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Can high altitude horizontal air showers be the source of the anomalous radar echoes observed with the high-power large-aperture Jicamarca radar?

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We report on the continuing presence of short duration (t < 10 µs) radar echoes in our datasets. First reported in 2007, these echoes were observed as part of an effort to identify cosmic-ray shower signals in radar data, as per the proposal of Blackett and Lovell. Subsequent experiments such as Mariachi and TARA have reported negative findings, and radar echoes from high density polyethylene point to difficulties in detecting cosmic-rays in the lower atmosphere using radars. The Jicamarca high-power large-aperture 50 MHz radar however is able to search for cosmic-ray showers at higher altitudes (>20km), where horizontal showers could occur. At these altitudes radar clutter is reduced and collisional damping could be less prominent, favouring radar echoes. In this paper we present new data recorded in 2023 (with hardware upgrades since 2007), which show similar signals, from a yet unknown physical source. We outline the plans to investigate the phenomena further.

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1. Introduction

Since the first proposal to detect extended air showers (EAS) by radar [1], the field has received fluctuating attention (see [2] for a recent review). Interest was rekindled by Peter Gorham's paper suggesting that EAS could be detected by a radar such as the one operated by the Geophysical Institute of Peru at the Jicamarca Radio Observatory [3]. Since then, dedicated experiments have been run hoping to find EAS signals in radar echos, for example Mariachi [4] and TARA [5]. However, these experiments did not report positive findings, and the final nail in the coffin came with the SLAC experiment T576, whose results seem to be incompatible with radar detection of reflections off EAS [6]. Nevertheless some hope remains, with proposals for non-reflective detection by radar [7]. And results have been reported from datasets from the IGP-JRO containing anomalous events at high altitudes, which present some expected features of cosmic-ray events (ie. a short duration)[8][9]. In this paper, we present the results of the analysis of data runs from 2023 which show the continued presence of anomalous events, and present statistics to help evaluate whether these events could be caused by EAS.

First, we present the concept of high-altitude horizontal air showers, introduced in [9]. Due to echos from surrounding mountains, the IGP-JRO radar is limited to detecting events occurring above 15 km, but our model proposes that EAS could exist at higher altitudes for paths that are close to horizontal. Next, we present the IGP-JRO and the anomalous events detected there. We then provide statistics on the detected events, which we argue does not definitely rule out radar reflections from high-altitude showers, but does present difficulties for that interpretation. Nevertheless, the events are persistent and unexplained, and warrant further investigation.

2. High Altitude Horizontal Air Showers

Unlike ground-based detectors, radar detectors are not limited to the detection of air showers that reach ground level. Below we show how the slant depth depends on altitude and zenith angle. Primary cosmic-ray interactions are typically assumed to occur between $70 - 100\ g/cm^2$. Fig. 1 presents the basic geometry of a primary cosmic-ray passing above the observatory at altitude h and zenith angle θ.

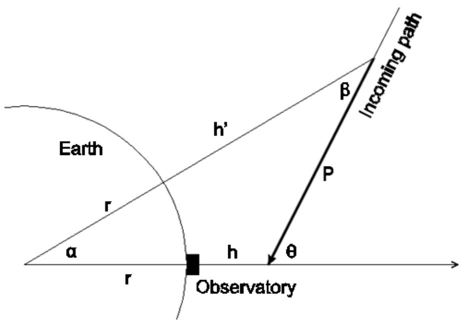

Figure 1: Relation between the zenith angle (θ), instantaneous altitude (h') and vertical crossing altitude (h)

The total path traveled (P) can then be found by solving the quadratic expression below for P:

$$(h' + r)^2 = P^2 + (h + r)^2 - 2(h + r)P\cos(\pi - \theta) \tag{1}$$

For our calculations we have assumed that h' is 200 km, beyond which the atmospheric density is 0. Importantly, high altitudes mean that slightly upward traveling cosmic-rays can also contribute to potential radar observations. The maximum zenith angle permitted (we assume earth blocks cosmic-rays) is then given by:

$$\theta_{\max} = \sin^{-1}\left(\frac{r}{r+h}\right) \tag{2}$$

Modeling atmospheric density as exponentially decaying [10], we can integrate the densities along the path to obtain the total slant depth.

$$X(h, \vartheta) = \int_0^P \rho\big(h'(p)\big)\, dp, \tag{3}$$

where P represents the total path traveled up to that point, and 0 represents the point directly over the observatory. We use the SciPy adaptive quadrature algorithm for the integration [11].

