Forward Scattering Radar for Ultra High Energy Cosmic Rays

Helio Tiko,1 Isaac Myers,2 John Belz,2 Gordon B. Thompson2 and Jamie S. Rankin2

1Brookhaven National Laboratory, Upton, New York 11973 U.S.A.
2University of Utah, Salt Lake City, Utah 84112 U.S.A.
contact: bti@bnl.phys.sci.utah.edu

Abstract: The use of a monostatic radar for the detection of cosmic rays was first suggested by Blackett and Lovell in 1941. Over the years that followed it became clear that this type of radar would require extremely high power transmitters and high gain antennas for its operation. The ion Radar Cross Section (RCS) is due to the details of electromagnetic wave scattering by the ionization electrons in the dense terrestrial atmosphere. A less known type of radar, bistatic radar, exhibits a strong enhancement in the RCS at forward directions. We present results of expected received power calculations for a bistatic radar used in the detection of extensive cosmic ray showers. The rapid movement of the shower front followed by extinction of ionization by Electronegative oxygen contributes to the formation of a phase modulated signal at the receiver. The signal frequency versus time signature is characteristic for the RCS of target, and present results of expected received power calculations for a bistatic radar used in the detection of extensive cosmic ray showers: the main advantage of bistatic radar is the increase in the radar cross section (RCS)

1 Introduction

The use of bistatic radar for the detection of cosmic ray showers (UHECR, $E > 10^{19}$ eV) requires detectors with very large aperture, for example the Telescope Array (800 km$^2$) [1] which has a detection rate of order one event per day. To advance the study of UHECR and explore the existence of high energy neutrinos [2], detectors with much larger aperture will be required. One technology that could be explored for their detection is a radar. The “monostatic” or backscattering radar detector of cosmic ray extensive air showers (EAS) is an idea dating to the 1940’s [3]. However it was later realized that the return power was far too weak to be detected by the technology of the time [4, 5, 6]. Experimental efforts to detect the radar backscatter of UHECR Air Showers have proceeded, including a recent attempt made by Terashima et al. using the pulsing 1 MW MIU-Radar, normally used for the detection of micrometeoroids [7]. A few signals of very short duration comparable to cosmic ray activity were observed, but confirmation with a conventional cosmic ray detector is required.

Scattering by the ionization electrons in the dense terrestrial atmosphere. A less known type of radar, bistatic radar, exhibits a strong enhancement in the RCS at forward directions. We present results of expected received power calculations for a bistatic radar used in the detection of extensive cosmic ray showers. The rapid movement of the shower front followed by extinction of ionization by Electronegative oxygen contributes to the formation of a phase modulated signal at the receiver. The signal frequency versus time signature is characteristic for the RCS of target, and present results of expected received power calculations for a bistatic radar used in the detection of extensive cosmic ray showers:

2 Modeling Forward Scattering by EAS

For a scattering regime in the far field of the transmitter and receiver the received power is given by:

$$P_{\text{R}} = \frac{P_{\text{T}} G_{\text{T}} G_{\text{R}}}{4 \pi d^2}$$

(1)

where $P_{\text{T}}$ is the received power, $P_{\text{T}}$ is the radar transmitter power, $G_{\text{T}}$ is the receiver (transmitter) station antenna gain, $\lambda$ is the wavelength of the scattered wave, $R_{\text{d}}$ is the distance between transmitter (receiver) and target, and $d$ is the RCS.

Radio waves are transmitted by the free ionization electrons produced by the EAS. We estimate the ionization using the Gaisser-Hillas shower parameterization [8] and the Nishimura-Kamata-Greisen [9, 10, 11] lateral distribution. The elongation rate of shower maximum $X_{\text{max}}$ is taken from CORSIKA [12] assuming a predominantly protonic composition [13]. We assume standard atmosphere from Reference [14]. We also assume that each particle track in the Bethe-Blom high ionizing rate depositing 2.3 eV/eµ/m of the deposited energy goes into producing electron-ion pairs, and a mean ionization energy of nitrogen of 33.8 eV [15].

For an exact calculation the receiver power requires a breakdown of the contribution from each individual electron in the shower before a realistic calculation takes place. Here we will make the approximation that the ionization occurs in a line along the shower axis, i.e. that contributions from the laterally distributed electrons are coherent. For the purpose of calculation, we divide the ionization column into segments of length $d = \lambda / \delta$ where $\delta$ is the wavelength of the incident radio wave. The free electron lifetime is expected to be short ($\sim 10$ ns) at altitudes typical of EAS [16], thus the contribution from each segment diminishes as a function of time. The total power is then the integration of each of these segments that produce an infinitesimal power:

$$dP_{\text{R}} = \frac{P_{\text{T}} G_{\text{T}} G_{\text{R}} e^{-d/\delta}}{4 \pi d^2} rac{1}{\sqrt{2\pi}\delta}$$

(2)

Figure 1: Forward Scattering Radar Geometry

where $q_{\text{R}}$ is the line ionization density calculated as the total number of electrons in a slice of the shower, $d$ is the segment length, $\delta$ the free electron lifetime [16], and $\gamma$ is the number of electrons in Thomson scattering cross section for electrons, and $\varepsilon$ is the electron energy correction due to the vector polarization at the receiver antenna given by the angle between $R_{\text{d}}$ and $R_{\text{t}}$. For the results presented here and for discussions we assume that the calculation of the Thomson scattering is performed with the differential cross sections for scattering by the ionization electrons in the dense terrestrial atmosphere. We assume that the transmitter power is $20$ kW. As for the antenna gains we will use realistic values of $G_{\text{T}} = 25$, $G_{\text{R}} = 4$, $\lambda = 10$ m, $d = 0.8$ m. For a numerical calculation it is very important that all phases are accounted properly especially because of the expected large amplitudes at forward angles. We then have to add amplitudes rather than power, in which case we use the relationship

$$V = \sqrt{2} Z_{\text{i}} \sin(\alpha ÷ \beta)$$

(3)

where $Z_{\text{i}}$ is the input impedance of the radio receiver, and $\alpha$ accounts for the phase of the scattering segment.

As noticed by Underwood [22], because the air shower front propagates at the speed of light, the forward scattered radar echo will undergo phase modulation and a substantial frequency shift as shown in Figure 3 (right panel). For the present geometry, this shift is manifest as a downward “chirp” of several tens of MHz in frequency. While this feature of the air shower echo signal will require large bandwidths to resolve, its uniqueness allows for triggers schemes which can identify chirp candidates in real time. Further, the geometrical dependence of these echoes will contribute to the reconstruction of astrophysically interesting air shower parameters as shown in Figure 4.

Figure 4: Peak frequency versus time for bistatic radar echoes from vertical EAS, located on a line connecting a 54.1 MHz transmitter to a receiver 50 km distant. The three graphs are for EAS 45, 30, and 15 km distant from the transmitter.

4 Conclusions

The calculations presented here represent an advance in the understanding of EAS radar echoes, and provide important feedback for the design of radar observatories. They support the idea that the greatest scattered power lies in the forward direction, and that therefore bistatic techniques hold the most promise for success. EAS radar echoes should be detectable by small antennas, which can be deployed due to the one currently under construction at the Telescope Array [19]. While the rapid frequency shift poses technical challenges, it also provides a unique signature allowing real-time triggering and may ultimately prove important in using echoes to reconstruct EAS geometry.

References

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