Forward Scattering Radar for Ultra High Energy Cosmic Rays

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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 low 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 ionization produced by extensive cosmic ray showers and will provide an optimal discrimination against spurious events.

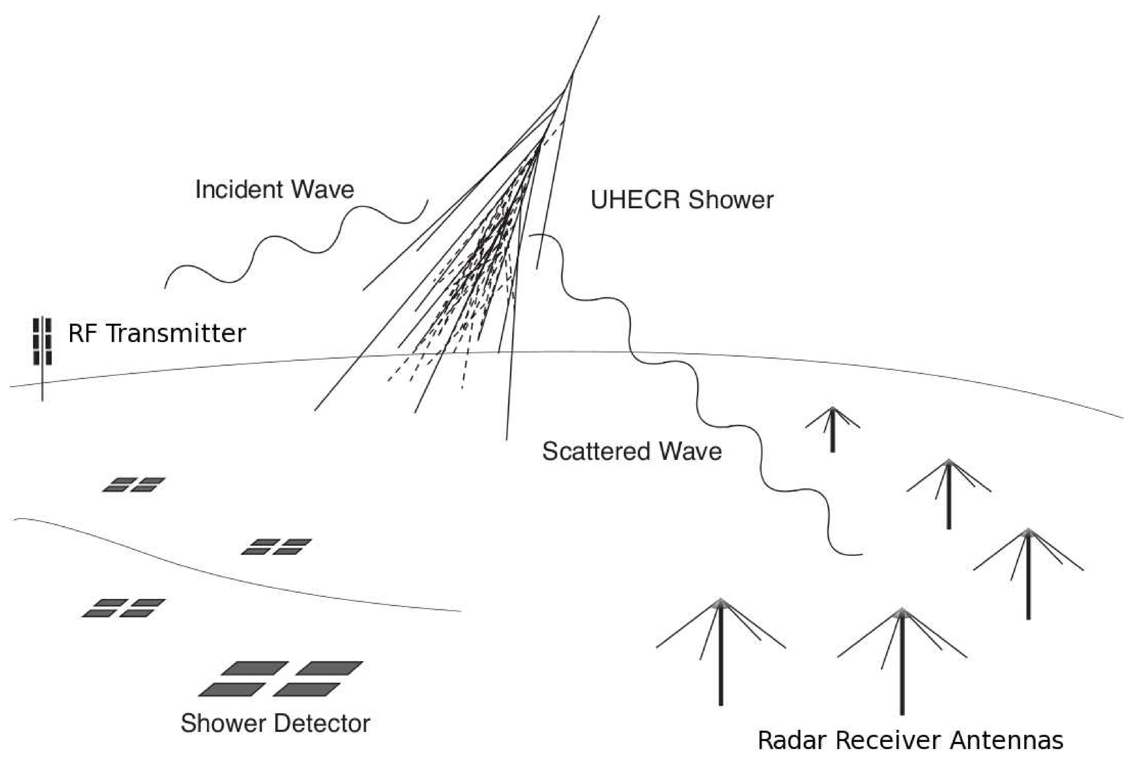
1 Introduction

The study of Ultra-High Energy Cosmic Rays (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 an 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 radar.

The "monostatic" or back-scattered radar detection 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 Terasawa *et al.*, using the pulsed 1 MW MU-Radar, normally used for the detection of micrometeors [7]. A few signals of very short duration compatible with cosmic ray activity were observed, but confirmation with a conventional cosmic ray detector is required.

Here, we present calculations considering a second possibility, the forward scattering or "bistatic" radar, in which case the transmitter is located far from the receiver and a Fraunhofer diffraction pattern is generated when an object appears between the two. The main advantage of bistatic radar is the increase in the radar cross section (RCS) in the forward direction. A typical experimental geometry is illustrated in Figure 1.

