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Investigations of the radio signal of inclined showers with LOPES

A. Saftoiu [a,*], W.D. Apel [b], J.C. Arteaga [c,1], T. Asch [d], L. Bähren [e], K. Bekk [b], M. Bertaina [f], P.L. Biermann [g], J. Blümer [b,c], H. Bozdog [b], I.M. Brancus [a], P. Buchholz [h], S. Buitink [e], E. Cantoni [f,i], A. Chiavassa [f], K. Daumiller [b], V. de Souza [c,2], P. Doll [b], R. Engel [b], H. Falcke [e,j], M. Finger [b], D. Fuhrmann [k], H. Gemmeke [d], C. Grupen [h], A. Haungs [b], D. Heck [b], J.R. Hörandel [e], A. Horneffer [e], D. Huber [c], T. Huege [b], P.G. Isar [b,3], K.-H. Kampert [k], D. Kang [c], O. Krömer [d], J. Kuijpers [e], S. Lafebre [e], K. Link [c], P. Łuczak [l], M. Ludwig [c], H.J. Mathes [b], M. Melissas [c], C. Morello [i], S. Nehls [b], J. Oehlschläger [b], N. Palmieri [c], T. Pierog [b], J. Rautenberg [k], H. Rebel [b], M. Roth [b], C. Rühle [d], H. Schieler [b], A. Schmidt [d], F.G. Schröder [b], O. Sima [m], G. Toma [a], G.C. Trinchero [i], A. Weindl [b], J. Wochele [b], M. Wommer [b], J. Zabierowski [l], J.A. Zensus [g]

[a] National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[b] Karlsruhe Institute of Technology (KIT), Institut für Kernphysik, 76021 Karlsruhe, Germany
[c] Karlsruhe Institute of Technology (KIT), Institut für Experimentelle Kernphysik, 76021 Karlsruhe, Germany
[d] Karlsruhe Institute of Technology (KIT), Institut für Prozessdatenverarbeitung und Elektronik, 76021 Karlsruhe, Germany
[e] Radboud University Nijmegen, Department of Astrophysics, The Netherlands
[f] Dipartimento di Fisica Generale dell' Universita Torino, Italy
[g] Max-Planck-Institut für Radioastronomie Bonn, Germany
[h] Universität Siegen, Fachbereich Physik, Germany
[i] INAF Torino, Istituto di Fisica dello Spazio Interplanetario, Italy
[j] ASTRON, Dwingeloo, The Netherlands
[k] Universität Wuppertal, Fachbereich Physik, Germany
[l] Soltan Institute for Nuclear Studies, Lodz, Poland
[m] University of Bucharest, Department of Physics, Bucharest, Romania

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ABSTRACT

We report in this paper on an analysis of 20 months of data taken with LOPES. LOPES is radio antenna array set-up in coincidence with the Grande array, both located at the Karlsruhe Institute of Technology, Germany. The data used in this analysis were taken with an antenna configuration composed of 30 inverted V-shape dipole antennas.

We have restricted the analysis to a special selection of inclined showers—with zenith angle $\theta > 40^\circ$. These inclined showers are of particular interest because they are the events with the largest geomagnetic angles and are therefore suitable to test emission models based on geomagnetic effects.The reconstruction procedure of the emitted radio signal in EAS uses as one ingredient the frequency-dependent antenna gain pattern which is obtained from simulations. Effects of the applied antenna model in the calibration procedure of LOPES are studied. In particular, we have focused on one component of the antenna, a metal pedestal, which generates a resonance effect, a peak in the amplification pattern where it is the most affecting high zenith angles, i.e. inclined showers.

In addition, polarization characteristics of inclined showers were studied in detail and compared with the features of more vertical showers for the two cases of antenna models, with and without the pedestal.

