A Station for the Detection of Ultra High Energy Cosmic Ray Induced Extensive Air Showers at the Telescope Array Radar (TARA)

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Abstract. The detection of ultra high energy cosmic rays is limited by the rarity of the most interesting rays striking Earth. We describe the development of an observatory based on a remote sensing technique known as bi-static radar, that aims to achieve remote coverage over large portions of the Earth's surface, cf. Telescope Array's $700km^2$ surface detector. Construction of the radar project's receiver and transmitter station was completed in the summer of 2013, in conjunction with North America's largest cosmic ray observatory (The Telescope Array) in radio quiet western Utah, giving insight into the detect-ability of air shower radar echoes. This has given impetus for further upgrades, including additional autonomously powered remote receiver stations. We describe the current status of the Telescope Array RAdar (TARA) project and the development of these stations.

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1. INTRODUCTION

In the atmosphere, cosmic rays with energies per nucleon in excess of 10^{14} eV [1] create a cascade of particles with electromagnetic and hadronic components, known as extensive air showers (EAS). EAS have primarily been detected by deploying Scintillation/Cerenkov detectors on the ground to study the footprint of these air showers [2] or with atmospheric fluorescence telescopes to study the full longitudinal development of the air shower [3]. However, at EeV energies, it has become clear that the extremely low flux of these ultra high energy cosmic rays (UHECRs) require detectors with apertures of hundreds or even thousands of square kilometers and close to one hundred percent duty cycle. The sheer scale that would be required of conventional detectors, to acquire sufficient statistics for mass - composition or anisotropy studies means that new techniques that reduce manpower and financial resources are constantly being sought.

As the EAS shower core ionizes the atmosphere, liberated charges form a plasma with a plasma frequency $\nu_p = (2\pi)^{-1}\sqrt{n_e e^2/m_e\varepsilon_0}$, where n_e is the electron number density, e is the charge of the electron, and m_e is the electron mass. Relative to a sounding frequency ν, the shower is denoted as either $under-dense$ or $over-dense$ dependent on whether $\nu_p > \nu$ or $\nu_p < \nu$ [4]. This is similar to micro - meteors in the Earths upper atmosphere, which have been detected for many decades using radar methods [5]. In an EAS, the $over-dense$ case is the most dominant contributor to the radar cross - section, σ_{EAS}, and approximated as a thin wire [6].

The Telescope Array Radar (TARA) project uses a bi - static radar configuration, where a transmitter (at 54.1 MHz) sends out the sounding signal. The radar echo(chirp) from the EAS is detected at a distant radar receiver, in conjunction with a set of conventional cosmic ray detectors in the low - noise environment at the Telescope Array in Millard County, Utah (www.telescopearray.org/tara/).

In addition to signal detection using matched filtering with TARA's FlexRIO Data Acquisition System [7], an alternate technique has been developed that accomplishes radar echo detection using an analog signal chain. Subject to less radio interference, the remote station, adds stereoscopic measurement capabilities which theoretically allow unique determination of cosmic ray geometry and core location. The analog data acquisition system with lower power consumption at a cost which is also comparatively inexpensive is discussed in the following sections.

2. RECEIVER ANTENNA AND FRONT END

The TARA receiver antenna site is located at Long Ridge, UT (39-14.560 N 113-05.291 W). The receiver antenna is a dual polarized Log Periodic Dipole Antenna designed to match the expected radar echo in the passband from 50 to 80 MHz. Each antenna channel is com-

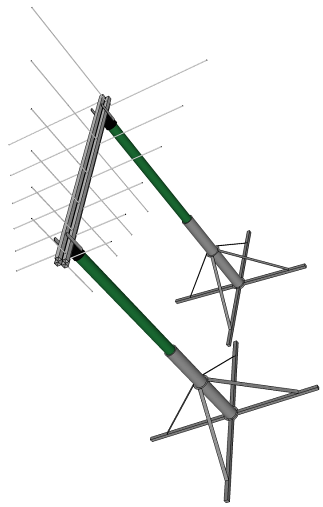

FIGURE 1. Dual polarized TARA Log Periodic Dipole Antenna (LPDA).

