Proposed experiment to detect air showers with the Jicamarca radar system

T. Vinogradova[1], E. Chapin[1], P. Gorham[1], D.Saltzberg[2]

[1] *Jet Propulsion Laboratory, Calif. Inst. Of Technology, Pasadena, CA 91109*
[2] *Department of Physics and Astronomy, University of California, Los Angeles, CA 90095*

Abstract. When an extremely high energy particle interacts in the atmosphere, the collision induces a multiplicative cascade of charged particles, which grows exponentially until the energy per secondary degrades enough to dissipate in ionization of the surrounding air. During this process the compact cloud of energetic secondary particles travels 10-20 km through the atmosphere, leaving a column of ionization behind it. This ionized column quickly recombines, but for a period of order 0.1 ms it is highly reflective at frequencies below 100 MHz. This ionization trail, which is comparable in ionization density to that of a micro-meteor, should be clearly detectable using standard radar methods. We propose radar measurements using the facilities operated by Cornell University and the Instituto Geofisico del Peru (IGP) at the Jicamarca Radio Observatory near Lima, Peru. This facility's primary instrument is 49.92 MHz incoherent scatter radar, transmitting up to 1.5 MW of pulse power.

I RADAR DETECTION OF IONIZATION COLUMNS

A detailed description of the physics and phenomenology of radar detection of air shower ionization is available in a recent paper. [1] Here we extract the major results of this work. For radar detection of the columns that result from meteors, extensive air showers (EAS) events, or lightning, there are two regimes to consider, depending on the plasma frequency, ν_p of the ionized region:

$$\nu_p = \sqrt{(n_e e^2)/(\pi m_e)} \ = \ 8.98 \times 10^3 \sqrt{n_e} \text{ Hz}, \tag{1}$$

where n_e is the electron density in cm^{-3}. These two regimes are known in as the under- and over-dense regimes, respectively, and traditionally (in the meteor radar literature) are divided at the line density of $\alpha = 10^{14}$ m^{-1}. However, because of the significant differences in the radial distribution of the electrons in EAS ionization compared to that of meteors, we distinguish them only on the basis of the ratio of radar frequency to plasma frequency, a distinction that is also common to radar lightning measurements. Thus we will consider the over-dense portion of an ionization column to be that region where the electron density is high enough that the plasma frequency exceeds the radar frequency, and the radar cannot penetrate it and is reflected. Underdense columns are those, which have electron densities such that the local plasma frequency is below the frequency of the incoming radar, which can therefore penetrate the ionized region, and will then scatter with varying degrees of partial coherence from the volume of free electrons present.

Given an estimate for the electron density and its radial profile [1], the radar cross section of the ionization column at a given radar frequency can be parameterized as following for over- (σ_b^{od}) and under- (σ_b^{ud}) cases. This parameterization shows the result for a horizontal shower at 10 km altitude:

$$\sigma_b^{od} = 2.6 \times 10^4 (f/30\ \mathrm{MHz})^{-1.45} (E/10^{20}\mathrm{eV})^{0.44} (R/10\ \mathrm{km})\mathrm{m}^2 \tag{2}$$

$$\sigma_b^{ud} = 33 (f/30\ \mathrm{MHz})^{-1.84} (E/10^{20}\mathrm{eV})^{1.9} (R/10\ \mathrm{km})\mathrm{m}^2, \tag{3}$$

where is f the radar frequency, E is the shower energy and R is the range in km.

The radar returned power, P_r is described in terms of a model where the radiation is emitted from an antenna with peak transmitted power, P_t and directivity gain $G = 4\pi\Omega_A^{-1}$, where Ω_A is the solid angle of the main beam of the antenna. In terms of the effective radar backscatter cross section, σ_b, transmitting and receiving system efficiency,η, the resulting returned power [2] is

$$P_r = P_t \sigma_b \eta \frac{G^2 \lambda^2}{(4\pi)^3 R^4}. \tag{4}$$

The noise power of the radar system is given by $P_N = kT_{sys}\Delta f$, where T_{sys} is the system noise temperature, k is Boltzmann's constant and Δf is the effective receiving bandwidth. Combining the noise power equation above with equation for radar-received power one can write the signal-to-noise ratio (SNR) as

$$\frac{P_r}{P_N} = \sigma_b P_t \eta \frac{G^2 \lambda^2}{(4\pi)^3 R^4} \frac{1}{kT_{sys}\Delta f} \tag{5}$$