1. Introduction

The goal of LOPES (LOFAR Prototype Station) [1] is to establish the possibility and explore the efficiency of detection of radio waves coming from extensive air showers believed to be generated through a geosynchrotron mechanism [2]. The experimental set-up is placed within the area covered by the particle detector array, KASCADE-Grande [3], a choice made because certain air shower parameters, taken from particle detectors, can be used to establish

* Corresponding author.
E-mail address: allixme@gmail.com (A. Saftoiu).

[1] Now at: Universidad Michoacana, Morelia, Mexico.
[2] Now at: Universidade de São Paulo, Instituto de Fîsica de São Carlos, Brasil.
[3] Now at: Institute for Space Science, Bucharest, Romania.

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radio emission properties and parametrization of the pulse height. The present analysis is concerned with the LOPES set-up consisting of 30 inverted V-shaped antennas detecting radio waves in the range of 40–80 MHz, 15 oriented along the East–West direction and 15 in the North–South direction. The set-up is absolutely amplitude calibrated.

The radio signal from an air shower recorded by the 30 antennas is obtained by performing a beamforming procedure. Afterwards analysis is performed to establish the correlation between various parameters of the air showers and the pulse height. More details on the general analysis procedure are given in Ref. [4], these proceedings]. In this study we investigate the effect of one of the antenna components on the analysis results.

2. LOPES antennas

The LOPES dual-polarization antennas are composed of two V-shaped rods, one for each polarization, and a metal pedestal.

The amplification factor used during the analysis of LOPES events to calculate the absolute field strength is given by [5]

$$V(\nu)=\frac{P_M(\nu)}{P_R(\nu)}=\left(\frac{4\pi r\nu}{c}\right)^2\frac{P_M(\nu)}{G_r(\theta,\phi,\nu)G_tP_t(\nu)\cos^2(\beta)} \quad (1)$$

where P_M is the power measured with the LOPES antenna and calculated in the frequency domain, P_R is the (calculated) incoming power to the LOPES electronic chain, ν is the frequency of the emitted signal, and r the distance between the external source and the LOPES antenna. $G_r(\theta,\phi,\nu)$ is the gain of the LOPES antenna taken from simulation, G_t is the reference source antenna gain, $P_t(\nu)$ is the power of the reference source and β is the angle between the polarization axis of the reference source and the field antenna, aligned during the measurements.

It can be seen from the above formula that the gain of the LOPES antenna taken from simulation is employed in the calculation of the absolute field strength.

Simulations performed so far for the real antenna, [5] show that a resonance effect induced by the metal pedestal appears around the frequency of 58 MHz. This effect is small for near vertical angles, becomes larger for zenith angles close to 45° and is negligible again for higher inclinations. Fig. 1(a) shows a simulation result when the pedestal is taken into account.The range from 40° to 50° zenith angles is where most of the inclined radio events are recorded and therefore it is important to study the possible influence of the resonance to the obtained results. Fig. 1(b) shows the amplification factor without the pedestal effect. It can be seen that the peak is no longer present.

