Air Shower Detection by Bistatic Radar

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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.

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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 an effort to begin 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 build at a fraction of the cost allowed by current technology.

THE BISTATIC RADAR TECHNIQUE

Radar detection of air showers is feasible because of the large ionization densities, approaching 10^{13} particles per m^3, 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. What may be the first observation by MARIACHI of radar echoes in coincidence with a conventional ground array was first reported at conferences by Takai [8] starting in 2010.

MARIACHI [9] is a high school cosmic ray outreach project based in Long Island, New York. MARIACHI made use of "parasitic" bistatic radar, in which emanations from ambient commercial television stations were used as a source of radio frequency electromagnetic waves. Over the course of several weeks' observation, coincidences in time were observed between radio an-

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tenna activity and ground array detectors located at several high schools. The timing distribution of these coincident events is shown in Figure 1.

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 airshower energy and geometrical properties.

As shown in Figure 2 (left panel), 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. This graph gives some indication of our expectations for an energy threshold. An additional challenge results from the significant "Doppler" shift of the signal reflecting off of an airshower moving near the speed of light. In Figure 2 (right panel), we show a spectrogram for a simulated echo under a typical airshower geometry. The "chirp" varies the frequency over 40 MHz in approximately 15 μsec. To resolve the echo over such a wide bandwidth will require sampling rates in excess of 80 MHz and a potentially enormous data volume unless a scheme for real-time triggering can be realized.

On the other hand, the rapid signal chirp can be seen as a feature unique to cosmic ray air shower echoes. It will depend on geometry at some level, and hence may serve as a constraint in the reconstruction of air showers from their radar echo.

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 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 the fall of 2010, and development of receiver stations is underway (Figure 3).

A radar receiving station will be composed of an array of four two-polarization log-periodic antennas (to detect wide-bandwidth signals with uniform gain), associated electronics and a host computer. The first receiver station to be deployed will be co-located with and tethered to the Long Ridge fluorescence detector station (Figure 4).

A crucial component to the execution of this project — and the key to dealing with the large Doppler excursions in frequency — is a flexible radio receiver to (1) receive the reflected signals from the air showers, (2) identify the occurrence of each air shower and capture the corresponding signal samples, and (3) store the captured signal in a host computer. To implement a radio that can be adapted to these requirements, we propose to develop a software-based radio (often called software defined radio — SDR). We plan to use a FlexRIO National Instrument FPGA board and two front-end four-channel digitizers with a sampling rate of 250 MHz. This sampling rate is sufficient to capture the air shower chirp signals whose frequency can be as high as 80 or 90 MHz. We believe the presence of a large Vertex-5 FPGA module and 512 MB of RAM on the FlexRIO will give us sufficient flexibility to develop a high-performance chirp detector/processor on the board.

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 this potentially low-cost, 24-hour, remote sensing tool.

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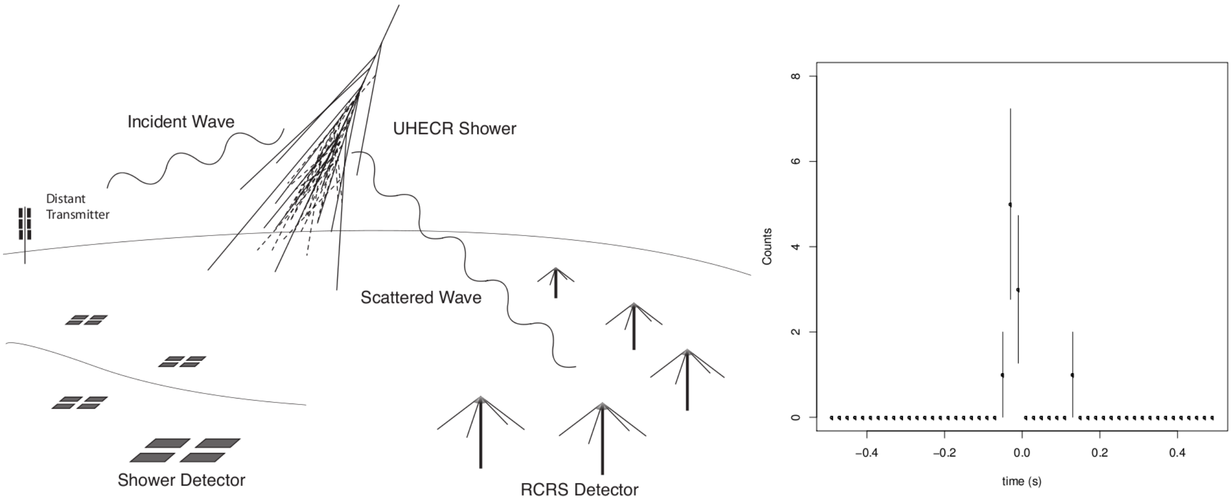

FIGURE 1. Left: The MARIACHI experiment. Small shower detectors are used to tag the presence of showers while Radio Cosmic Ray Scattering (RCRS) stations listen to forward scattered echo. Typical distances between RCRS stations and scintillators is 40 to 80 km. Right: Histogram of events found in coincidence with the scintillator sites in a period of 2 weeks. The offset from zero is due to data acquisition timing issues.