Figure 1: **Forward Scattering Radar Geometry**



2 Modeling Forward Scattering by EAS

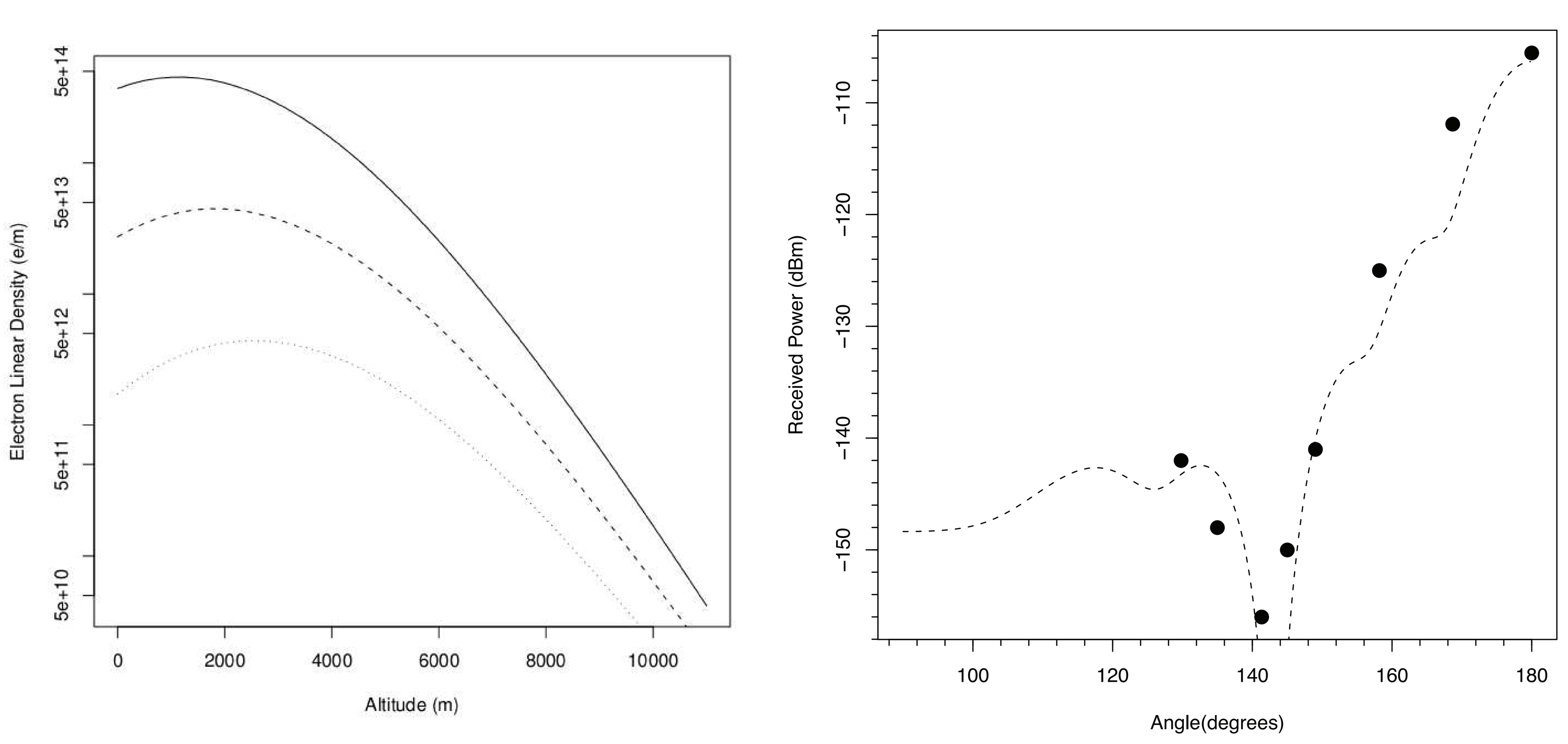
For a scattering regime in the far field of the transmitter and receiver the received power is given by:

$$P_R = \frac{P_T G_T G_R \lambda^2 \sigma}{64\pi^3 R_T^2 R_R^2} \tag{1}$$

where P_R, is the received power, P_T is the radar transmitter power, G_R (G_T) is the receiver (transmitter) station antenna gain, λ is the wavelength of the scattered wave, R_T (R_R) is the distance between transmitter (receiver) and the target, and σ is the RCS.

Radio waves are Thomson scattered by the free ionization electrons produced by the EAS. We estimate the ionization using the Gaisser-Hillas shower parametrization [8] and the Nishimura-Kamata-Greisen [9, 10, 11] lateral distribution. The elongation rate of shower maximum X_{max} is taken from CORSIKA [12] assuming a primarily protonic composition [13]. We assume standard atmosphere from Reference [14]. We also assume that each particle track is in the Bethe-Bloch minimum ionizing regime depositing 2.3 eV/g/cm^2, that all of the deposited energy goes into producing electron-ion pairs, and a mean ionization energy of nitrogen of 33.8 eV [15]. Figure 2 (left panel) shows the ionization line density for three energies and for an angle of $30°$ with respect to the zenith.