Given the above equation, the problem of detectability of the ionization columns, initiated by EAS reduces to evaluating of the effective radar cross section (RCS) for a given choice of operating parameters for radar system and to tuning radar system parameters to achieve the highest efficiency in experiment.

II PROPOSED JICAMARCA EXPERIMENT

From the parameterization for the radar cross section for detecting the ionized column from the cosmic-ray showers and from the estimates of the plasma frequency of the shower cores described above, it follows that the most promising regime for investigating radar echoes from EAS is in the HF to VHF range. In addition, because of a large uncertainty in the magnitude of the echoes, a transmitter system with the highest possible pulse power should be used. For these reason we

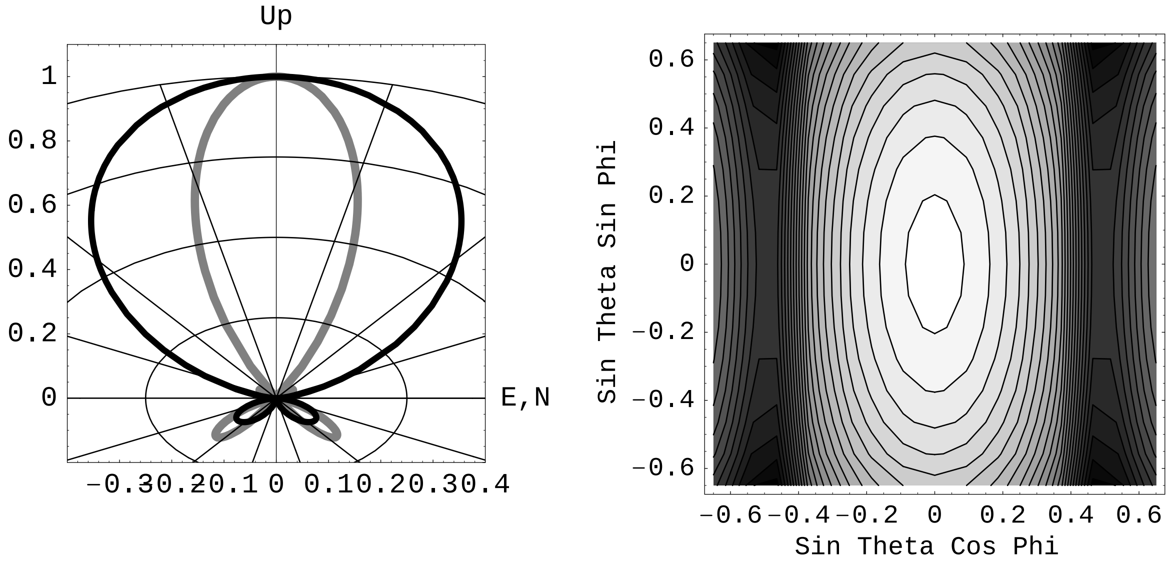

FIGURE 1. (a) Principal plane radiation patterns for Jicamarca "mattress" array. Light gray curve corresponds to the Up-East plane pattern, dark gray curve - to the Up-North. (b) Expanded view of the central region of the polar diagram. Contours are in 2 dB steps.

propose to perform the observations at the Jicamarca Radio Observatory, a facility sponsored by the National Science Foundation and operated by Cornell University near Lima, Peru.

The Observatory is the scientific facility for studying the equatorial ionosphere. It has a 1.5 MW transmitter and a main antenna with 18,432 dipoles covering an area of nearly 85,000 square meters. It is located at geographic latitude of 11.95° south and a longitude of 76.87° west (Peru). There are three additional 50 MHz "mattress" array antennas steerable to ±70° zenith angles in the east-west direction only. Each consists of 4×2 half-wave dipoles mounted a quarter wavelength above a ground screen. Two of these arrays can handle high powers. We are proposing to use the "mattress" array for detection of radar echoes from the cosmic ray showers.

