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Searching for Cosmic Ray Radar Echoes In TARA Data

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Abstract: The TARA (Telescope Array Radar) cosmic ray detector has been in operation for over two years. This bistatic CW radar detector was designed with the goal of detecting the radar echoes of cosmic rays in coincidence with Telescope Array (TA). Thus far, TARA1.5 has operated with a 1.5 kW transmitter broadcasting through a single Yagi antenna into the air above the TA surface detector array. Potential radar echoes are detected in a receiver station 50 km away utilizing a 12.5 MHz USRP2 PC-controlled radio triggered by both the TA fluorescence detector and an independent threshold trigger. In spring 2013 a 40 kW transmitter with high-gain phased Yagi array was commissioned, increasing the power available for radar scattering by a factor of over 300 (TARA40). Additionally we have deployed a 250 MHz sample rate detector employing intelligent self-triggering algorithms that can detect radar echo signals below the level of sky noise, thus increasing sensitivity by another two orders of magnitude in power. Together these advances make TARA40 the most ambitious effort by far to test the hypothesis that cosmic ray air showers can scatter RF waves. The focus of this paper is to describe the analysis used in comparing TARA radar triggers with TA data, including both a synopsis of TARA1.5 findings and preliminary results from the TARA40 configuration.

Keywords: cosmic ray, radar.

1 Introduction

1.1 Modern CR Detection Limitations

There are two primary methods used in modern UHECR detection. One method utilizes a number of ground based detectors that are triggered when struck by incident shower products. Wave forms from multiple counters are analyzed to reconstruct information about the original cosmic ray particle. Such ground based arrays are operational around the clock but expensive to build and maintain because a large area must be instrumented to obtain a reasonable event rate.

Another modern detection method only works in low light conditions. As shower particles stream down through the atmosphere, molecular nitrogen is excited into a state that emits ultraviolet light. Specially designed fluorescence telescopes record the tracks made in the sky by passing air showers. Cosmic ray fluorescence light is dim compared to even moonlight so fluorescence telescopes can only be operated on clear, moonless nights which gives a duty cycle of about 10%. Their benefit is remote detection of showers up to ~ 40 km away.

Blackett and Lovell [1] wrote a paper that investigated the possibility of *radar* detection of cosmic rays. It was inspired by T.L. Eckersley [2], who originally suggested that anomalous military radar echoes were caused by cosmic ray events. Some early radar experiments were conducted, but no useful results were reported. Throughout the twentieth century and beyond the radar detection method has been confronted on several occasions. TARA is the first experiment to use a 100% duty cycle high power transmitter in conjunction with a well known cosmic ray observatory.

1.2 Radar Revisited

The need for a less-expensive alternative to the two conventional methods employed by CR researchers spurred the creation of MARIACHI [3], an outreach program on Long Island, NY. MARIACHI coupled parasitic bistatic radar with a small custom built ground detector. Local analog TV stations provided the radar signal.

Pulsed military radars (see for example Wahl [4] and Terasawa [5]) have been used to look for CR air showers. The stochastic nature of CR phenomena makes this avenue of detection extremely difficult. Also, dedicated low power transmitters have been built along side conventional arrays [6]. Results have been unconvincing or absent. Recently, Gorham [7] explored RF scattering by CR air showers.

TARA is an extension of the MARIACHI model, utilizing a dedicated transmitter along side Telescope Array [8], a state of the art CR observatory. As sister collaborations, TARA will employ TA data to assist in data analysis and eventually determine or put limits on the radar cross-section (RCS).

2 Experimental Setup

TARA is a bistatic radar detector in which the constant, unmodulated sounding wave is broadcasted directly over the TA scintillator array. The transmitter broadcasts from a location northeast of the array with a bearing of 251° (clock-wise from north) to the receiver station which is co-located with the Long Ridge fluorescence detector to the southwest.

