The search for vertical extended air shower signals at the Jicamarca Radio Observatory

D. WAHL[1], J.CHAU[1], J. BELLIDO[2,3].
[1]*Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima*
[2]*The University of Utah, Department of Physics, Salt Lake City, UT-84112, USA*
[3]*The Pennsylvania State University, 104 Davey Laboratory, University Park, PA-16802, USA*
cosmicrays@jro.igp.edu.pe

Abstract: The detection of cosmic rays by radar relies on the reflection of radio waves by the ionisation the EAS produces in the atmosphere. High power mono-static radars like the Jicamarca Radio Observatory (http//jro.igp.gob.pe) are excellent instruments to look for extended air showers (EAS) in the case that the reflected signals are weak. The following paper presents algorithms used to look for vertical EAS signals at Jicamarca. The advantage of searching for vertical EAS signals is that their coincidence with particle detectors can easily be verified. Preliminary results searching for these signals in meteor data are presented. Though anomalous signals which ressemble EAS are detected, dedicated EAS runs are required in order to determine their origin.

Introduction

The study of extended air showers (EAS) produced by ultra-high energy cosmic rays has led to the construction of numerous large facilities using different detection methods such as Kascade [1] (scintillator array), HESS [2] (Chérenkov) and the Pierre Auger Observatory [3] (water tank array + fluorescence). Recent progress in radio detection of EAS [4] has prompted a renewed interest in other radio based detection methods, for example using radar echo [5]. The detection of cosmic rays by radar relies on the reflection of radio waves by the ionisation the EAS produces in the atmosphere. As for all EAS detectors, the viability of the technique will depend on its sensitivity and on the possibility of using large surface areas to accumulate sufficient statistics. There exist two types of radar configuration: bi-static (transmitter and receiver in separate locations) or mono-static (transmitter and receiver in the same place). The advantage of the first method is that large areas can be used as a detection volume; however the power of the transmitters is reduced. An example of a proposed cosmic ray experiment based on this design is Mariachi [6]. The advantage of the second method is that high power transmitters can be used, but the area of illumination is small. Examples of cosmic ray experiments using mono-static radars are [7, 8] and current searches at the Jicamarca Radio Observatory (JRO). In both mono-static and bi-static radars, there are multiple background signals which may be misidentified for EAS reflections. A conclusive identification of an EAS could be obtained by observing a coincidence between a positive radar signal and a signal from a detector with known responses to EAS, such as an array of particle detectors. The following paper presents a search algorithm for vertical EAS signals in radar data. Results of preliminary analysis at the JRO are presented.

The Jicamarca Radio Observatory

The JRO consists of 18,432 dipole elements spread over 85,000m^2 close to Lima, Peru. The transmitter operates at 50MHz with a maximum power of 2MW. The antenna is sufficiently remote (and is further shielded by mountains from communication devices) for there to be only a modest background due to human activities. The antennas are divided into 64 modules which can be combined in a variety of ways. All data presented in this paper were acquired using three channels of 4x4 arrays of modules which allows the performance of interferometry. The signal received in each channel is digitised and recorded as a complex voltage. The JRO operates in pulsed mode, where the time between the emitted pulse and the received signal is used to infer the range of the detected object. The range is related to the time difference by:

$$\frac{R_n}{c} = t + n.IPP \tag{1}$$

where IPP is the inter-pulse parameter which is the time difference between successive emitted pulses and n is an integer. An IPP often used at the JRO for meteor trail experiments corresponds to a range of 60km, with a resolution on signals of 150m. The received signal is therefore the sum of the signals from the different ranges (R_n). In order obtain the highest possible power and resolution, the pulses can be coded at emission, and decoded upon reception [9]. Results are presented in range-time intensity (RTI) maps, where the horizontal axis corresponds to the number of IPPs that have passed and the vertical axis is the range[1]. In this paper the contours correspond to the sum of power received in the three channels in arbitrary units. The phase difference between the signal in two modules provides information on the angular location of the point by:

$$\theta_x = sin^{-1}\Big(\frac{-\lambda}{2\pi d_{AB}}\Delta\phi_{AB}\Big) \tag{2}$$

Further information can be retrieved from the phases of the signals, for details on the use of radar interferometry readers are referred to [10]. In the 1941 Blackett and Lovell proposed that signals observed in radars could be due to the ionisation trails produced by EAS [11]. More recently, P. Gorham calculated possible signals due to EAS in radars by comparison with the methods used for the detection of micrometeors (MM) trails [5]. Using narrow beam mono-static radars, the method proposed by Gorham is best suited for the detection of EAS with a path perpendicular to radar beam. It would therefore not be possible to perform the simultaneous detection of particles which could provide conclusive evidence of the cosmic ray origin of the signal. Search algorithms and results for perpendicular path EAS at the JRO will be published elsewhere. Henceforth, the search algorithm will be focused on detecting vertical EAS signals.