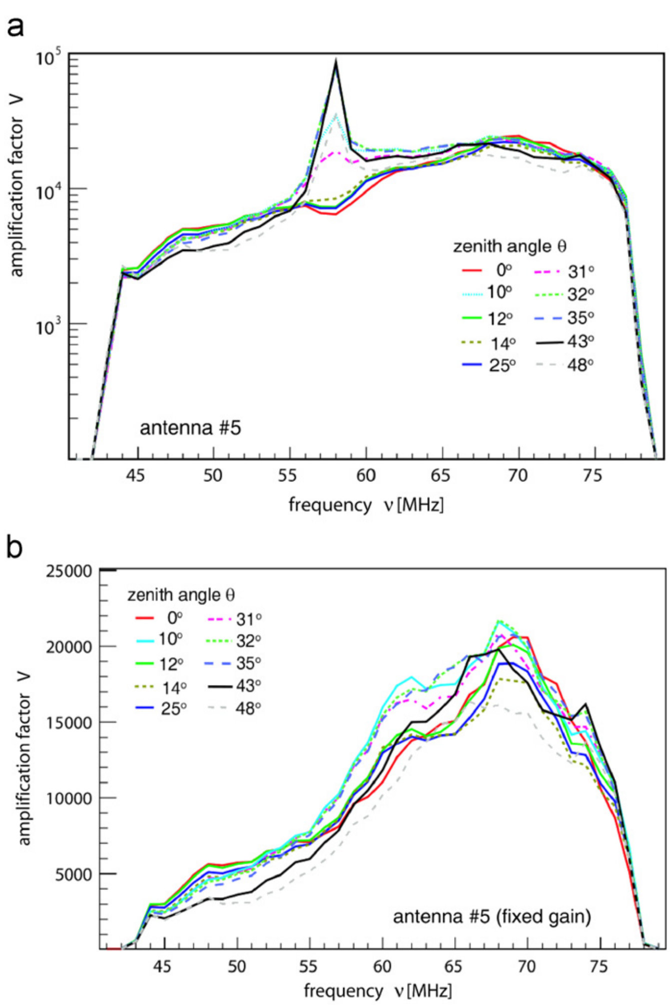

Fig. 1. Amplification factor distribution for one antenna for different zenith angles, with the metal pedestal included in the simulation (a), and without metal pedestal included in which case G_t is fixed to 4.0 [5].

3. Data processing and correlations

In the present study we use dual-polarization data recorded in 2007 and 2008 in coincidence with KASCADE-Grande. For the purpose of studying only bright and inclined events we have made a cut for zenith angle $\theta > 40^\circ$ and muon number, $N_\mu > 10^6$, corresponding to a primary energy of above $\approx 10^{17}$ eV. We also impose an area cut for the events reconstructed from Grande data. This leaves us with 5582 events where LOPES data are recorded. In order to be clear of any atmospheric electric field contribution we ignored the events which occurred during thunderstorms which rejects 12 events.

The errors employed in the analysis are: 50% error for muon number, 0.6° for direction, 20 m error for core coordinates and 20% error on the radio amplitude calibration.

Due to the high level of noise in KIT and to the fact that LOPES events are distant (Grande triggered) we impose an additional cuts on the pulse height. After performing the selection cuts only 49 events remain.

The correlations we are usually investigating with LOPES data are:

- pulse height, ε, vs. the cross product of the direction of the incoming shower and Earth's magnetic field, $P=|\vec{v}\times\vec{B}|$,
- pulse height vs. distance from antennas to shower axis, R, and
- pulse height vs. the number of muons in the respective air shower which is an estimator for primary energy, N_μ.

$$\varepsilon = const1(P+const2)\exp\left(\frac{-R}{R_0}\right)\left(\frac{N_\mu}{10^5}\right)^{const3}\left[\frac{\mu\text{V}}{\text{m MHz}}\right]. \quad (2)$$

The constants, $const1$, $const2$ and $const3$ are obtained from iterative separation of parameters and we will discuss their values in the next section. R_0 is the scaling radius parameter.

4. Results

In order to investigate the influence of the presence of the pedestal in the simulations we perform the standard LOPES processing and then the analysis described above for the two cases: with and without taking into account the effect induced by the pedestal.

The dependencies between pulse height and various shower parameters obtained as described in the previous section are displayed in Fig. 2(a)–(c).

Using these results we can write the pulse height, as Eq. (3) for the case with pedestal, and Eq. (4) for the case without the pedestal.

$$\varepsilon = 2.82 \pm 0.20\ (1.03 \pm 0.18 + P)\exp\left(\frac{-R}{218.77 \pm 26.00}\right)\left(\frac{N_\mu}{10^6}\right)^{0.93 \pm 0.05}\quad\left[\frac{\mu\mathrm{V}}{\mathrm{m\ MHz}}\right] \tag{3}$$