TARA triggers are time correlated with TA data. Even in the radio quiet Utah west desert, spurious radio clutter would make positive detection without TA confirmation extremely difficult. TARA have employed both self and fluorescence detector triggered DAQ schema. Self-triggered data are compared with surface detector (SD) events. A strong correlation in time would imply radar detection. FD-triggered data by definition correspond in time to CR events. Several analysis techniques are employed to find signals in these data.

3 TARA1.5

A Salt Lake City, UT TV station (KUTV2) donated both a 20 kW analog channel two transmitter and a 2 kW backup transmitter to TARA after the nation wide conversion to digital TV in 2009. For two and a half years, the backup transmitter broadcast a 1.5 kW, 54.1 MHz radar signal from the Cosmic Ray Center located in Delta, UT from a single narrow-band Yagi-Uda antenna. Figure **??** shows the location of the TARA1.5 transmitter site, call sign WF2XHR, and the receiver 50 km away.

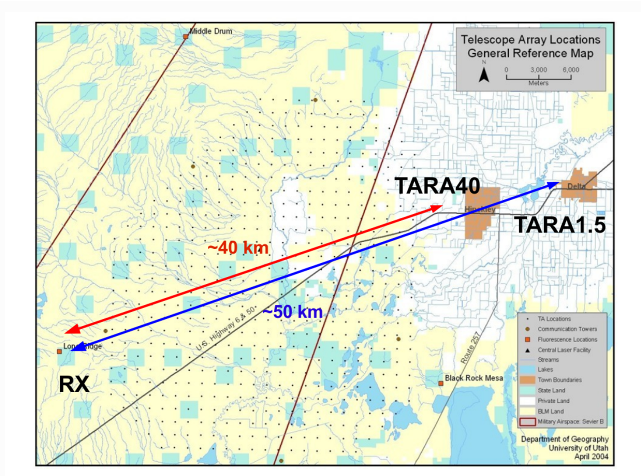

Figure 1: Map showing the Telescope Array surface and fluorescence detector facilities relative to Delta and Hinckley, UT. Also shown are the different positions of the two TARA transmitter facilities in Delta and west of Hinckley (WF2XHR and WF2XZZ, respectively) and the receiver located at the Long Ridge fluorescence detector. labelfig:tamap

Early CR radar echo simulation predictions [9] indicated that a higher gain antenna and increased transmitter output would be necessary to detect UHECR. During the operation of this initial phase of the experiment, plans were being made to commission the full 20 kW transmitter at a site closer to the surface detector array.

During its operation from August 2010 to March 2013, TARA1.5 collected over 100 million triggers in self-triggered mode. An Ettus Research[1] USRP2 PC controlled radio used simple 5σ voltage threshold triggering logic. DAC occurred in a TVRX daughter board which limited the bandwidth to 6 MHz. A clear channel was observed with near Gaussian background noise when the USRP2 was tuned higher than the carrier, 58.0 - 60.4 MHz. Doppler up-shifted radar echoes were predicted by the simulation and originally suggested by Underwood [10].

The vast majority of triggers were large amplitude pulses that only spanned one to several ADC bins. These high-frequency, short duration triggers couldn't be resolved by the low sampling rate receiver, the absolute timing resolution of which is about 65 μs. A time comparison ($\Delta t = t_{SD} - t_{USRP2}$) of self-triggered data was made with TA SD events. No significant time correlation was found between the two data sets. The subset of higher energy well-reconstructed SD events were also compared (see Figure 2). Again, no significant correlation was found. An event display for one of the USRP2 triggers that was matched to a well-reconstructed SD event is shown in Figure 3. Note that this matching window is greater than the timing resolution of the system. There were no matches with well-reconstructed events that fell within the system resolution window. The 5 σ triggering sample can be seen at 90 μs in the time domain plot. Nearly uniform background noise is shown in the spectrogram.