Scenarios for the detection of vertical EAS with radar

In mono-static radars, echoes are received when the transmitted pulse is backscattered by electrons. The scattering can be either coherent or incoherent. Specular reflection occurs when the plasma frequency (ν_p):

$$\nu_p = \sqrt{\frac{n_e e^2}{m_e}} \tag{3}$$

is greater than the radar frequency, meaning the radar pulse cannot penetrate the plasma and is reflected at the surface. In such cases, the plasma is said to be in the over-dense regime. Reflection also occurs when the radar pulse penetrates the plasma and comes across a sharp transition in electron density (i.e. change in refractive index). In this case the radar pulse is partially reflected by the volume of a non-homogeneous medium [12]. Incoherent scattering occurs when no coherent effects are observed and the signal strength is the sum of the contributions from individual electrons. Surface type reflections by the EAS front are discarded since the double high blue shift (transmitted wave to EAS front, reflection from EAS front to receiver) would require a radar with low emission frequency and a highly shifted receiver frequency. However, just after the passage of the EAS front, secondary processes occur which result in the rapid creation of near-thermal electrons. Hence the EAS leaves a high number density wake of non-relativistic electrons which could act as a surface reflector for the radar pulse. Whether the wake acts as a surface will depend on the exact mechanisms of the transition between the ballistic phase and the thermal phase. Otherwise, fluctuations in the density of electrons may still be sufficient to cause partial coherent reflections. Finally, if no coherent scattering is observed, a signal may still be received by incoherent scattering as in the case of under-dense plasma. The current paper will focus on the

1. The range is often presented in terms of alias range, i.e. when n≠0 in Eq. 1

ICRC 2007 Proceedings - Pre-Conference Edition

detection of anomalous coherent scattering events which implies algorithms based on detecting reflected power as opposed to Faraday rotation [13]

Requirements for the selection of candidate EAS events

Searches were carried out on JRO meteor data from Feb. 2006. The following requirements are imposed for the selection of events:

1. The event occurs between 20km and 33km of range. 20-33km corresponds to a meteor alias range of 80-93km (n=1 in equation 1). 80km is the lowest recorded range for meteor data and the 93km maximum is chosen to avoid signals from the equatorial electrojet[2].
2. All observed points must be observed coherently where the coherence (C) between all channels is defined by:

$$C = \sqrt{\frac{|\rho_{AB}|}{\left(\frac{|V_A|^2+|V_B|^2}{2}\right)} \times \frac{|\rho_{BC}|}{\left(\frac{|V_B|^2+|V_C|^2}{2}\right)}}$$
$$|\rho_{AB}| = |\langle V_A V_B^* \rangle| \quad (4)$$

3. At least one anomalously high power (AHP) point is observed per event
4. At least three high power (P $>$ AHP/10) points is observed per event
5. The event appears vertically on the RTI map (i.e. that the event is produced by an object travelling close to the speed of light)
6. All detected points are approximately aligned or in a point in the interferometry plot.

In order to estimate which values of coherence and high power are to be considered anomalous, a statistical histogram of coherence versus power was plotted as shown in Fig. 1. The histogram is obtained using only data which is free from other high power signals such as meteors or electrojet fluctuations. Fig. 1 shows a couple of points which lie clear of the area in which most points are found. Using the figure, the power required to fulfil condition (3) is set at 7x10^4. Points with C>0.9 are considered as coherent.

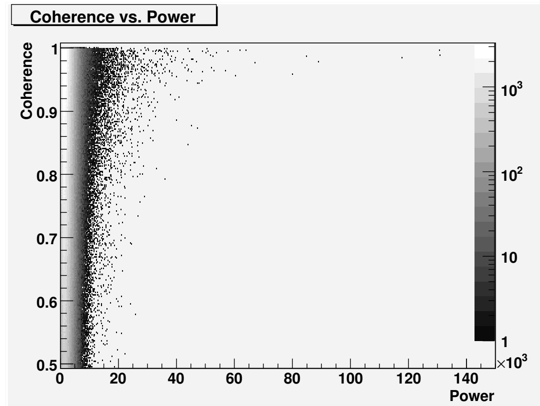

Figure 1: *Coherence versus power histogram for 30 seconds of data. Note: the colours representing bin content go from black (minimum) to white (maximum).*

Discussion of candidate events

The search algorithms return events which do not currently have an explanation in terms of standard events observed at JRO. An example of such an event is shown in Fig. 2. The RTI map of the candidate event shows an event produced by an object moving close to the speed of light and appearing coherently in all three channels. Interferometric measurements shown in Fig. 3 indicate that the points of the event occur nearly vertically. Though the data seems consistent with what could be expected from a vertical EAS, the rate ($\sim$0.1s^{-1}) and altitude (>25km) do not correspond to values typically associated with highest energy cosmic rays. The origin of the signals may be due to cosmic rays of lower energy or to high altitude effects (alias range >80km) which had not previously been studied in high power radars. Dedicated EAS experiments with a longer IPP are planned at the JRO in order to determine the range of the vertical signals.