TABLE 1. Length and relative boom position of antenna elements of the TARA Log Periodic Dipole Antennas. All elements have a diameter of 0.25″.

Element	Length (in)	Position (in)
1	21.875	3.625
2	26.625	18.0625
3	32.5	35.625
4	39.625	57.0
5	48.3125	83.125
6	58.3125	115.0

prised of a series of six $\lambda/2$ dipoles. The ratio of successive dipole lengths is equal to the horizontal spacing between two dipoles (the defining characteristic of LPDA units). Table 1 gives the lengths and positions of the antenna elements on the boom from the front edge. Successive dipoles are connected alternately to opposite sides of a transmission line with the feed at the end with the shorter elements. All elements are constructed of aluminum tubing of $1/4''$ outer diameter. Fig. 1 shows a schematic of the receiver LPDA.

Terminal Voltage at the antenna feeds is related to the incident electric field, $V = \vec{h}\cdot\vec{E} = hE cos\theta$ [8] where, h is the effective height and θ the angle between the electric field polarization and the dipole. The effective height is given by (see Fig. 2),

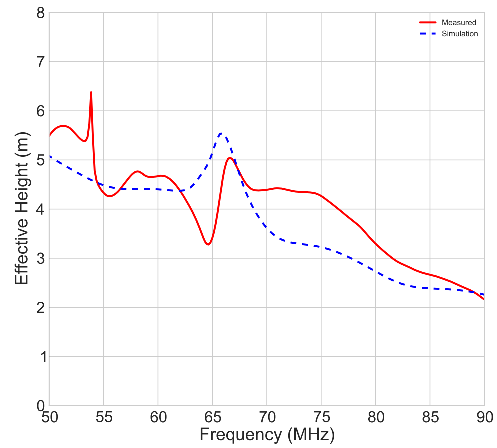

FIGURE 2. Effective Height of the TARA LPDA.

$$h(f) = 2 \times \sqrt{\frac{G}{4\pi}\frac{c^2}{f^2}\frac{Z}{Z_0}} \tag{1}$$

where G is the unit-less gain, c the speed of light, f the frequency, Z the impedance at the antenna terminals and Z_0 the impedance of free space.

Receiver antenna gain is also a factor in the bi-static radar equation that affects detection threshold. Numerical Electromagnetic Code (NEC) [9] was used in simulating the radiation pattern of the antenna with elements in the horizontal plane to confirm directionality (see Fig. 3). Simulated forward gain is 12.6 dBi and the vertical beam-width is 23° at the carrier frequency, 54.1 MHz.

Currently both polarizations are connected to the Transient Detector Apparatus with only the Horizontal polarization connected to the Chirp Accusation Module (see Sec 3.2). RF signal from the antenna first passes through a bank of filters and amplifiers. These components include a FM band stop filter (NBSP-108+; Mini - Circuits), a chain of three band pass filters (NBP-70; Mini - Circuits) and a custom notch filter to attenuate the 54.1 MHz carrier to prevent saturation of the 61 dB amplifier (AU-1525; MITEQ) that follow the filters. A 12 V bias voltage is provided via a bias Tee (ZFBT-4R2G-FT+; Mini - Circuits).

