ambitious effort yet

to test this method. We will present the latest data collected in the TARA40 configuration at the 33rd ICRC, both in this talk and in greater detail in the poster presentation of I. Myers [14].

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