The dipoles in the array are arranged in a group of four with a spacing of $\lambda/4$, where is a dipole wavelength. The spacing between 2 groups of 4 dipoles is $\lambda/2$. The principal plane patterns which are profiles along the East and North directions are shown in Figure 1a. Dark gray profile corresponds to the Up-North principal plane and the light gray profile corresponds to the Up-East plane. The half-power beam width is 0.3 rad in the North-Up plane and 0.8 rad in the East-Up plane. Figure 1b shows the polar diagram of the radar beam when oriented to transmit vertically, as predicted by numerical model. Antenna beam solid angle is 0.44 sr for the "mattress" array. The instrument parameters proposed for our observations are listed in Table 1.

Fixed parameter	Value
Transmitter pulse power	1.5 MW
Wavelength	6 m
Main beam lobe diameter	$0.3 - 0.8$ rad
Antenna gain	20.0 dB
Effective bandwidth	1 MHz
Duty cycle	6%
Tunable parameters	**Value**
Pulse duration	$10^{-6} - 10^{-3}$ s
Pulse rep. interval	0.2 m
Num, pulses	$1 - 100$

TABLE 1. Fixed and tunable parameters of the system.

In order to avoid decoding difficulties we propose using a simple square pulse with a width of 1 μs and the pulse repetition interval (PRI) of 0.2 ms, which corresponds to a one-way unambiguous sampling region up to 30 km altitude range. The resulting signal to noise ratio (SNR) can be written in the following parameterization:

$$\frac{S}{N} = 132(\frac{\sigma_b}{1\mathrm{m}^2})(\frac{P}{10\mathrm{kW}})(\frac{\eta}{0.1})(\frac{G}{10})^2(\frac{\lambda}{6\mathrm{m}})^2(\frac{R}{10^4\mathrm{m}})^{-4}(\frac{T_{sys}}{10^3\mathrm{K}})^{-1}(\frac{\Delta t}{10\mu\mathrm{s}}), \tag{6}$$

where P is the pulse power, η the efficiency after losses, G the directivity gain of the antenna, T_{sys} the system thermal noise temperature, and Δt is the pulse duration. Figure 2 shows curves of the calculated RCS at 50 MHz as a function of initial cosmic ray energy for the different altitudes. The lowest through highest curves correspond to 10, 15 and 20 km altitudes, respectively. The showers are assumed to be propagating horizontally.

The other important issue for determining the efficiency of the proposed technique is the nature of the background noise. In the HF-VHF regime the effective background noise temperature for a remote site can be written as [2] $T_{\mathrm{bkg}} = 2.9 \times 10^6 (f/3\ \mathrm{MHz})^{-2.9} K$ which yields 830 K at 50 MHz. Considering a receiver noise in the range of 150 K, an overall system noise temperature of 1000 K is achievable at the Jicamarca site.

Using these assumptions and the discussed beam pattern above, we show an example SNR budget, in dBm (decibels referenced to 1 milliwatt) in Table 2. This is derived from numerical evaluations of the RCS for a horizontal shower of the energy 10^{19} eV, at an altitude 17 km and distance 50 km from the transmitter. These chosen parameters correspond to the beam pointing angle of 20 degrees above the horizontal plane with the maximum range of observation up to 175 km at altitudes up to 60 km.

To estimate the total number of the expected events above the given primary energy of the cosmic ray shower we use the same configuration as listed in Table 1.

