Radar Detection of UHECR Air Showers at the Telescope Array

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Abstract: Progress in the field of high-energy cosmic rays is currently limited by the rarity of the most interesting rays striking the Earth. Indeed, the continuation of the field beyond the current generation of observatories may become financially and practically impossible if new ways are not found to achieve remote coverage over large portions of the Earth's surface. We describe the development of an observatory based on such a new technique: the remote sensing via bistatic radar technology of cosmic ray induced extensive air showers. We build on pilot studies performed by MARIACHI which have demonstrated that air shower radar echoes are detectable, the opportunity afforded by the location of the Northern Hemisphere's largest "conventional" cosmic ray observatory (The Telescope Array) in radio-quiet western Utah, and the donation of analog television transmission equipment to this effort by a local television station. We will present a description of the transmitter and receiver stations, as well as the most recent observational data from the bistatic radar observatory.

Keywords: cosmic rays, 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 [1] 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 [2]), the Askaryan effect in solids (ANITA [3]), and molecular bremsstrahlung [4].

Here, we describe studies of air shower detection using the *bistatic radar* technique, in conjunction with the Telescope Array experiment 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 [5] 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 [6] 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 [7] reignited interest in radar in a 2001 paper, and updated several critical calculations. Experimental efforts to detect EAS were made by several authors including a recent attempt made by Terasawa *et al.*, using the MU-Radar, a pulsed 1 MW radar used for the detection of micrometeors [8]. A few signals of very short duration compatible with cosmic ray activity were observed, but confirmation is required.

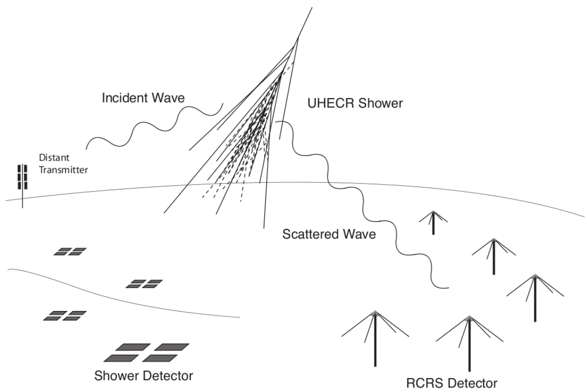

Figure 1: The bistatic radar technique, as pioneered by the MARIACHI experiment. Conventional surface detectors are used to tag the presence of air showers while radar receiver stations detect the forward scattered echo.

An important advance comes from the realization that the radar cross section is greatest in the forward direction [9], and hence that bistatic or two-station radar is advantageous in detecting the faintest echoes, in comparison with monostatic or ranging radar. This idea, illustrated in Figure 1, were first explored by the MARIACHI [11] project. Data collected by MARIACHI — which may contain the first observations of air shower radar echoes in coincidence with a conventional ground array — was first reported by Takai [10] in 2010.

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.

The next logical step in the development of the bistatic radar technique is to observe air shower echoes in coincidence with a state-of-the-art "conventional" cosmic ray detector. This will enable the characterization of echoes as a function of air shower energy and geometrical properties.

3 Radar at the Telescope Array

Radio-quiet western Utah is an ideal location in which to pursue this next step. Not only is the dearth of radio 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 bistatic radar effort at Telescope Array received a substantial boost from the donation of 2 kW and 20 kW analog television transmitters from KUTV Channel 2 in Salt Lake City. Under U.S. Federal Communications Commission (FCC) license WF2XHR, we have obtained permission to broadcast a single carrier frequency at 54.1 MHz. The 2 kW transmitter was commissioned in January of 2011 (Figure 2).

Figure 2: 2 kW transmitter donated by KUTV-2, in operation at Millard County, UT Cosmic Ray Center.

To understand the technical challenges of the radar receiver stations, we have done extensive work in simulating the characteristics of air shower echoes. As shown in Figure 3, we have estimated the received power for a radar echo in a typical geometry and compared that power to the thermal, electronic and sky noise backgrounds. (Details of this calculation are presented elsewhere in this conference [12].) This graph gives some indication of our expectations for an energy threshold. As noticed by Underwood [13], an additional challenge results from the significant frequency shift due to phase modulation of the signal reflecting off of an air shower moving near the speed of light. In Figure 4, we show a spectrogram for a simulated echo under a typical air shower geometry.