Conclusions

Suggestions for methods for the detection of EAS using radars have tended to focus on passive bi-

2. For a review of MM parameters, readers are referred to [14].

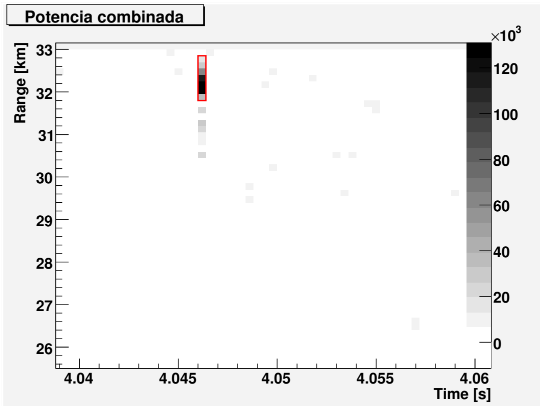

Figure 2: *RTI map of an event selected by the search algorithm. The points vertically below the selected event are due to ambiguity introduced by the coding/decoding process.*

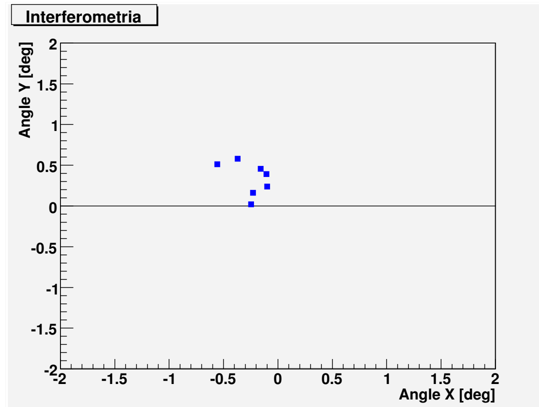

Figure 3: *Interferometry plot of the event selected in Fig. 2*

static radar methods for which the observation of a coincident particle/radar event is difficult. Search strategies for the detection of vertical EAS using the JRO high power radar have been presented. The advantage of searching for vertical EAS signals is that their coincidence with particle detectors can easily be verified. The search strategies require simultaneous conditions of multiple coherent high power points which are aligned in space and occur within one IPP. Candidate events were presented from past JRO meteor run. The events match all the algorithm conditions, however their frequency and range do not correspond to values typically associated with ultra high energy cosmic rays. Dedicated EAS runs at teh JRO are planned in order to lift ambiguities associated with high altitude reflections.

Acknowledgements

The research was performed thanks to funding received by the Instituto Geofísico del Perú. D. Wahl would like to thank K. Dookayka for comments on the radio detection of cosmic rays, as well as B. Degrange and P. Gorham for their useful advice.

References

[1] T. Antoni et al. [Kascade Collaboration]. *Nucl. Instr. Meth.A*, 513:490, 2003.

[2] K. Bernlöhr et al. *Astropart. Phys.*, 20:111, 2003.

[3] J. Abraham et al. [Pierre Auger Collaboration]. *Nucl. Instr. Meth.A*, 523:50, 2004.

[4] T. Huege and H. Falcke. *Astronomy & Astrophysics*, 412:19, 2003.

[5] P.W. Gorham. *Astropart. Phys.*, 15:177, 2001.

[6] D.O. Damazio. *Nucl. Phys. B (Proc Suppl)*, 134:217, 2004.

[7] T. Vinogradova, E. Chapin, P. Gorham, and D. Saltzberg. *AIP Conf. Proc.*, 579:271, 2001.

[8] A. Iyono et al. In *International Cosmic Ray Conference, 28th, Tsukuba, Japan*, page 217, 2003.

[9] J.L Chau et al. *Icarus*, 188:162, 2007.

[10] D.T. Farley et al. *J. Geophys. Res.*, 86:1467, 1981.

[11] P.M.S. Blackett and A.C.B. Lovell. *Proc. Royal Soc. (London) Ser. A*, 177:183, 1941.

[12] R.F. Woodman. *J. Geophys. Res.*, 96:7911, 1991.

[13] D.T. Farley. *Radio Science*, 4:143, 1969.

[14] J.D. Mathews. *J. Atmos. Sol. Phys.*, 66:285, 2004.

ICRC 2007 Proceedings - Pre-Conference Edition