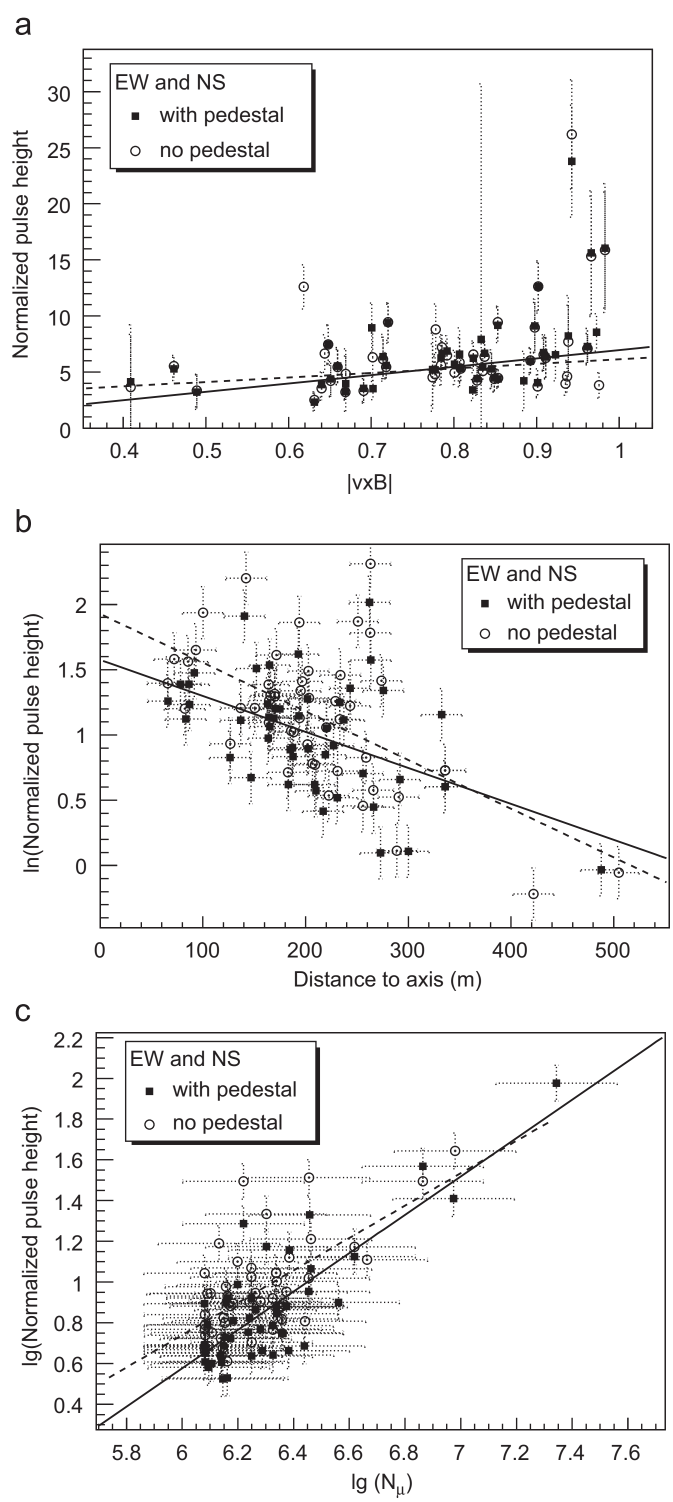

Fig. 2. Dependence of pulse height on polarization vector modulus, $P = |\vec{v} \times \vec{B}| = \sqrt{(P_{EW}^2 + P_{NS}^2)}$ (a), on distance from antennas to shower axis (b) and dependence of $\log_{10}$ of pulse height on log of muon number.

$$\varepsilon = 3.21 \pm 0.40(0.53 \pm 0.50 + P)\exp\left(\frac{-R}{268.18 \pm 25.00}\right)\left(\frac{N_\mu}{10^6}\right)^{0.79 \pm 0.06}\quad\left[\frac{\mu\mathrm{V}}{\mathrm{m\ MHz}}\right]. \tag{4}$$