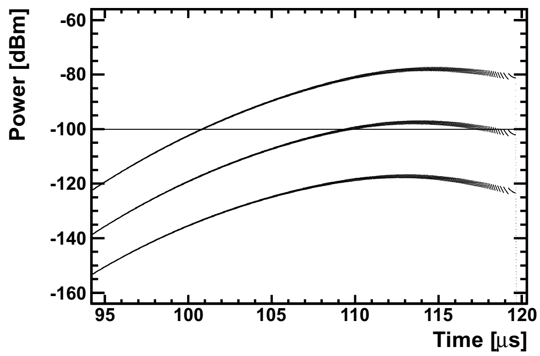

Figure 3: Calculation of received power (referenced to milliwatts) for echoes off of air showers initiated by 10^{20} eV (top), 10^{19} eV (middle), and 10^{18} eV (bottom) primary cosmic rays. Transmitter power is assumed to be 20 kW. The air showers are midway between 54.1 MHz transmitter and receiver separated by 50 km, and are inclined at a zenith angle of 30° in a plane perpendicular to a line connecting transmitter and receiver. The horizontal line indicates the galactic sky noise "floor" integrated over a 4 MHz bandwidth [15].

Development of receiver stations for the bistatic radar observatory is underway. We have deployed several dual-polarization log-periodic antennas at the Long Ridge Fluorescence Detector (LRFD) site (Figure 5). Currently, we are in the process of improving the reliability and sensitivity of our receiver data acquisition system. We have begun taking preliminary data using the Ettus Research USRP-II software-defined radio receiver. Using the USRP-II we are taking data in three modes: (1) triggered by the LRFD at approximately 1 Hz and read out at 12.5 Megasamples per second, (2) self-triggered by threshold comparison and read out at 6.25 Megasamples per second, and (3) "streaming" or continuous sampling at 250 kilosamples per second (0.6 Terabytes per week).

Because of the large frequency excursions, it is ultimately desirable to detect echoes with a bandwidth of several tens of MHz. Two such data acquisition systems are currently under development. The first is an oscilloscope-based system, which will employ both self-threshold triggering and triggering by the LRFD while reading out at 300 Megasamples per second. The second high-bandwidth system utilizes the National Instruments FlexRIO software-defined radio receiver, which can sample at up to 250 MHz, and will involve real-time self triggering on signals characterized by the large frequency shifts or "chirps" expected to be seen from air shower radar echoes. Preliminary estimates indicate that air shower echoes can be identified in this manner at a signal-to-noise ratio of order 10%. First

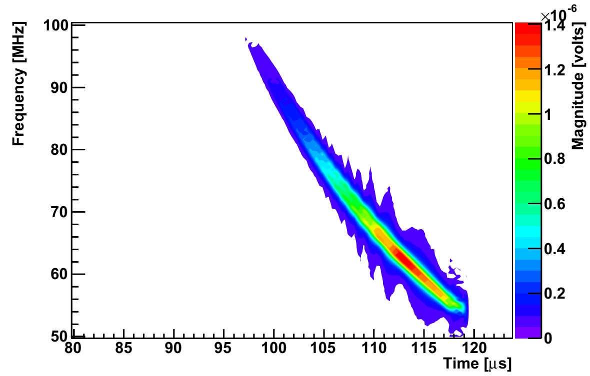

Figure 4: Spectrogram of "chirp" for simulated air shower, initiated by 10^{19} eV cosmic ray midway between 54.1 MHz transmitter (TX) and receiver (RX), located 50 km apart. The shower is inclined at a zenith angle of 30° in a plane perpendicular to a line connecting transmitter and receiver.

deployments for the high-bandwidth DAQ systems are expected in Summer 2011.

In parallel, we are also planning to utilize the radar transmitter in conjunction with the TA *Electron Light Source* facililty [14] (Figure 6). In addition to testing our ability to calculate received power from a known airborne plasma, by measuring the duration of radar echoes produced by this 40 MeV electron gun we hope to obtain a direct measurement of the free electron lifetime in air.

In conclusion, bistatic radar is a candidate remote-detection technique for the observation of the highest energy cosmic rays. We are deploying low-VHF transmitters and receiver stations at the Telescope Array site in western Utah. The aim of these pilot studies is to demonstrate the feasibility of using this potentially low-cost, 24-hour, remote sensing tool for astrophysical research.

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Figure 5: Radar receiver antenna at Long Ridge fluorescence detector site.

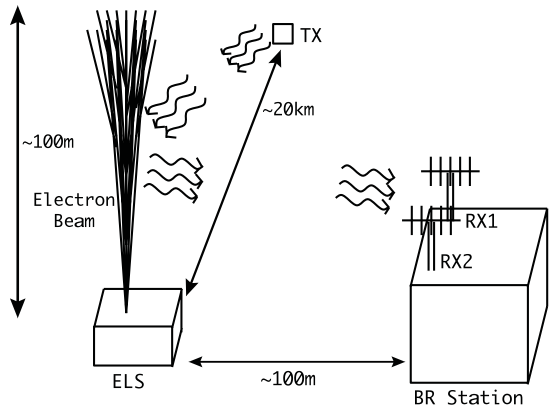

Figure 6: Plan for radar studies in conjunction with the Telescope Array's Electron Light Source (ELS). Receiver antennas will be placed at right angles to a line joining the transmitter and 40 MeV ELS electron beam. Two antennas will be separated by one half-wavelength, to allow supression of the direct illumination by the transmitter.

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