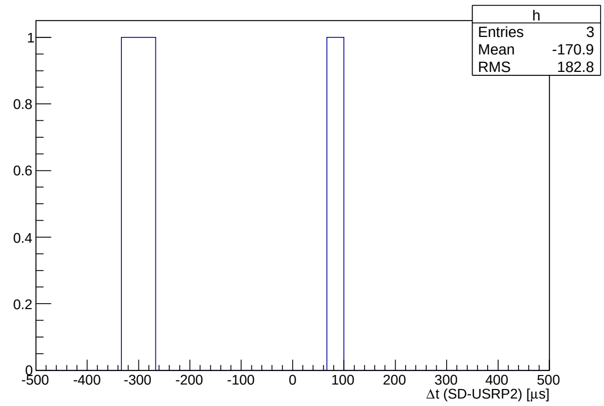

Figure 2: Time difference histogram comparing well-reconstructed Telescope Array surface detector events and self-triggered TARA1.5 data. Δt is defined as the USRP2 time stamp subtracted from reconstructed SD event time. USRP2 timing resolution is about 65 μs. Evidence of radar echo detection would present as a peak centered on zero.

FD-triggered data were also recorded with the USRP2. A low level hardware trigger, an OR of individual fluorescence detector (FD) telescopes, was fed into the DAQ. 1.2 million triggers were recorded during a period which is equivalent to 50 observation nights. There is de facto agreement between some FD-triggered TARA1.5 data and TA FD events. Only a very small subset of all low level FD triggers emerge as reconstructed events. The $\Delta t = t_{FD} - t_{USRP2}$ histogram (Figure 4) serves as confirmation of system DAQ timing.

1. www.ettus.com

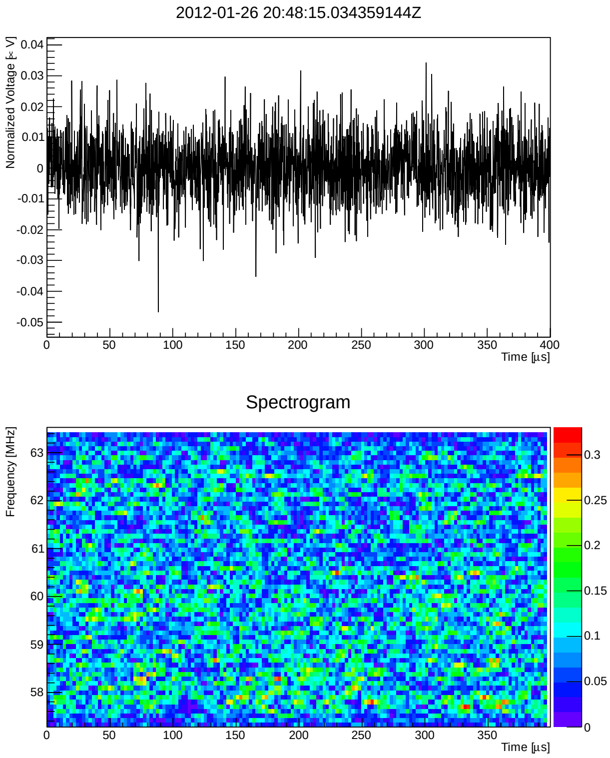

Figure 3: An example event display for a self-triggered TARA1.5 event that occurred within a $\pm 500\mu$s window a well-reconstructed SD event, but not within timing resolution. The top plot is the time domain wave form; below it is a spectrogram. The triggering sample can be seen in the time domain at about 90 μs.

Several data analysis techniques were used to search for signals in these data. One interesting event is shown by Othman et. al. [11] in these proceedings. An insignificant fraction of matched events had characteristics above background noise. The description of TARA1.5 analysis in this paper is merely a synopsis. Please see the poster presentation during the conference which will explain similar analysis techniques for TARA40 data.

4 TARA40

In May, 2013 the TARA collaboration celebrated the commissioning of WF2XZZ, a new transmitter site located just outside of Hinckley, UT, USA. The Hinckley site represents a major upgrade to the TARA detector. Two 20 kW transmitters (Figure 5) feed a custom two (row) by four (column) phased Yagi array pictured in Figure 7. Figure 6 shows the simulated radiation pattern of the new array. One of the 20 kW transmitters was a donation from KUTV2. The other was purchased.

