



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.

Keywords: cosmic rays, radar

1 Introduction

The study of cosmic rays at extreme energies ($E > 10^{19}$ eV) requires detectors with very large aperture. Two of the largest detectors using hybrid technologies in operation today are the Telescope Array (800 km²) [1] and the Pierre Auger Observatory (3000 km²) [2]. At these apertures the detection rate of the highest energy cosmic rays, $E \gtrsim 10^{19}$ eV is only a few per day. To detect the highest energy cosmic rays and explore the existence of other particles and processes such as high energy neutrinos [3], mini-black holes produced in the atmosphere [4], detectors with much larger aperture will be required. One technology that could be explored for their detection is radar.

The concept of implementing a radar for cosmic ray detection was first discussed by Blackett and Lovell in 1940 [5]. The original concept was to use a monostatic (ranging) radar to detect echo from the ionization produced by the extensive atmospheric shower. The initial estimates for the return power made by Blackett and Lovell indicated that it would be possible to detect showers produced by $E \gtrsim 10^{15}$ eV cosmic rays. However, we know today that these estimates were overly optimistic. As Sir Bernard Lovell describes in his 1993 memoirs [6], shortly after the publication of their initial work, L. Eckersley (see Ref. [6]) noted that the electron multiple scattering by neutral molecules attenuates the return power by as much as 30 dB. That would put the detection threshold at $E \sim 10^{20}$ eV for the best technology at that time for a 100 kW radar transmitter.

K. Suga in 1962 independently reached the same conclusion and points to the need for high gain antennas and perhaps new technologies to deal with weak signals (a few dB above sky noise) [7]. Recently, Gorham discussed a second issue that needs to be considered for the description of the return signal: the short free electron lifetime [8]. Electron attachment to molecular O_2 quickly depletes the free electrons which are responsible for the scattering, shortening the signal duration. Therefore the literature suggests that monostatic radar would be feasible if operated with high power transmitters (> 100 kW) and with directional antennas (gain = 30 dBi). In fact experimental efforts to detect Extensive Air Showers (EAS) were made by several authors including a recent attempt made by Terasawa *et al.*, using the MU-Radar, a pulsed 1 MW radar used for the detection of micrometeors [9]. A few signals of very short duration compatible with cosmic ray activity were observed, but confirmation with a conventional cosmic ray detector is required.

In the early days of radar a second type of radar implementation, the forward scattering or “bistatic” radar, was also popular [10]. In this type of radar the transmitter is located far from the receiver and a Fraunhofer diffraction pattern is generated when an object appears between the two. The bistatic radar presents one advantage over the back scatter radar: an increase in the radar cross section (RCS) of order $4\pi A^2/\lambda^2$, where λ is the electromagnetic wave wavelength and A is the target object’s cross sectional area. This represents a substantial gain, and depending on the geometry

it can be as high as ~ 30 dB. As most of the technological issues concerning synchronization at large distances is now possible, *e.g.* using GPS conditioned clocks, the gain that is attainable makes forward scattering radar a good candidate for the detection of extensive atmospheric 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:

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

where P_R is the received power, P_T is the radar transmitter power, G_R is the receiver station antenna gain, G_T is the transmitter station antenna gain, λ is the wavelength of the scattered wave, R_T is the distance between transmitter and the target, R_R is the distance between the target and the receiver, and σ is the RCS, a function of the scattering angle and the target's characteristic size.

The concept of detecting EAS via radar is based on the principle of scattering radio waves from the atmospheric ionization produced by the energetic charged particles within the shower. It is the Thomson scattering by the free ionization electrons that produce the scattered waves. The number of ionization pairs per unit volume, electron and positive ions, is estimated using the Gaisser-Hillas shower parametrization [11] and the Nishimura-Kamata-Greisen [12, 13, 14] (NKG) model for the lateral distribution. The elongation rate of shower maximum X_{max} is taken from CORSIKA [15] assuming a primarily protonic composition [16]. We assume standard atmosphere from Reference [17]. We also assume that each particle track is in the Bethe-Bloch minimum ionizing regime depositing 2.3 eV/g/cm², that all of the deposited energy goes into producing electron-ion pairs, and a mean ionization energy of nitrogen of 33.8 eV [18].

