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Radio emission of energetic cosmic ray air showers: Polarization measurements with LOPES

P.G. Isar [a,*,1], W.D. Apel [a], J.C. Arteaga [b,1], T. Asch [c], J. Auffenberg [d], F. Badea [a], L. Bähren [e], K. Bekk [a], M. Bertaina [f], P.L. Biermann [g], J. Blümer [a,b], H. Bozdog [a], I.M. Brancus [h], M. Brüggemann [i], P. Buchholz [i], S. Buitink [e], E. Cantoni [f,j], A. Chiavassa [f], F. Cossavella [b], K. Daumiller [a], V. de Souza [b,2], F. Di Pierro [f], P. Doll [a], R. Engel [a], H. Falcke [e,k], M. Finger [a], D. Fuhrmann [d], H. Gemmeke [c], P.L. Ghia [j], R. Glasstetter [d], C. Grupen [i], A. Haungs [a], D. Heck [a], J.R. Hörandel [e], A. Horneffer [e], X. Huang [a], T. Huege [a], K.-H. Kampert [d], D. Kang [b], D. Kickelbick [i], Y. Kolotaev [i], O. Krömer [c], J. Kuijpers [e], S. Lafebre [e], P. Łuczak [l], H.J. Mathes [a], H.J. Mayer [a], J. Milke [a], B. Mitrica [h], C. Morello [j], G. Navarra [f], S. Nehls [a], A. Nigl [e], J. Oehlschläger [a], S. Over [i], M. Petcu [h], T. Pierog [a], J. Rautenberg [d], H. Rebel [a], M. Roth [a], A. Saftoiu [h], H. Schieler [a], A. Schmidt [c], F. Schröder [a], O. Sima [m], K. Singh [e,3], M. Stümpert [b], G. Toma [h], G.C. Trinchero [j], H. Ulrich [a], W. Walkowiak [i], A. Weindl [a], J. Wochele [a], M. Wommer [a], J. Zabierowski [l], J.A. Zensus [g,4]

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

LOPES Collaboration

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ABSTRACT

LOPES is a radio antenna array co-located with the Karlsruhe Shower Core and Array DEtector, KASCADE–Grande in Forschungszentrum Karlsruhe, Germany, which provides well-calibrated trigger information and air shower parameters for primary energies up to 10^{18} eV. By the end of 2006, the radio antennas were re-configured to perform polarization measurements of the radio signal of cosmic ray air showers, recording in the same time both, the East–West and North–South polarization directions of the radio emission. The main goal of these measurements is to reconstruct the polarization characteristics of the emitted signal. This will allow a detailed comparison with theoretical predictions. The current status of these measurements is reported here.

1. Introduction

Radio detection is a new technique of cosmic ray air shower measurements which utilizes the radio emission from particles generated in the Earth's Atmosphere. Therefore, to see whether radio emission is indeed detectable and useful in a modern cosmic ray experiment, we have built the LOPES experiment, designed as a 'LOfar PrototypE Station' to detect the short radio pulses in the

* Corresponding author.
E-mail address: gina.isar@ik.fzk.de (P.G. Isar).

[1] Leave of absence from Institute for Space Sciences, Magurele, Bucharest, Romania.
[2] Now at: Universidad Michoacana, Morelia, Mexico.
[3] Now at: Universidade São Paulo, Instituto de Fisica de São Carlos, Brasil.
[4] Now at: KVI, University of Groningen, The Netherlands.

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frequency domain of 40–80 MHz. LOPES is a phased array of simple V-shape antennas with digital electronics. Compared to the historical experiments, it provides an order of magnitude increase in bandwidth and time resolution, effective digital filtering methods, and for the first time true interferometric imaging capabilities.

The LOPES experiment has started operating from 2004 with an initial configuration of 10 antennas (LOPES10) oriented only in the direction of East–West. Soon after starting of data taking, the LOPES team has discovered the first bright radio pulses of energetic cosmic showers in the air [2]. Then, the radio array was extended by 20 additional antennas forming LOPES30 [7]. LOPES benefits on a large scale by being triggered by and using reconstructed air shower parameters provided by both experiments, KASCADE and its extension, KASCADE–Grande.

2. Polarization measurements

Initially, LOPES30 antennas were set-up only for the East–West polarization measurements. By the end of 2006, the array was re-configured to both polarizations, such that currently, LOPES is performing polarization measurements. The antenna array is formed now by distributing the 30 antennas at 25 positions: five of them are equipped with both polarization channels at the same place, detecting in the same time both, the East–West and North–South polarization directions; 10 are equipped with East–West channels and 10 with North–South channels [3] (see Fig. 1).