Figure 2: **Left: Electron line density for** 10^{20} **(solid),** 10^{19} **(dashed), and**10^{18} **eV (dotted) extensive air showers, at an angle of** $30°$ **with respect to the zenith. Right: Comparison between integration and geometrical approaches. Points are for the integration and dashed line for a geometrical calculation.**



An exact calculation for the received power requires the integration of the contribution from each individual electron in the shower before attachment 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 $ds = \lambda/10$ where λ is the wavelength of the incident radio wave. The free electron lifetime is expected to be short (~ 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 from each of these segments that produce an infinitesimal power:

$$dP_R = \frac{\kappa P_T G_T G_R \lambda^2 \sigma_e \sin^2 \gamma \; q e^{-t/\tau} ds}{64\pi^3 R_T^2 R_R^2} \tag{2}$$

where q is the line ionization density calculated as the total number of electrons in a slice of the shower, ds is the segment length, τ the free electron lifetime [16], and κ the dampening due to multiple scattering [5, 17]. σ_e is the Thomson scattering cross section for electrons, and γ in the equation takes care of the vector polarization at the receiver antenna given by the angle between $\vec{R_T}$ and $\vec{R_R}$. For the results presented here and for discussions we choose an experiment with a transmitter and receiver separated by 50 km at an elevation of 1,420 meters M.S.L., and a transmitter power of 20 kW. As for the antenna gains we will use realistic values of $G_T = 25$, and $G_R = 4$.

For a numerical calculation it is very important that all phases are accounted properly especially because of the expected positive interferences at forward angles. For phasing we need to add amplitudes rather than power, in which case we use the relationship

$$V = \sqrt{P \cdot Z_i} sin(\omega t - \phi) \tag{3}$$

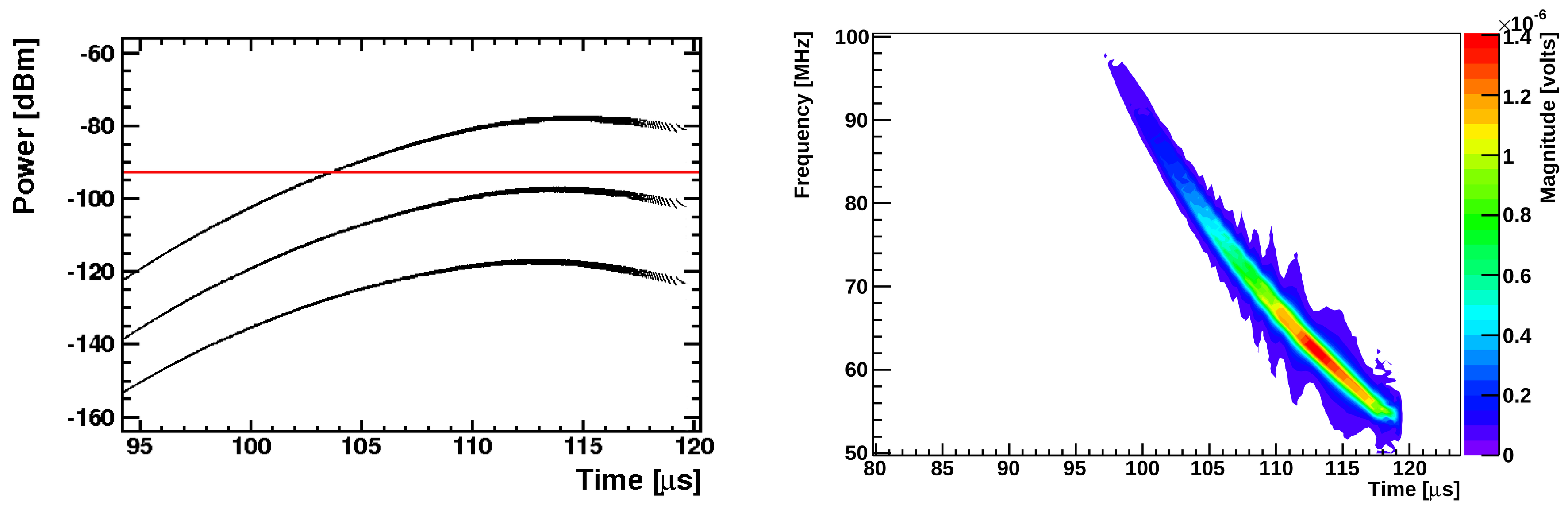
where Z_i is the input impedance of the radio receiver, and ϕ accounts for the phase of the scattering segment.