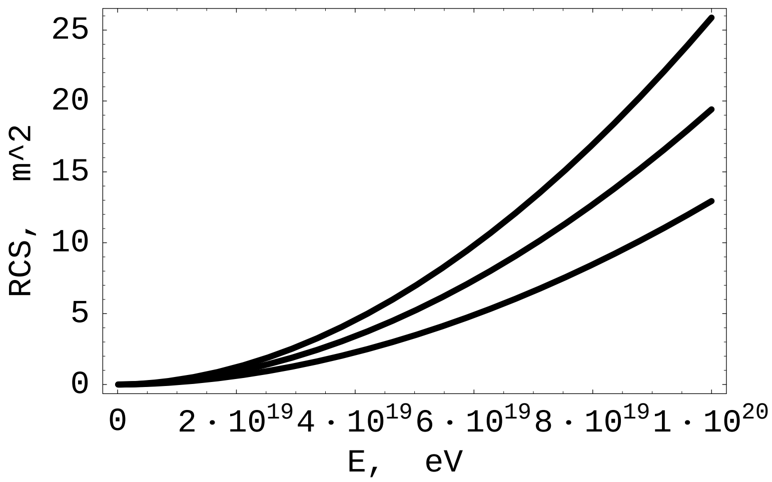

FIGURE 2. RCS for horizontally propagating showers at 10, 15 and 20 km altitudes (lowest to highest curves).

We required SNR to be more than 5.0 for the detection and estimated the effective aperture of the system based on the radiation beam profile as described above. From the energy spectrum for the ultra high-energy cosmic rays we calculated the flux of the particles as a function of energy per seconds per volume element (volume element in sr-cm^2 units). Based on the required SNR for the detection we determined the maximum range of the detection and integrated this range over projected beam area. The number of expected events for the period of observation is then the expected flux per energy bin for the time period mulitplied by the effective volume of the system (which is range-dependent as described above). Figure 3 shows the results of our estimation for 80 hours of the run time.

There are several uncertainties and possible risks for the proposed experiment. One of them is related to detailed understanding of the lifetime of the free electrons produced in the air shower ionization column; in fact radar detection of EAS events can provide independent measurements of these quantities or the limits if they cannot be detected. The other class of uncertainties is related to the ground clutter and the scattering effects. Ground-wave refraction and scattering cannot be accurately assessed until the experimental conditions are seen, and such clutter may significantly impact the SNR and usable range gate for our observations. We are going to collect data at Jicamarca during two runs of 40 hours each to demonstrate the efficacy of the technique to better estimate the lifetime of the air showers.

1. Gorham, P. W., 2000, Astropart.Phys. **15**, 177 (2001).
2. Skolnik, M.I., ed., Radar Handbook, 2nd ed., New York; McGraw-Hill, 1990.

Parameter	Value
Received power:	
Pulse power	1.5 MW
Pulse duration	1 μs
Number of repetitions	1
Antenna gain	20.0 dB
Wavelength	6 m
RCS at 10^{19} eV	0.82 m^2
Range to EAS	50 km
Loss factor	0.1
Noise power:	
System temperature	1000 K
Effective bandwidth	1 MHz
SNR	10.5

TABLE 2. SNR budget for one possible configuration of Jicamarca system.

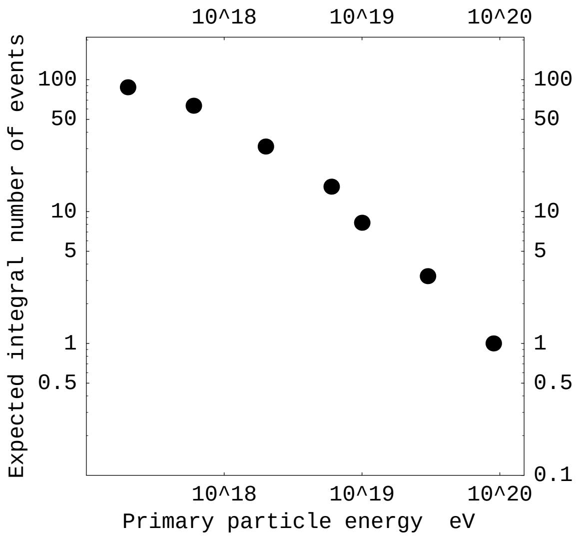

FIGURE 3. Predicted rates of the detected ultra-high energy cosmic ray showers with the Jicamarca system for a 6-days run.