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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]

[a] University of Utah, 115 S 1400 E #201 JFB, Salt Lake City, UT 84112, USA
[b] University of Kansas, Lawrence, KS 66045, USA
[c] Purdue University, West Lafayette, IN 47907, USA
[d] Gillman & Associates, Salt Lake City, UT 84106, USA
[e] Utah State University, Logan, Utah 84322, USA
[f] Brookhaven National Laboratory, Upton, NY 11973, USA
[g] Moscow Engineering and Physics Institute, 31 Kashirskaya Shosse, Moscow 115409, Russia

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ABSTRACT

Construction was completed during summer 2013 on the Telescope Array RAdar (TARA) bi-static radar observatory for Ultra-High Energy Cosmic Rays (UHECR). TARA is co-located with the Telescope Array, the largest "conventional" cosmic ray detector in the Northern Hemisphere, in radio-quiet Western Utah. TARA employs an 8 MW Effective Radiated Power (ERP) VHF transmitter and smart receiver system based on a 250 MS/s data acquisition system in an effort to detect the scatter of sounding radiation by UHECR-induced atmospheric ionization. TARA seeks to demonstrate bi-static radar as a useful new remote sensing technique for UHECRs. In this report, we describe the design and performance of the TARA transmitter and receiver systems.

1. Introduction

Cosmic rays with energies per nucleon in excess of $\approx 10^{14}$ eV [1] create cascades of particles with electromagnetic and hadronic components in the atmosphere, known as Extensive Air Showers (EAS). Conventional cosmic ray experiments detect events through coincident shower front particles in an array of surface detectors [2,3] or through fluorescence photons that radiate from the shower core [4–6] which permit fluorescence telescopes to study shower longitudinal development. Another technique takes advantage of two naturally-emitted radio signals: the Askaryan effect [7] and the geomagnetic radiation from interactions with the Earth's magnetic field [8].

With ground arrays, air shower particles are observed directly. The land required to instrument ground arrays is large, cf. Telescope Array's 700 km^2 surface detector covers roughly the same land area as New York City. The costs of the equipment required to instrument such a large area are substantial 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 10% duty cycle by the sun, moon and weather.

The possibility of radar observation of cosmic rays dates to the 1940s, when Blackett and Lovell [9] proposed cosmic rays as an explanation of anomalies observed in atmospheric radar data. At that time, a radar facility was built at Jodrell Bank to detect cosmic rays, but no results were ever reported. Recent experimental efforts utilizing atmospheric radar systems were conducted at Jicamarca [10] and at the MU-Radar [11]. Both observed a few signals of short duration indicating a relativistic target. However in neither case where the measurements made synchronously with a conventional cosmic ray detector.

A new approach, first attempted by the MARIACHI [12,13] project, is to utilize *bi-static* or two-station radar in conjunction

* Corresponding author. Tel.: +1 801 5879986.
E-mail address: isaac@cosmic.utah.edu (I. Myers).

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with a conventional set of cosmic ray detectors. Air shower particles move very close to the speed of light, so the Doppler shift is large compared with airplanes or meteors. The bi-static configuration in which the sounding (interrogating) wave Poynting vector is generally perpendicular to shower velocity (as shown in Fig. 3) minimizes the large Doppler shift in frequency expected of the reflected signal (see [14,15], and Section 2 below.) This scenario is unlike that explored in [15] in which the two vectors are roughly anti-parallel. In the latter case, the relativistic frequency shift is maximized. Also, depending on the size of the radar cross-section relative to the square of the sounding wavelength, scattering in the forward direction might be enhanced relative to back scatter [16], thus providing an advantage in detecting the faintest echoes in comparison to mono-static radar (ranging radar).

Co-location with a conventional detector allows for definitive coincidence studies to be performed. If coincidences are detected, the conventional detector's information on the shower geometry will allow direct comparison of echo signals with the predictions of air shower Radio Frequency (RF) scattering models.

The Telescope Array Radar (TARA) project is the next logical step in the development of the bi-static radar technique. Whereas MARIACHI made parasitic use of commercial television carriers as a source of sounding radiation (now impossible due to the transition to digital broadcasts), TARA employs a single transmitter in a vacant VHF band which is under the experimentalists' control. The TARA receiver consists of broadband log-periodic antennas, which are read out using a 250 MS/s digitizer. TARA is co-located with the Telescope Array, a state-of-the-art "conventional" cosmic ray detector, which happens to be located in a low-noise environment. The layout of the TA and TARA detection facilities is shown in Fig. 1.

This work begins with a brief description of the nature of air shower echoes expected for the TARA configuration. Next, we describe the transmitter and receiver system in some detail, including tests of system performance. Finally we describe upgrades to the system which are currently in progress.