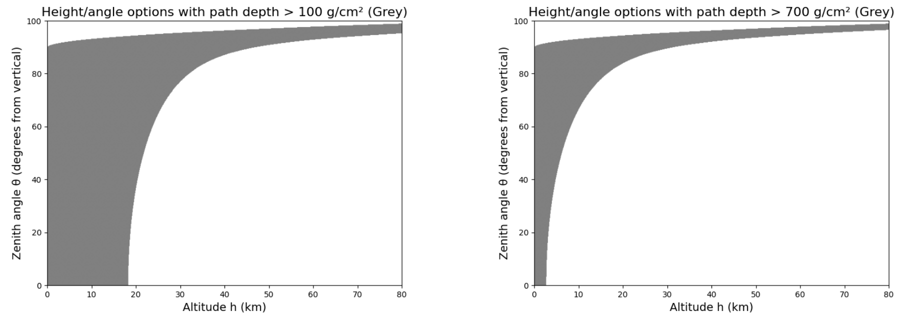

Figure 2: (left) Angle/height combinations leading to path depths of 100 g/cm^2 (grey = conditions leading to shower initiation). (right) Angle/height combinations leading to path depths of 700 g/cm^2 (grey = conditions leading to a shower maximum above the radar)

Fig. 2 show the result of these integrations which indicate that even for high altitudes ($h > 20$ km), primary cosmic-rays coming in at high zenith angles could travel through sufficient atmosphere to initiate an "air shower". Moreover, horizontal or slightly upward traveling primary cosmic-rays could travel through sufficient atmosphere such that the shower maximum (assumed to be at 700 g/cm^2) could occur directly above the radar station.

Although the range of permitted angles is small at high altitudes, two additional phenomena occur that could favor radar detection. Firstly, the radar observation volume increases, meaning that it may be possible to observe more cosmic-ray showers at higher altitudes, rather than less. For example, figure 3 shows the expected detection rate vs altitude as predicted by a toy model in which the impact of the increasing volume is tuned to show that under the right conditions, the detection rate could increase with altitude (note: no shower modeling or radar intensity modeling is used).

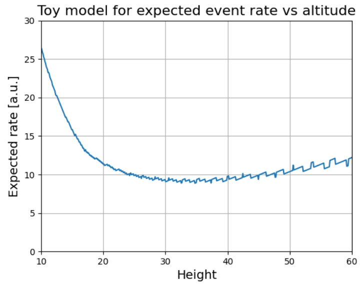

Figure 3: Expected observation rate vs altitude when radar aperture is taken into account

Secondly, low atmospheric density is likely to reduce collisional damping, which is thought to limit the chance of observing air shower reflections at lower altitudes. Admittedly these are optimistic extrapolations from "low-altitude" models, but they at least hint that the possibility of radar detection of high-altitude horizontal air showers cannot be fully discarded based on results to date. With this in mind, the next section presents the Jicamarca Radio Observatory of the Geophysical Institute of Peru(JRO) and high-altitude anomalous results which were obtained there.

3. Configuration of the Jicamarca Radio Observatory (JRO)

The JRO is located about 20 km inland (east) from Lima, at 11.95° south, 76.87° west. Its altitude is 520 $m.a.s.l.$ and the magnetic dip angle is about 1°, varying slightly with signal altitude and year. The 49.92 MHz radar (bandwidth 1MHz) is the main instrument of the facility. The radar antenna consists of a 300×300 m^2 square array of 18,432 half-wave dipoles arranged into 64 separate modules. The transmitters can deliver a peak power of 2 MW, with a maximum duty cycle of 5%. The Jicamarca radar can detect meteors as the plasma generated by the collisions of the meteor with molecules in the atmosphere reflects the transmitted radio waves.