Figure 1 shows the ionization line density (the integral of all ionization along the shower axis) for three energies and for an angle of 30° with respect to the zenith. As the energy increases the elevation of the shower maximum decreases and approaches sea level. All of the ionization is produced in the lower part of the troposphere ($h < 25$ km), where three main considerations should be taken into account: (a) short free electron lifetime, (b) electron multiple collision with neutral molecules, and (c) the low density ionization cloud that will surround the heavily ionized core. The short free electron lifetime is caused by the attachment process to the molecular O_2 . According to Vidmar [19] the free electron lifetime at sea level is approximately 10 ns, increasing quickly with altitude. The electron multiple collision with neutral molecules will cause an overall damping of the scattered wave. The media around the shower core is also ionized in a lesser degree, and it might represent a strong diffractive media.

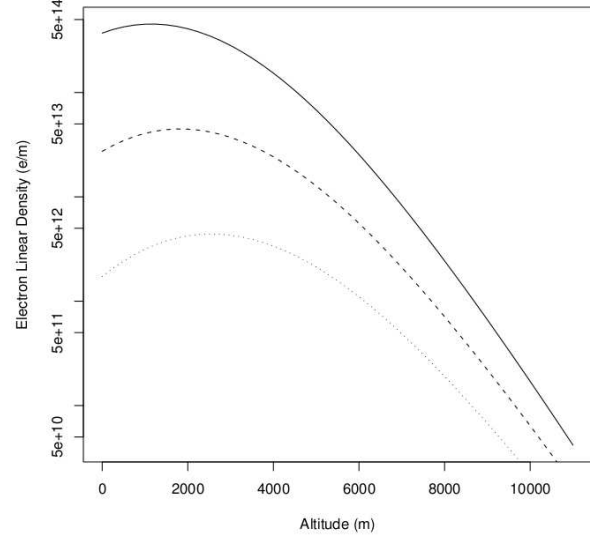


Figure 1: **Electron line density for 10^{20} (solid), 10^{19} (dashed), and 10^{18} eV (dotted) extensive air showers, at an angle of 30° with respect to the zenith.**

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 contribution from each segment diminishes as function of time due to recombination. The total power is then the integration from each of these segments that produce an infinitesimal power:

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

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 [19], and κ the dampening due to multiple scattering [7, 20]. 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 $G_R = 4$ with respect to isotropic.

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

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

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

Before presenting results on the integration of showers, 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. For the geometrical calculation we use a conical shape object as discussed previously and use the formalism given by Glaser [21]. The 40 m long segment is a section of the shower maximum and all quantities are taken at that altitude. Figure 2 shows the comparison between two methods where no normalization was applied between the two. From this study we conclude that the integration method is equivalent to a geometrical calculation with good agreement.

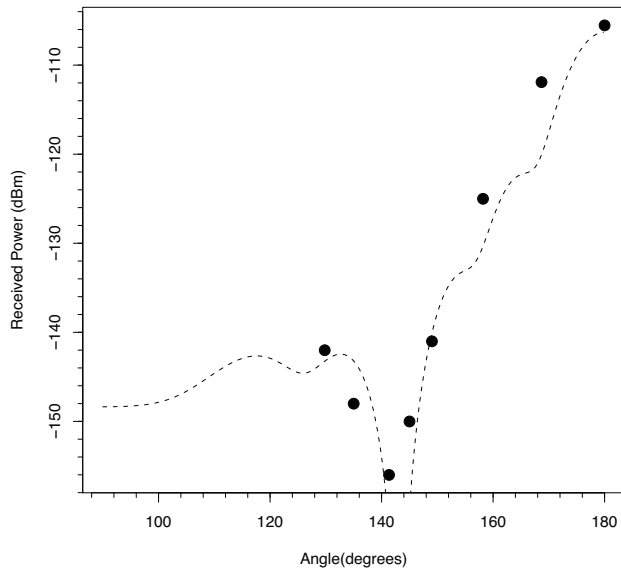


Figure 2: Comparison between integration and geometrical approaches. Points are for the integration and dashed line for a geometrical calculation.