On the receiving end, TARA40 now utilizes a DAQ with 250 MS/s sampling rate. The National Instruments FlexRIO modular RF platform includes a powerful FPGA for intelligent self-triggering. A simple FD-triggered mode is still included in the design. Intelligent self-triggering is accomplished via a bank of matched filter detectors [12]. More details about the relative benefits of TARA40 over

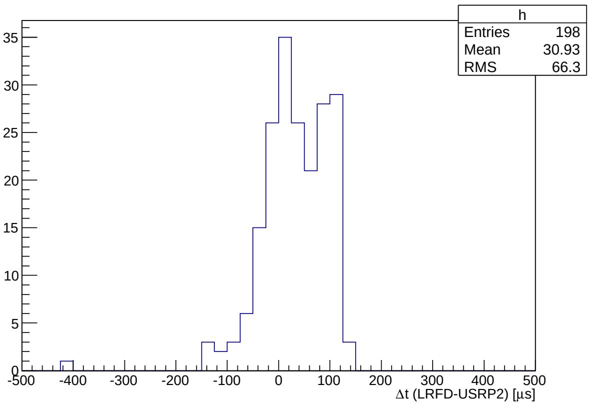

Figure 4: Timing comparison of TARA1.5 FD-triggered data and reconstructed Telescope Array FD events. Δt is defined as the USRP2 time stamp subtracted from the FD time stamp. DAQ timing precision is shown to be better than $\pm 100\mu$s. Correlated triggers are further analyzed.

Figure 5: TARA40 radar transmitter is comprised of two 20 kW analog TV transmitters. Modifications have been made to broadcast a single 54.1 MHz tone with 100% duty cycle.

TARA1.5 can be found in the conference proceedings mentioned in Section 3.

Due to the large receiver bandwidth, understanding and characterizing background is now a challenge in itself. A description of background characterization and results from trigger comparisons with TA data will be the domain of the poster given during the conference.

5 Conclusion

TARA is a cosmic ray radar experiment complimented by the Telescope Array facility for confirmation or rejection of radar detection of cosmic rays. It utilizes a dedicated high power 100% duty cycle constant wave transmitter and a receiver station located directly across the array. This geometry emphasizes the goal of coincident detection.

The results of the first phase of the experiment, TARA1.5, have been discussed. No significant correlation with TA cosmic ray events were observed. An overview was given of the recently commissioned TARA40 phase of the experiment. The first results from the analysis of these data will be discussed during the conference.

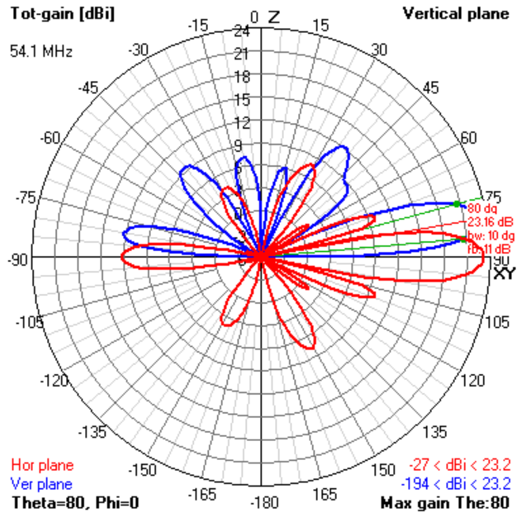

Figure 6: Simulated azimuthal (red) and elevation (blue) radiation patterns for the eight Yagi phased array TARA40 radar transmitting antenna. Main lobe gain is calculated to be in excess of 23 dBi.

Figure 7: Fixed azimuth phased Yagi-Uda radar transmitter array. Wood masts allow vertical or horizontal polarization. Maximum power handling is 40 kW, equivalent to over 8 MW effective radiated power.

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