3. RECEIVER DAQ

3.1 Triggering Mechanism

The triggering is based on an analog frequency mixer. The input signal is mixed with a delayed copy of itself,

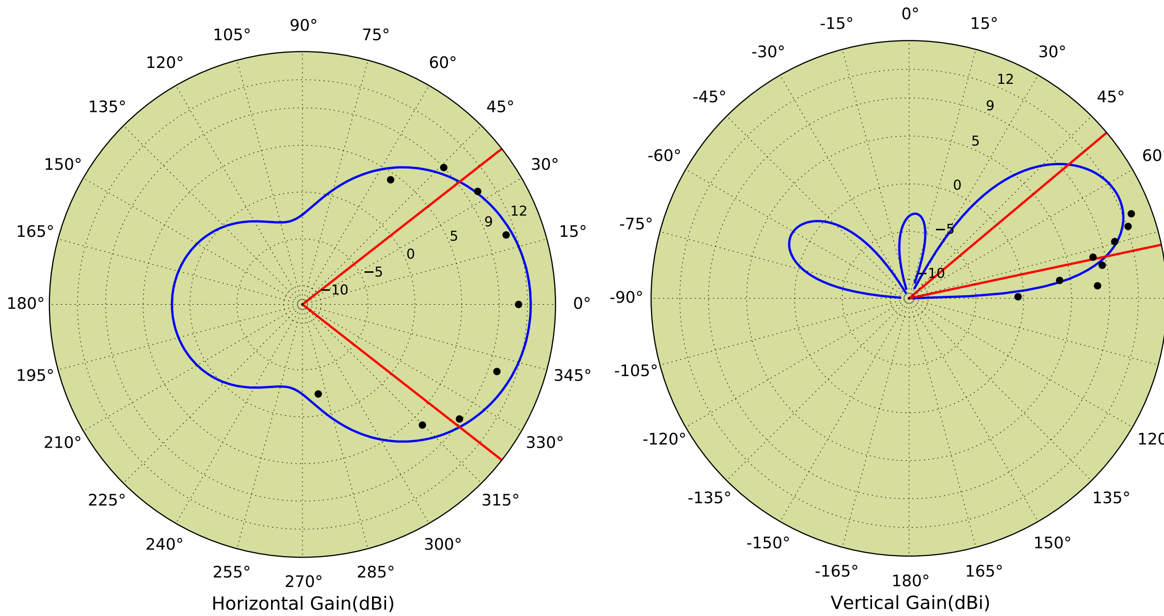

FIGURE 3. Simulated horizontal (left) and vertical (right) radiation pattern of a horizontally polarized TARA LPDA at the transmitter sounding frequency of 54.1 MHz. Beam-widths (-3 dB below peak gain) are shown with red lines. Peak gain is 12.6 dBi.

i.e, $s(t) \otimes s(t-\tau)$, where τ is the delay time. For an incident chirp signal, the non-linear components in the mixer result in a product term that yields a monotone at a beat frequency $f_{beat} = \kappa\tau$; dependent only on the delay time τ and the chirp rate κ. The delay is created with 95 ft of LMR-600 cable (chosen so that the DC offset due to the frequency mixing caused by the 54.1 MHz carrier is mitigated), which produces negligible losses and removes the need for power consuming active components. With appropriate filtering, the problem of chirp detection is ultimately reduced to that of detecting a down-converted monotone.

The expected value of chirp rates from EAS echoes is typically between -1 to -10 MHz/μs [7].To trigger on such signals, the de-chirped signal is split into multiple copies. Each copy is then passed through custom band-pass filters and an envelope detector. Different frequency bands are then compared by majority logic in an FPGA, requiring no more than two bands to form a trigger in order to suppress impulsive noise. Each of the frequency banded outputs corresponds to a separate range of chirp rates. The block diagram in Fig. 4 outlines this triggering procedure.