Performing polarization measurements, we record the full pulsed radio signal generated by the charged air shower secondary particles (e− and e+) in the Earth's Atmosphere, which provide the 'tool' that can verify the geo-synchrotron mechanism of the radio emission. Each individual LOPES antenna is absolute amplitude calibrated by a commercial bi-conical reference source; for an antenna which is equipped with both polarization channels at the same place, we rotate the reference source on top of it, and therefore we calibrate each polarization channel independently. No significant crosstalk between the channels was found [5] (see Figs. 2 and 3).

3. Polarization analysis

For the present analysis we considered events recorded during approximately 8 months (December 2006–August 2007). Selection cuts were applied (for example, KASCADE core <91 m,

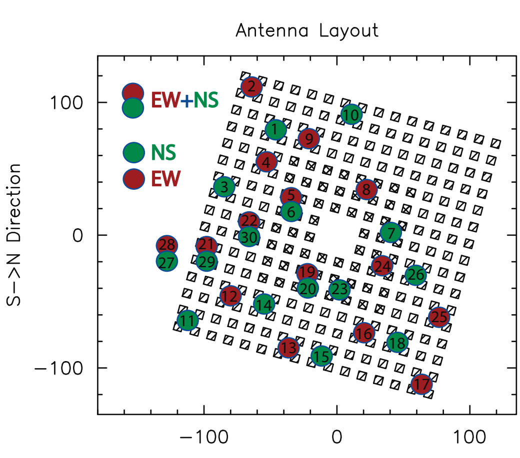

Fig. 1. Layout of the current set-up of the LOPES antennas at the KASCADE array.

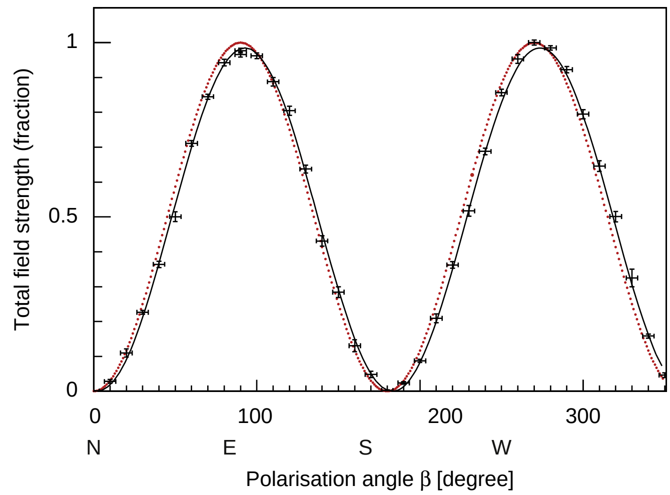

Fig. 2. Fraction of the total field strength seen by the linearly polarized LOPES antenna (sensitive to E–W polarization) as a function of the polarization angle β, the angle between the position of the external source relative to the antenna axis. Points: experimental data, solid line: data fit by a sinβ-function, dotted line: theoretical sinβ-distribution (normalized to the value at $\beta = 270^\circ$) [5].

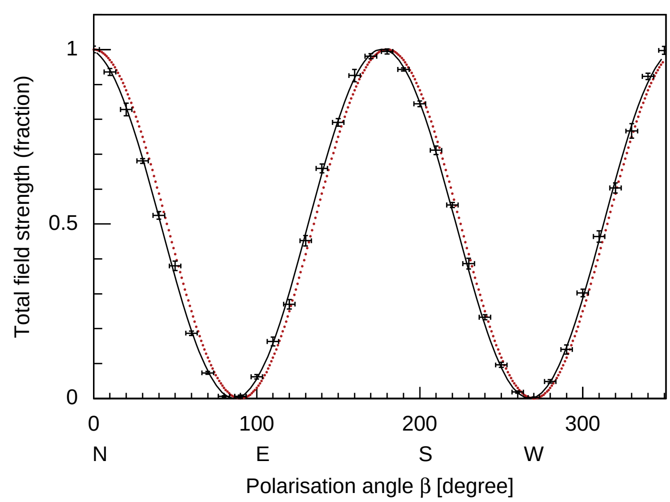

Fig. 3. Same as Fig. 2, but now for the antenna sensitive to the N–S polarization direction of the radio signal. The dotted curve is normalized to the value at $\beta = 180^\circ$ [5].

Grande core <300 m, $\log(Ne) > 6$, $\log(N\mu) > 6.2$) to get the good reconstructed and high-energy events with the shower core inside KASCADE–Grande. A complete pipeline was applied for each individual East–West and North–South polarization channel to get the needed information of the radio pulse height per event (see Fig. 4). The observable considered is the so-called CC-Beam pulse height [1].