So far we have taken into account the total polarization vector, $P = |\vec{v} \times \vec{B}| = \sqrt{(P_{EW}^2 + P_{NS}^2)}$, but we can treat separately each component, for East–West and North–South polarizations respectively. If we perform the same analysis for the cases with and without pedestal, but on separate polarizations we arrive at the next parametrizations for the pulse height. With pedestal:

$$\varepsilon_{EW} = 3.8 \pm 1.6\ (1.08 \pm 0.30 + P_{EW})\exp\left(\frac{-R}{437 \pm 86}\right)\left(\frac{N_\mu}{10^6}\right)^{0.83 \pm 0.05}\quad\left[\frac{\mu\mathrm{V}}{\mathrm{m\ MHz}}\right] \tag{5}$$

$$\varepsilon_{NS} = 4.25 \pm 0.41\ (0.74 \pm 0.40 + P_{NS})\exp\left(\frac{-R}{411 \pm 70}\right)\left(\frac{N_\mu}{10^6}\right)^{0.71 \pm 0.06}\quad\left[\frac{\mu\mathrm{V}}{\mathrm{m\ MHz}}\right]. \tag{6}$$

Without pedestal:

$$\varepsilon_{EW} = 2.97 \pm 1.90\ (2.04 \pm 2.80 + P_{EW})\exp\left(\frac{-R}{760 \pm 270}\right)\left(\frac{N_\mu}{10^6}\right)^{0.58 \pm 0.09}\quad\left[\frac{\mu\mathrm{V}}{\mathrm{m\ MHz}}\right] \tag{7}$$

$$\varepsilon_{NS} = 1.37 \pm 1.02\ (1.0 \pm 2.3 + P_{NS})\exp\left(\frac{-R}{600 \pm 160}\right)\left(\frac{N_\mu}{10^6}\right)^{0.38 \pm 0.08}\quad\left[\frac{\mu\mathrm{V}}{\mathrm{m\ MHz}}\right]. \tag{8}$$

In a coherent signal we expect the power in the N_μ dependence to be close to 1. It can be seen that the results come closer to this assumption in the case with the pedestal and approach the incoherent case in the case without the pedestal. This is a hint that the pedestal and therefore the resonance is really there and has to be considered. Another problem is the scatter of the data points around the "coherence" line, which is larger than the uncertainty of the measurements and even larger when the pedestal is not taken into account. When all the dependencies are well assumed and corrected for this scatter should be smaller. This is a hint that the parametrization seems to miss contributions. This gets even more pronounced when studying the dependence on $\vec{v} \times \vec{B}$.

If the emission mechanism is purely geomagnetic we expect to have a value very close to 0 for *const*2, in $const2 + |\vec{v} \times \vec{B}|$. This value is systematically lower in the case *without* the pedestal than in the case *with* the pedestal, but it is close to 1 instead of 0. If the assumption is right than the case with the pedestal seems to be better.

In both cases the non-zero value of this parameter may indicate that the emission is not purely geomagnetic and other effects are superimposed. Other possible mechanisms are described in Refs. [9,12].

The fit of the $|\vec{v} \times \vec{B}|$ dependence is linear because we assume an emission mechanism which would present this feature, but for showers with $|\vec{v} \times \vec{B}| \backsimeq 1$ a clear enhancement is visible which is not discussed yet.

The quality of the fit for the R_0 dependence for the EW and NS components separately is worse in the case without the pedestal than the case with the pedestal because the data points are more scattered.