The calculation also shows that the expected enhancement will happen mostly in the forward direction, which is approximately $\pm 15^\circ$. The agreement between the two also indicates that the line approximation is acceptable for an estimate, especially in the forward direction.

3 Results

The integration of Equation 2 for extended air showers yields waveforms at the receiver input that allow us to examine the total received power relative to sources of noise, and differences in signal shape due to primary cosmic ray energy and air shower scattering geometry. Figure 3 shows

the expected received power for cosmic rays of three different energies, and a geometry and conditions typical for a proposed bistatic radar observatory [22].

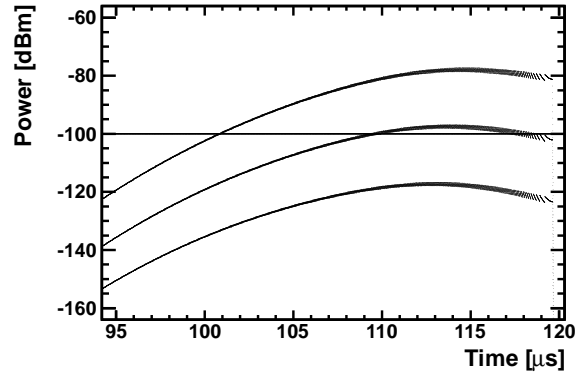


Figure 3: Calculation of received power (referenced to milliwatts) for echoes off of air showers initiated by 10^{20} eV (top), 10^{19} eV (middle), and 10^{18} eV (bottom) primary cosmic rays. Transmitter power is assumed to be 20 kW. The air showers are midway between 54.1 MHz transmitter and receiver 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 [23, 24].

For a signal to be detectable it is (to first order) necessary that it is above the minimum achievable noise given by the sky noise:

$$N_g = kT_{sky}B_n \quad (4)$$

where k is Boltzman's constant, T is the sky temperature and B_n is the receiver bandwidth. (In some scenarios it may be possible to identify signal patterns below the noise, see *e.g.* Reference [22] for a proposed scheme.) In the low-VHF band, the dominant source of sky noise is the Milky Way Galaxy, with an effective temperature of several thousand Kelvin [23, 24]. The galactic background noise is compared with the signal in Figure 3.

As noticed by Underwood [25], 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 4. For the geometries which we consider here, the propagating shower is shortening the transmitter \rightarrow target \rightarrow receiver distance at a decreasing rate, thus the typical airshower echo will be manifest as a downward "chirp" of several tens of MHz in frequency which terminates close to the transmitter frequency. While this feature of the air shower echo signal will require large bandwidths to resolve, its uniqueness may allow 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.

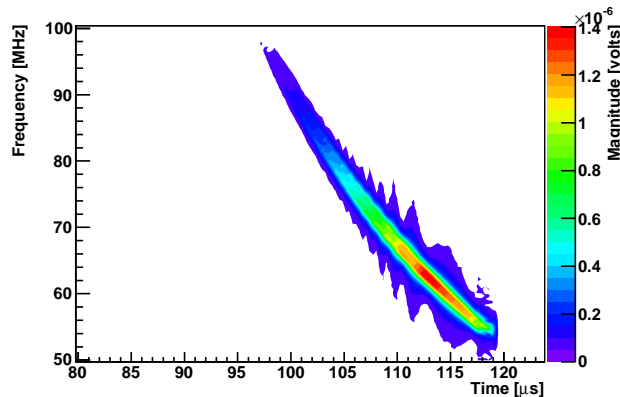


Figure 4: Spectrogram of “chirp” for simulated air shower, initiated by 10^{19} eV cosmic ray midway between 54.1 MHz transmitter (TX) and receiver (RX), located 50 km apart. The shower is inclined at a zenith angle of 30° in a plane perpendicular to a line connecting transmitter and receiver. Transmitter antenna gain is 25 (14 dB) referenced to isotropic, and receiver antenna gain is 4 (6 dB) referenced to isotropic.