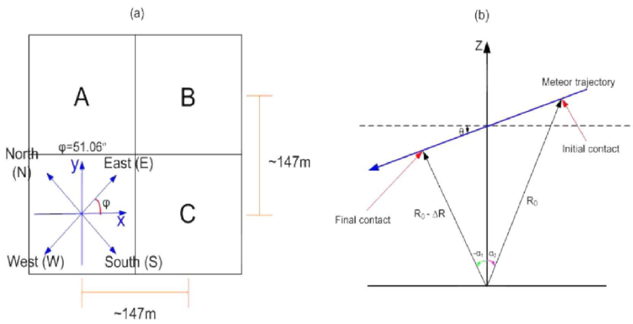

Figure 4: Layout of the Jicamarca Radio Observatory [12]

The JRO antenna is divided into four independent quadrants (Fig. 4). In meteor-head echo experiments where we have looked for anomalous EAS echoes, one quadrant is typically used for transmission, and the three others are used for reception. Using three independent receptors means that it is possible to check for coherence in the three channels (reducing the risk of spurious events), and we can measure spatial characteristics by interferometry.

3.1 Identification and processing of Anomalous Events in JRO Data

Radar experiment data are stored as complex voltage readings from each acquisition channel. Data is organized in profiles, where each profile corresponds to the reception of echoes from a single transmitted pulse over time. The time between profiles is call the inter-pulse period (IPP). The time delay of the returned signal allows us to calculate the distance (range) between the radar and the location of the reflection (modulo the IPP). Over multiple pulses, the data form a matrix: rows represent range, and columns represent time or (ie. successive IPPs). This matrix can be represented visually in a graph, showing range-time-intensity (RTI) of the reflected signals.

In our experiments, the transmission pulse was coded using Barker13 encoding to increase transmission power without sacrificing range resolution. On reception, pulses are decoded and the signals are stored in three RTI matrices (one per acquisition channel). The power for each channel is computed from the decoded complex voltages according to the following expression:

$$\rho_{ij}^{(k)} = V_{ij}^{(k)*} \cdot V_{ij}^{(k)} \tag{4}$$

Here, i denotes the range bin, j indexes the profile, and k identifies the acquisition channel. The matrices are then processed to detect anomalous events that satisfy two criteria:

- Simultaneous significance : To eliminate spurious noise, the signal from every channel was required to exceed 5 standard deviations above the local noise level (ie. all channels must be simultaneously significant).
- Relevance: A shape filter was applied, selecting only isolated vertical structures that spanned at least three consecutive range bins within a single IPP. This is to remove other time persistent signals that are known to originate from other sources, such as meteor trails or the Equatorial Electrojet. Furthermore, a convolutional neural network (CNN)-assisted selection was performed to eliminate any remaining false positives.

Applying these filters yields a set of events for which we present statistics in section 4.

3.2 Previously Identified Anomalous Events

In 2007 and 2009, we reported the detection of anomalous events in meteor-head echo experiments at JRO [8, 9] (using slightly different filters at the time). An example RTI graph of an event from 2007 is shown in the left panel of Figure 5.

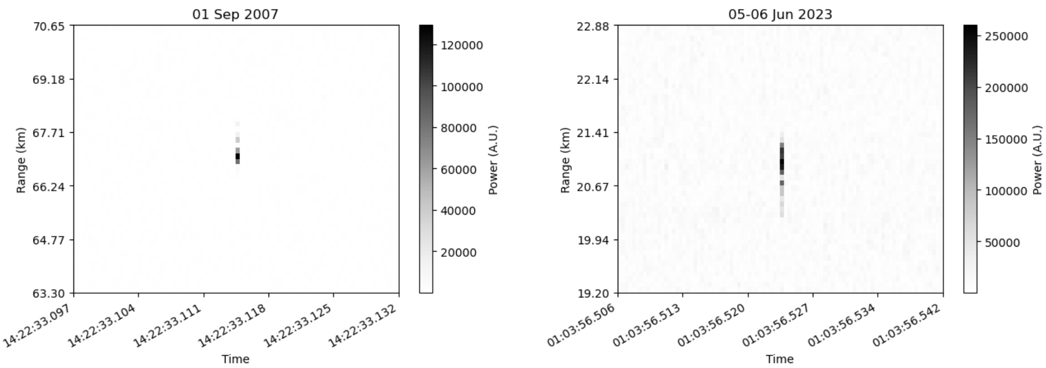

Figure 5: Range/time/intensity (RTI) graphs for two anomalous events from September 2007 (left) and May 2023 (right). Both RTI graphs show the detection of an event that is simultaneously significant in all three independent channels of the detector

Since then, the JRO main radar has undergone several hardware upgrades. In the following section, we report on more recent data (2023) which also shows the continued presence of anomalous events (with one representative example shown in the right panel of Figure 5).