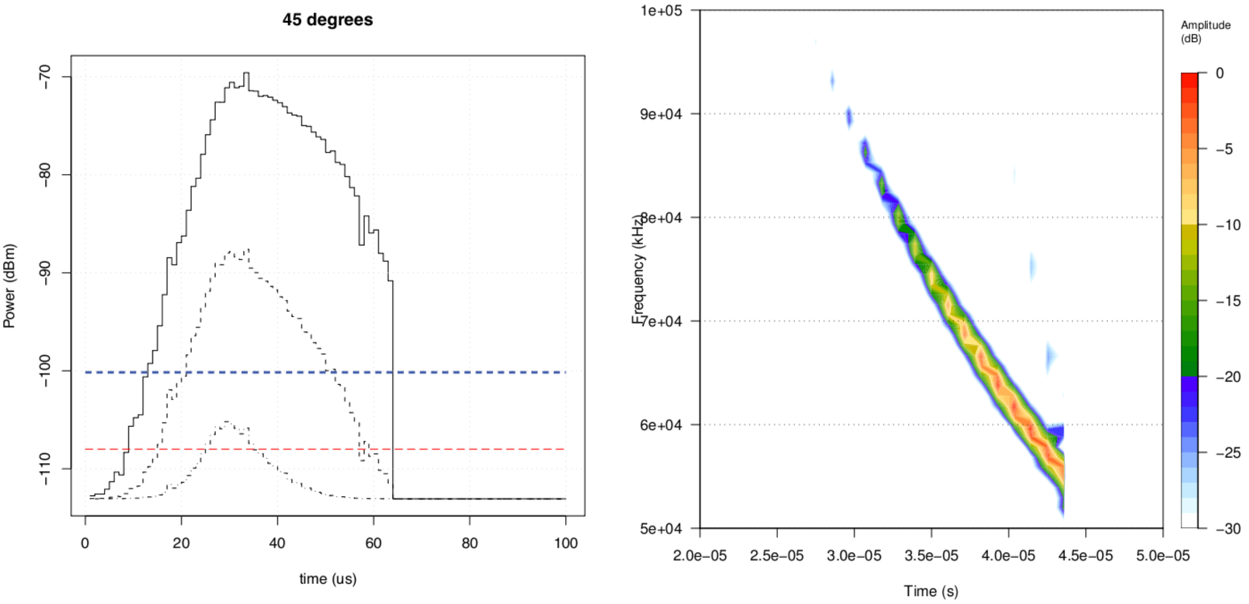

FIGURE 2. *Left:* Calculation of received power (referenced to milliwatts) for echoes off of air showers initiated by 10^{20} eV (solid), 10^{19} eV (dashed), and 10^{18} eV (dot-dashed) primary cosmic rays. Transmitter power is assumed to be 20 kW. The air shower is midway between transmitter and receiver separated by 50 km. The horizontal red line is the background from thermal noise [10] integrated over a 4 MHz bandwidth. The horizontal blue line is the background including electronics and sky noise. *Right:* Spectrogram of "chirp" for simulated air shower, initiated by vertical 10 EeV cosmic ray midway between 54.1 MHZ transmitter (TX) and receiver (RX), located 50 km apart.

FIGURE 3. *Left:* 2 kW “Channel 2” transmitter donated by KUTV-2, in operation at Delta Cosmic Ray Center. *Right*: Radar receiver antenna at Long Ridge fluorescence detector site. First of four. (Photos: Helio Takai)

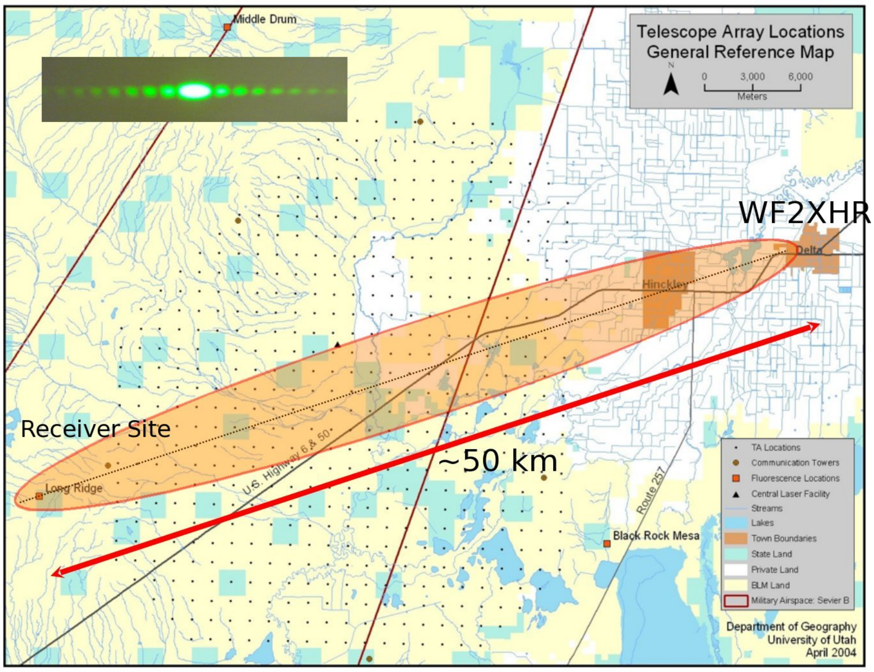

FIGURE 4. Radar sensitive area (ellipse) superimposed on map of Millard County, Utah and the Telescope Array site. Transmitter location (WF2XHR) and receiver location at Long Ridge fluorescence detector are also indicated.