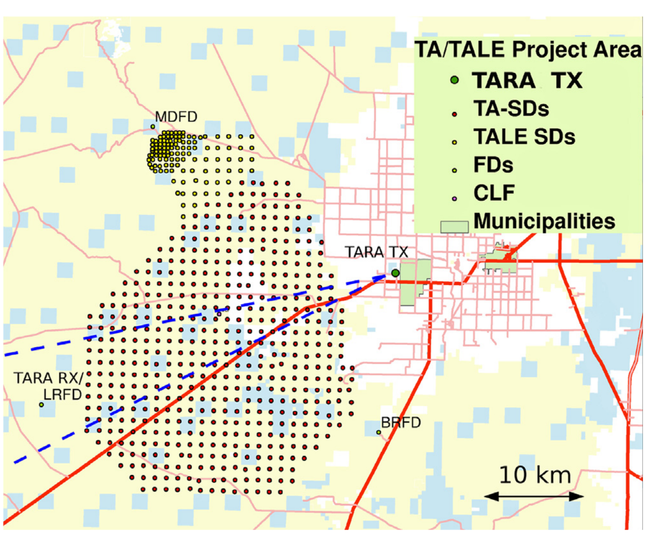

Fig. 1. Map of TARA observatory sites (transmitter and receiver) along with the Telescope Array (TA) detector facilities. The transmitter broadcasts as station WF2XZZ near Hinckley, Utah, towards a receiver site located at the TA Long Ridge Fluorescence Detector (FD). The sounding radiation illuminates the air over the central portion of the TA Surface Detector array, shown with dashed blue lines that indicate the beamwidth 3 dB below the peak gain. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

2. Extensive air showers, radar echoes

As the EAS core ionizes the atmosphere, liberated charges form a plasma with plasma frequency $\nu_p = (2\pi)^{-1}\sqrt{n_e e^2/m_e \epsilon_0}$, where n_e is the electron number density, e is the charge of the electron, and m_e is the electron mass. A shower is denoted *under−dense* or *over−dense* (See Fig. 3 in [17]) relative to the sounding frequency ν depending on whether n_e corresponds to $\nu_p > \nu$ or $\nu_p < \nu$. The radar cross-section of the underdense region is expected to be greatly attenuated due to collisional damping [18–20]. Therefore, we expect the dominant contribution to EAS radar cross-section σ_{EAS} to be the over-dense region, which is modeled as a thin-wire conductor [21]. Fig. 2 displays a "typical" EAS echo from simulation, where standard shower models of particle production and energy transport have been assumed [22].

The mechanism of radar echo detection of EAS differs from other radio applications because the target is small (i.e., small RCS) and moving near the speed of light. However, letting R_T and R_R represent the transmitter/shower and receiver/shower distances, respectively, the bi-static geometry (Fig. 3) minimizes the phase shift because the total path length $L = R_R + R_T$ evolves slowly with time. The time-dependence of the path length causes the phase of the echo to evolve, while the transmission maintains a constant frequency. The result is an echo that has a time-dependent frequency – a *chirp* signal [14] (Fig. 2).

Chirp signals are ubiquitous in nature, although CR radar echos have very unique signatures. A simulation [23] has been designed that requires as inputs the CR energy, geometry and transmitter and receiver details, and which evolves an EAS according to standard particle production and energy transport models [22] while tracking the phase and amplitude of the radar echo. Shower parameters are functions of the primary particle energy [24]. The simulation indicates (see, for example, a "typical" TARA geometry simulation spectrogram in Fig. 2) that CR radar echoes are short in duration (comparable to the shower life-time, ≈ 10 μs), have chirp

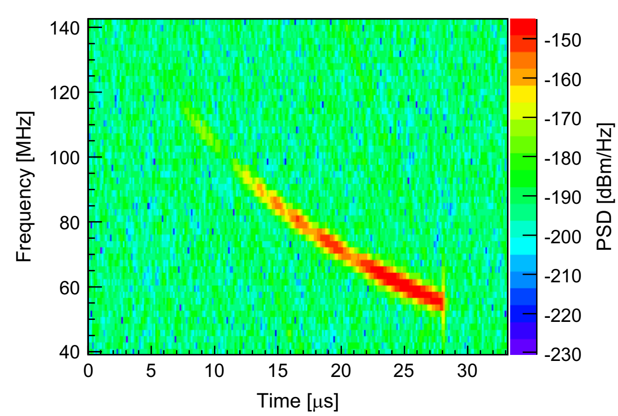

Fig. 2. Spectrogram of a chirp signal produced by the radar echo simulation for an EAS located midway between the transmitter and the receiver with a zenith angle of 30° out of the transmitter–receiver plane. A weighted fit to the power of this signal gives a −2.3 MHz/μs chirp rate. Color scale is Power Spectral Density (PSD) given as dBm/Hz. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Fig. 3. Bi-static geometry of a radar sounding wave interrogating an EAS to scale in the TARA geometry. R_T and R_R are the distances from transmitter (TX) to shower and shower to receiver (RX), respectively. The TX/RX antenna symbols represent location only. Actual antenna sizes are smaller than a pixel if represented to scale.