We have also performed the same type of analysis on inclined showers data recorded with LOPES in previous configurations, only

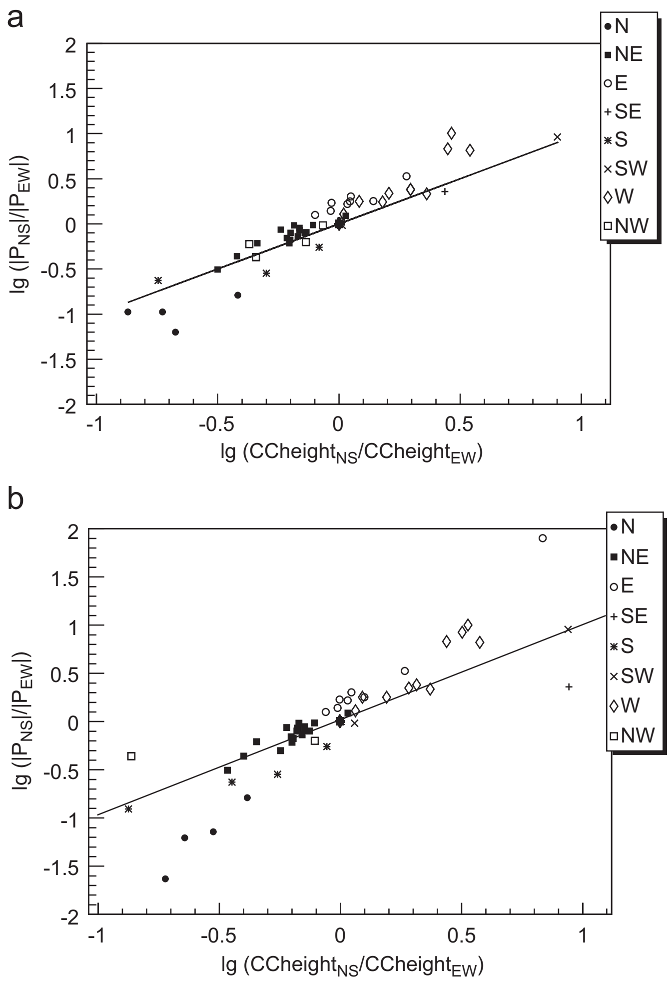

Fig. 3. $|\vec{v}\times\vec{B}|_{NS}/|\vec{v}\times\vec{B}|_{EW}$ vs. the ratio of the pulse heights for the NS and EW polarizations, in the case with pedestal (a), and without pedestal (b). The different markers denote air shower arrival directions.

10 antennas sensitive to the East–West polarization [10] and 30 antennas sensitive to the same polarization [11], both with the pedestal contribution included. We can say that the results are consistent with those presented here for the case with the pedestal taken into account.

Many similar analyses were performed with LOPES data [4,6–8], *including* the pedestal. The results of the parametrization are in rough agreement to these for the inclined showers.

5. Comparison with the simplified geomagnetic model

The influence of the geomagnetic angle on the radio emission features has been observed since the 70's [12].

A geosynchrotron mechanism has been proposed, [2], which explains the emission as coming from positively and negatively charged particles bent in opposite directions in the magnetic field which then emit *coherent geosynchrotron radiation* [2]. The synchrotron electric field produced near the axis of particle motion is to first-order proportional to the cross product $|\vec{v}\times\vec{B}|$, where $\vec{v}$ is the direction of the EAS motion and $\vec{B}$ the geomagnetic field [13].

Assuming that this model is correct, the dependence shown in Fig. 3(a) and (b) should be close to the diagonal. It can be seen then again the data points are more scattered in the case without the pedestal than in the case with the pedestal.

Also in both figures it can be seen that there are clear deviations from the diagonal for showers coming from North, which, again is a hint that the geomagnetic emission may not fully describe the measured signal.

6. Conclusions

We have studied the influence of the presence or the absence of the effect induced by the metal pedestal in the amplification factor pattern, by analyzing the final correlations of pulse height with shower parameters in both cases. If the effect is overestimated in the simulations an improvement should be seen in the results. Instead the data points are more scattered around and the fits behave worse than expected. Therefore, the simulated resonance effect seems to be true and have to be taken into account during the reconstruction procedures. In addition, the analysis also gives some hints that the geomagnetic emission is not the only production mechanism and other phenomena contribute to the overall radio signal.

Acknowledgements

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