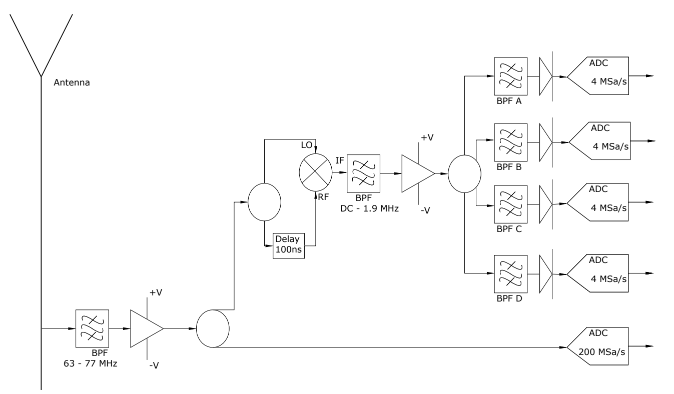

FIGURE 4. Block diagram of the event triggering to be employed in the remote station.

3.2 Receiver Electronics

The layout of the full remote station, including the Chirp Acquisition Module (CAM), power systems, acquisition electronics, and communications blocks is shown in Fig. 5.

The Chirp Acquisition Module has a modular design enabling quick debugging of the constituent components. This unit is comprised of a custom triggering board encompassing four band pass filters and envelope detectors, and a four channel ADC (AD80066; Analog Devices)

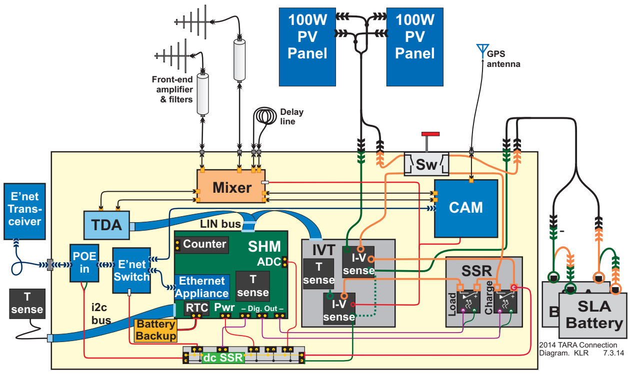

FIGURE 5. Schematic block diagram of the remote detector electronics. Chirp acquisition module (CAM), power systems, acquisition electronics, and communications blocks are all shown in this figure.

with 16 bit resolution sampling at 4 MS/s per channel to sample the signal out of the envelope detectors. A high speed ADC (AD9634 evaluation board; Analog Devices) sampling at 200 MS/s directly samples the raw data from the Antenna and an FPGA (Spartan - 6 LX16; Xilinx) performs the majority comparison logic to trigger and capture triggered data before transferring to a single board computer. A Raspberry Pi (Rev. 2) single board computer stores triggered data in an SD card along with GPS time stamps (M12M; i-Lotus).

TABLE 2. Estimated power budget for the remote station.

Component	Power Consumption(W)
Single Board Computer	5.0
Low Speed 4 Ch. ADC	0.5
High Speed 1 Ch. ADC	0.4
FPGA	3.0
RMS Counter	2.0
System Health Monitor	1.0
60 dB Amplifier (x2)	4.0
25 dB Amplifier (x2)	0.4
GPS	0.2
GPS and GPS Antenna	0.4
Communication Antenna	3.0
Total	19.9

Another major component is the System Health Monitor [10] (SHM), which both monitors performance and controls, via Solid State Relays (SSRs), the system solar (two 100 Watt photo-voltaic panels) and battery (sealed lead acid) power. The SHM also records antenna data digitized by the TDA (Transient Detector Apparatus) receiver on local SD flash memory. The TDA receiver has two channels with filters and a logarithmic amplifier. Finally, the SHM and CAM are connected to a 5 GHz ethernet transceiver via a switch for remote system control and data access.

4. CONCLUSION

The Telescope Array Radar is an ambitious attempt using a bi - static radar configuration for the observation of the highest energy cosmic rays. TARA completed its construction of the transmitter station in the summer of 2013 and immediately began work on an autonomously powered remote receiver station, which was deployed in the summer of 2014.

The design and development of the remote station has been discussed. The station implements an analog triggering mechanism removing the need for power hungry active components and lowering costs while adding to stereoscopic measurement capabilities.

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