4. Results

We report on 3 datasets from different meteor experiments. All datasets have an IPP of 60 km, a 1.95 km long transmission pulse coded in Barker 13, 1 channel for transmission and 3 for reception. The beam direction is different across the datasets: during 05–06 June 2023 the beam was pointing perpendicular to the geomagnetic field (B), in 06–08 June 2023 obliquely to B, and in May 2007 the beam direction was not recorded (though standard setup at the time was oblique to B).

4.1 Height Distributions

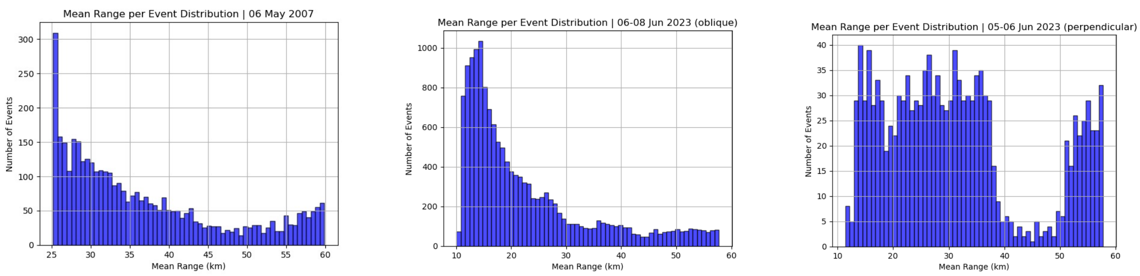

Figure 6: Distribution of ranges at which events are detected in May 2007 (left), 06-08 June 2023 (center) and 05-06 June 2023 (right)

Fig. 6 shows the range distributions obtained from the runs. The distributions from May 2007 and 06-08 June 2023 have common features with the toy distribution shown in Fig. 3 stemming from the high-altitude horizontal air shower model. Perhaps most striking is the slight uptick with altitude which is compatible with a radar aperture model (though we have not modeled the exact radar configuration). Events generated by sources other than radar reflection would be expected to be uniformly distributed across range. So it seems likely these events must be from a physical sources which reflect the radar pulse, especially in light of our selection criteria requiring coincidence in all channels. High-altitude showers may be a good candidate. However, in the dataset from June 5th-6th we get different results. Though the frequency of events is much lower (for currently unknown reasons), the uniform distribution between ranges of 15-38km is compatible with events that do not originate from radar reflection (the dip between 40-50km is compatible with atmospheric phenomena such as the Equatorial Electrojet which masks other signals), contradicting the other two datasets.

4.2 Time Distribution

Fig. 7 shows the time distribution of events for the dataset from 6-8 June 2023. The high temporal variation is difficult to reconcile with radar reflections of EAS - especially the variation of rates on the 08 June between midnight and 1am which occur whilst all other phenomena are stable. However at the same time it is difficult to reconcile with any other source, either physical or noise.

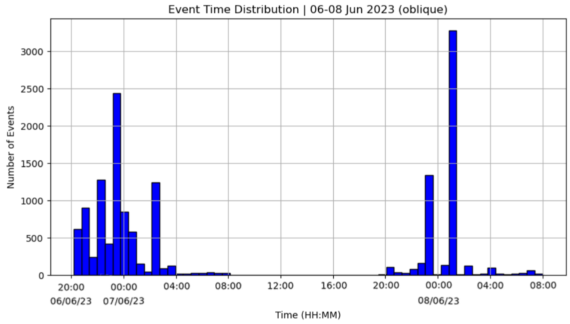

Figure 7: Time distribution of events (6-8 June 2023)

4.3 Angular Distribution

We analyzed the interferometry of the signals based on the phase differences between the complex voltages of the receiving channels. This allowed us to locate the average position of the reflection measured at each sample and thus attempt to reconstruct the event path. The direction of the path was determined by applying principal component analysis (PCA) to the XY positions of each sample. For the angular distribution statistics, we only considered paths in which the PCA yielded an eigenvalue ratio greater than 0.95 and an RMSE lower than 0.05 times the reconstructed path length, amounting to about 20% of the data. This filtering should not favor any specific orientation, but allows us to focus on higher confidence paths.