For the results of the applied pipeline per individual polarization component we do not consider any correction, because the air shower geometry is the same for both polarization directions. Instead, we investigated the ratio of the pulse height (the North–South pulse height versus the East–West pulse height) for correlations of the un-modified (un-normalized) pulse height to shower parameters (e.g., geomagnetic angle, muon number, primary energy) per individual polarization component. As example of correlations of the pulse height ratio, see Fig. 5.

During the analysis of the polarization measurements, we notice that the polarization is directly related to the shower azimuth for a given zenith angle. By generating a simple sky-map based on zenith relative to the azimuth angle of the selected events per polarization components independently, we conclude the following:

(a) For the East–West selection (events with coherent signal in the East–West polarization direction only), the highest radio pulse heights are for the showers coming from North; see Fig. 6.
(b) For the North–South selection (events with coherent signal in the North–South polarization direction only), the highest

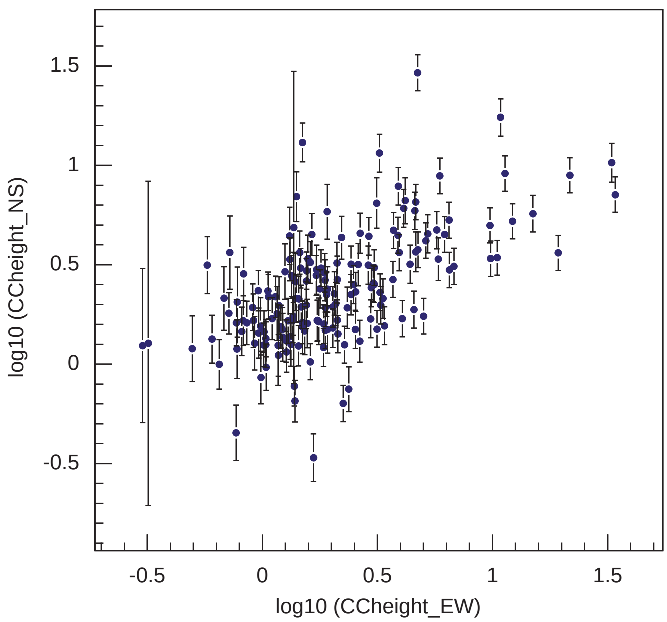

Fig. 4. Result of the individual East–West and North–South pipeline applied to LOPES events. Plotted in the logarithm scale we have the pulse height for the North–South components vs. the pulse height of the East–West components. The error bars include the uncertainties of the calibration procedure [1].

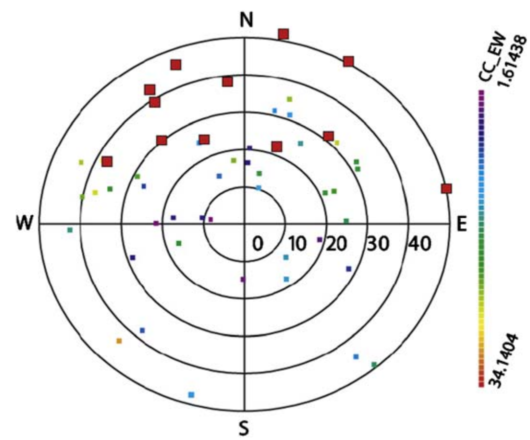

Fig. 6. The sky-map (azimuth relative to the zenith angle which is less than 50°) of the East–West selected events which are mostly coming from North. The color code represent the CrossCorrelation-Beam of the recorded pulse heights (pulse height >1.5 μV/m/MHz); the values are decreasing from the bottom to top. The large cubic points represent the highest recorded pulse heights. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