4 Conclusions

We have presented new calculations of the nature of air shower radar echoes, via phase analysis of scattered radio frequency radiation. The calculations presented here provide important feedback for the design of radar observatories. They support the idea resulting from geometrical optics analysis, that the greatest scattered power lies in the forward direction within approximately $\pm 10^\circ$ of the incident radiation. Thus forward-scattered or “bistatic” techniques hold the most promise for success.

We have also shown that radar echoes are expected to be characterized by a rapid phase modulation-induced frequency shift, covering several tens of MHz in 10–15 μsec . While this feature poses challenges, these challenges are surmountable with current radio receiver technology and may in fact prove to be an asset: The chirp is a unique signature of air showers, and thus may be used for real-time triggering. Also, since the chirp rate itself is tied to air shower location, zenith and azimuthal angles, it may ultimately prove important in the reconstruction of air shower geometry.

These calculations show that the air shower echoes should be detectable by radar observatories such as the one currently under construction at the Telescope Array [22], which is described elsewhere in this conference. Radar is thus a plausible remote detection technology for air shower observations which could cover large areas of the Earth’s

surface at a fraction of the cost of conventional detection methods.

5 Acknowledgments

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

References

- [1] J.N. Matthews *et al.*, proceedings of this conference.
 - [2] J. Abraham *et al.*, proceedings of this conference.
 - [3] V.S. Berezinsky and G.T. Zatsepin, *Phys. Lett.* **28B** 423 (1969); *Sov. J. Nucl. Phys.* **11** 111 (1970).
 - [4] J.L. Feng and A.D. Shapere, *Phys. Rev. Lett.* **88** 021303 (2002).
 - [5] P.M.S. Blackett and A.C.B. Lovell, *Proc. Roy. Soc.* **A177** 183 (1940).
 - [6] A.C.B. Lovell, *Rec. R. Soc. Lond.* **47** 119 (1993).
 - [7] K. Suga, *Proc. Fifth Interamerican Sem. on Cosmic Rays*, La Paz, Bolivia, XLIX-1 (1962).
 - [8] P.W. Gorham, *Astropart. Phys.* **15** 177 (2001).
 - [9] T. Terasawa *et al.*, *Proc. 31st Intl. Cosmic Ray Conf.*, Lodz (2009).
 - [10] Nicholas J. Willis, *Bistatic Radar*, Scitech Publishing Inc. (1995).
 - [11] T.K. Gaisser and A.M. Hillas, *Proc. 15th ICRC, Plovdiv, Bulgaria* **8** 353 (1977).
 - [12] K. Kamata, J. Nishimura, *Suppl. Progr. Theoret. Phys* **6** 93 (1958).
 - [13] K. Greisen, in J. G. Wilson (Editor) *Prog. Cosmic Ray Physics.*, Vol. III, North Holland, Amsterdam, 1965,1
 - [14] T. AbuZayyad, C.C.H. Jui and E.C. Loh, *Astropart. Phys.* **21** 163 (2004).
 - [15] D. Heck and J. Knapp, Forschungszentrum Karlsruhe, Tech. Report (2001).
 - [16] R.U. Abbasi *et al.*, *Phys. Rev. Lett.* **104** 161101 (2010).
 - [17] *U.S. Standard Atmosphere* U.S. Government Printing Office, Washington, D.C. (1976).
 - [18] International Commission on Radiation Units and Measurements (ICRU) Report 31 (2007).
 - [19] R.J. Vidmar, *IEEE Trans. on Plasma Science* **18** 733 (1990).
 - [20] K.G. Budden, *The Propagation of Radio Waves*, Cambridge University Press (1985).
 - [21] W. Glaser, *Z. Phys.* **80** 450 (1933).
 - [22] M. Abou Bakr Othman *et al.*, proceedings of this conference.
 - [23] H.V. Cane, *Mon. Not. R. Astr. Soc.* **189** 465 (1979).
 - [24] J.F. Heagy, J. Iams, and J.M. Ralston, *Institute for Defense Analysis, Paper P-3395* (1988).
 - [25] D. Underwood, *IEEE Conference Proceedings, Radar Conference* (2008).
- <http://ieeexplore.ieee.org>, archive 04721089.