Fig. 8 shows the angular distribution of the reconstructed (filtered) events. Separate analysis shows that these distributions are constant over time. Furthermore, the direction corresponding to the peak of the histogram shows no apparent correlation with Earth's rotation, the ecliptic, or the Galactic plane. The fact that our events are highly directional is not compatible with an isotropic cosmic-ray source.

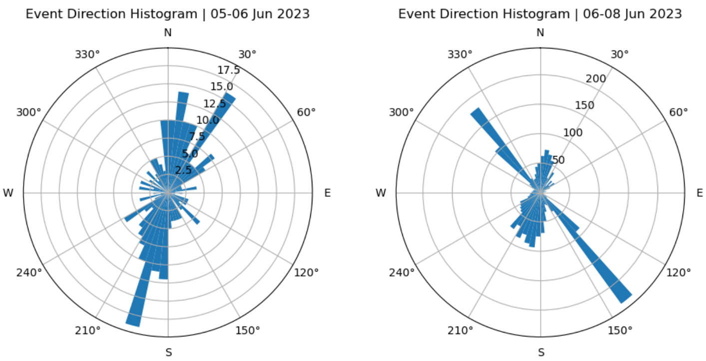

Figure 8: Angular distribution of events in the dataset from 05-06 June 2023 (left) and 06-08 June 2023 (right)

5. Conclusion

We have presented results which extend the first set of anomalous results presented in 2007. Occurring with 16 years difference and through hardware upgrades, there events present coherently and significantly across the three independent acquisition channels of the JRO radar. At first sight some of the features of our events could be compatible with very simple models of EAS at high altitudes. Nevertheless, time and angular distributions are not compatible with this scenario, nor seemingly with others. We plan to run new dedicated data collection runs - but it is too early to be able to conclude that our events are linked to cosmic-rays.

References

[1] P. M. S. Blackett and A. C. S. Lovell, “Radio echoes and cosmic ray showers,” *Proc. R. Soc. Lond. A*, vol. 177, no. 969, pp. 183–186, 1941.

[2] E. Huesca Santiago. Understanding Radar Echoes from High-Energy Particle Cascades. Diss. PhD thesis. Vrije Universiteit Brussel, 2024.

[3] P. Gorham. “On the Possibility of Radar Echo Detection of Ultra-High Energy Cosmic Ray- and Neutrino-Induced Extensive Air Showers”. In: Astroparticle Physics 15.2 (2001), pp. 177–202

[4] S. Eraly, J. Grossberg, and M. Tkaczyk, “MARIACHI Experimental Detection of Radio Wave Reflection off a High Energy Ionization Beam,” Stony Brook University, Department of Electrical and Computer Engineering.

[5] R. U. Abbasi *et al.*, “First upper limits on the radar cross section of cosmic-ray induced extensive air showers,” *Astropart. Phys.*, vol. 87, pp. 1–17, 2017.

[6] S. Prohira *et al.*, “Observation of radar echoes from high-energy particle cascades,” *Phys. Rev. Lett.*, vol. 124, no. 9, p. 091101, 2020.

[7] D. Bakunov *et al.*, "The no-reflection regime of radar detection of cosmic ray air showers." New Journal of Physics 17.5 (2015): 053015.

[8] D. Wahl, J. Chau, and J. Bellido, “The search for vertical extended air shower signals at the Jicamarca Radio Observatory”. In *International Cosmic Ray Conference*, vol. 5, 2008.

[9] D. Wahl *et al.*, “The search for extended air showers at the Jicamarca Radio Observatory,” in *AIP Conf. Proc.*, vol. 1123, no. 1. American Institute of Physics, 2009.

[10] S. Kedare and S. Ulrich, *Design and evaluation of a semi-empirical piece-wise exponential atmospheric density model for CubeSat applications*, AIAA Modeling and Simulation Technologies Conference. 2015.

[11] R. Piessens, E. de Doncker-Kapenga, C.W. Überhuber, and D.K. Kahaner, *QUADPACK: A Subroutine Package for Automatic Integration*, Springer-Verlag, 1983.

[12] J. Chau and R. F. Woodman, *Observations of meteor-head echoes using the Jicamarca 50MHz radar in interferometer mode*, Atmos. Chem. and Physics 4.2 (2004): 511-521.

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