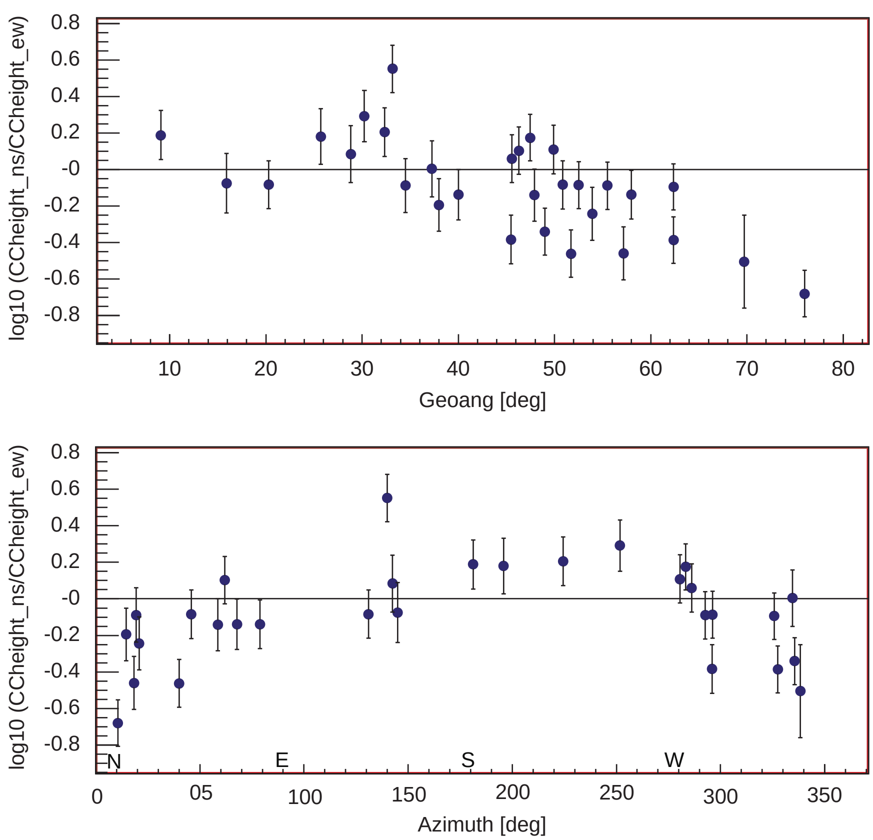

Fig. 5. Correlation between the un-modified pulse height ratio (North–South pulse height vs. East–West pulse height) with the geomagnetic angle (top) and azimuth angle (bottom). One clearly sees the good correlation with the geomagnetic angle which confirms an emission mechanism related to the geomagnetic field, as well as the azimuth dependence of the pulse height ratio (e.g., ratio > 0, radio pulse recorded mostly in the N–S component of the polarization direction; ratio < 0: E–W component dominant).

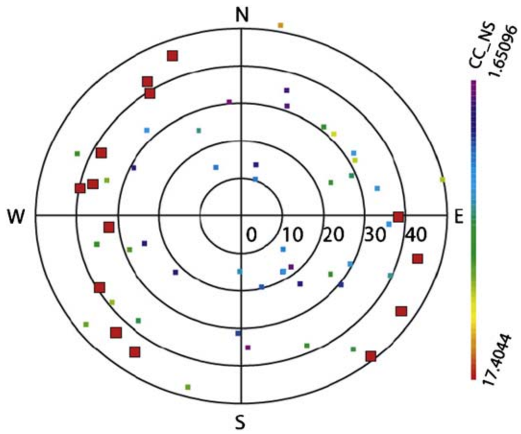

Fig. 7. The sky-map (same as Fig. 6) of the selected North–South events which are coming from East and West. The color code represent the CrossCorrelation-Beam of the recorded pulse heights (pulse height $>1.5\,\mu V/m/MHz$). The large cubic points represent the highest recorded pulse heights. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

radio pulse heights are for the showers coming from West and East; see Fig. 7.

(c) For the dual-polarization selection (events with coherent signal in both, East–West and North–South polarization directions), we use the pulse height ratio, the ratio between the North–South pulse height versus the East–West pulse height; the highest pulse height ratio is for the showers coming from South. Within the correlation of this ratio with the azimuth angle, we confirm as predicted by theoretical simulations the azimuth dependence of the polarized signal; see Fig. 5.

Monte Carlo simulations [4] of air shower radio emission predict a highly linearly polarized signal, usually present in both polarization components, East–West and North–South, as well as the dependence of the recorded signal on the position of the observer relative to the incoming shower direction.

4. Summary and outlook

LOPES is performing polarization measurements which allow a much more detailed analysis of the radio events, than with East–West polarization measurements only. The array is absolute amplitude calibrated in order to estimate the electric field strength of the short radio pulse (of some tens of nanoseconds) generated by the cosmic ray air showers in the atmosphere. With the help of these two features, now we can fully compare our measurements with Monte Carlo simulations.

As next steps in the analysis, we will consider:

(a) The normalization of the pulse height [6] using different iteration steps based on air shower parameters, like primary energy, geomagnetic angle, muon number, etc.
(b) The reconstruction of the original signal by up-sampling (interpolation between the sampling points) per single antenna [1].
(c) The reconstruction of the polarization vector, e.g. per dual-polarized antenna, to draw the path to the comparison with simulations.

Once we have understood the radio signals generated by air showers, including polarization characteristics, we open a new window in measuring the most energetic particles coming from the Universe. Therefore, we improve and optimize the hardware for large scale application in ultra high-energy cosmic ray experiments, like Pierre Auger Observatory and LOFAR.

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