In Figure 2 (right panel) we make a test of this method by integrating a 40 m long segment using the approach above described and compare it to what we expect from a geometrical calculation [18]. We conclude that the integration method is equivalent to a geometrical calculation with good agreement. The calculation also illustrates the expected signal enhancement in the forward direction.

3 Results

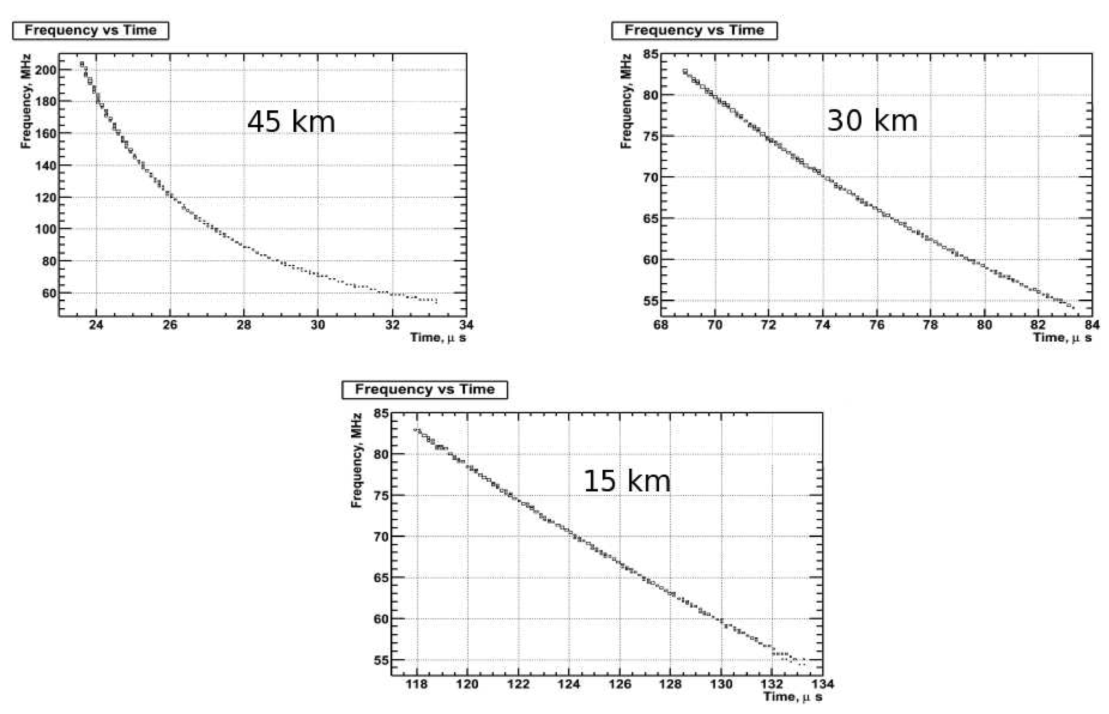
The integration of Equation 2 for extended air showers yields waveforms at the receiver input. Figure 3 (left panel) shows the expected received power for cosmic rays of three different energies, and a geometry and conditions typical for a proposed bistatic radar observatory [19].

Figure 3: **Left: 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. Transmitter antenna gain is 25 (14 dB) referenced to isotropic, and receiver antenna gain is 4 (6 dB) referenced to isotropic. The horizontal line indicates the galactic sky noise in the VHF range, integrated over a 4 MHz bandwidth [20, 21]. Right: 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. Transmitter antenna gain is 25 (14 dB) referenced to isotropic, and receiver antenna gain is 4 (6 dB) referenced to isotropic.**



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 trigger 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 radar observatories such as 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.

This work is supported by the U.S. National Science Foundation grant PHY-0969865.

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