Polarization studies of the EAS radio emission with the LOPES experiment

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***Abstract.* During the development of high-energy cosmic ray air showers in the atmosphere the charged particles are deflected by the geomagnetic field. This causes the geo-synchrotron emission leading to a short radio signal observable on ground. This model predicts characteristic dependences of the polarization of the radio signal on general shower parameters, and thus such dependences are investigated with the LOPES experiment. LOPES is an array of dipole radio antennas designed to detect such radio signals in the frequency range between 40-80 MHz. LOPES is located at the area of the ground particle detector array KASCADE-Grande providing the trigger and well-calibrated shower information for primary energies in the range of 10^{16}-10^{18} eV. For investigating the polarization, half of the LOPES antennas are orientated in east-west and respectively half in north-south direction. In this work, the variation of the polarization of the signal with the direction of the incoming air-shower with respect to the geomagnetic field is studied.**

***Keywords*: air showers, radio emission, polarization**

I. INTRODUCTION

Due to the interaction with the Earth's atmosphere, an Ultra High Energy Cosmic Ray (UHECR) generates a shower of elementary particles propagating towards the ground with almost the speed of light. Electrons and positrons, as major part of the charged particles in the Extensive Air Shower (EAS), emit synchrotron radiation due to their deflection in the Earth's magnetic field which initiate a short radio flash measurable on ground. The LOPES experiment, a radio array of Λ-shape digital antennas is designed to record such signals and takes data since 2004. In its initial phase, LOPES-10, 10 antennas were equipped with channels sensitive to the east-west polarization direction of the electric field only. After one year of operation [1], the antenna set-up has been changed to a larger array by an addition of further 20 antennas, forming LOPES-30 [2]. Within LOPES-30, the antennas have an absolute amplitude calibration in order to estimate the electric field strength of the radio signal generated in the atmosphere [3]. Moreover,

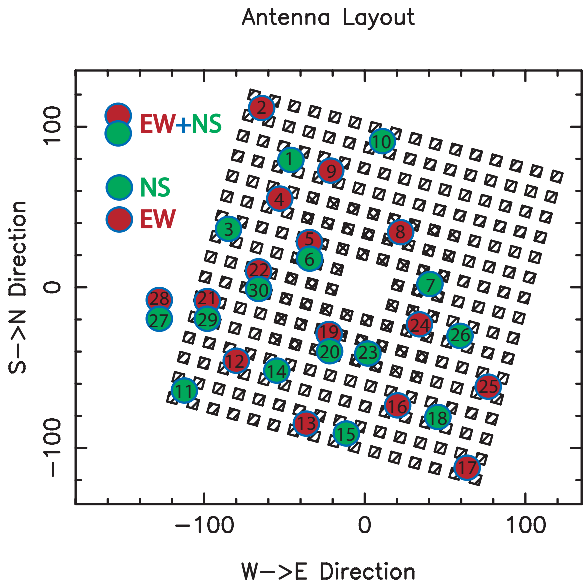

Fig. 1: LOPES antenna layout at the KASCADE array at Forschungszentrum Karlsruhe, Germany.

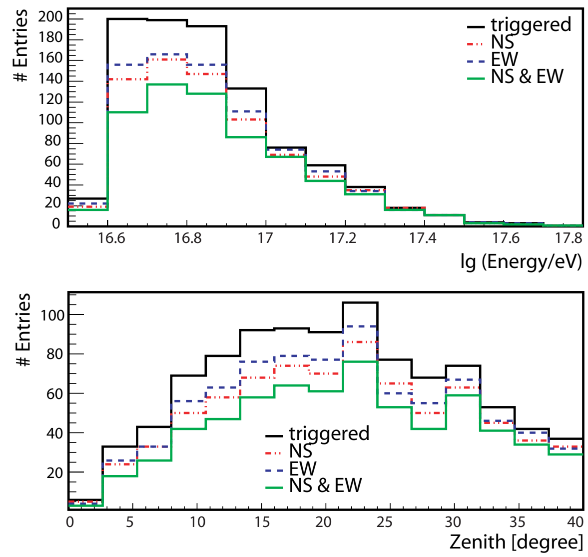

Fig. 2: Primary energy and zenith angular distributions of the triggered (by KASCADE) and of the radio (by LOPES) detected events.

to investigate the radio emission from these EAS in detail and clarify if the technique is useful for large scale application, the LOPES set-up has been changed to perform polarization measurements in 2006.

II. Detector configuration

East-west polarization measurements alone do not provide the full radio emission information. The recording of both together, the east-west and the north-south polarization components, is a key measure in understanding the radio emission and will allow us to verify the geo-synchrotron effect as the dominant emission mechanism in cosmic ray air showers. Therefore, LOPES-30 was reconfigured to perform polarization measurements by the end of December 2006. Within the new configuration, 15 channels are installed to measure the east-west direction and 15 the north-south direction, where 5 antennas have sensitivity to both polarization components at the same place recording the full radio signal at the same time (Fig. 1). The LOPES antennas are triggered by the original KASCADE and in addition by the KASCADE-Grande particle detector array which benefits from the extended detection area, and allows the analysis of higher-energy events at larger distances with better accuracy [4].

III. Data selection and polarization analysis

For the current studies we have used data recorded during roughly two years of polarization measurements, by using the well-reconstructed shower parameters provided by KASCADE in the energy range of about $10^{16.5}$-$10^{17.8}$ eV. Large statistics in radio detected events are obtained by requiring high particle numbers measured by KASCADE and the shower center close to the antennas. Therefore, only showers falling inside the KASCADE array were used for the moment. The analysis of the radio signal is performed by applying the LOPES standard reconstruction pipeline [2] to each polarization direction separately and independently (15 channels, each). The considered observables are the CC-Beams (cross-correlation beams) calculated per individual polarization component from the measured field strengths per antenna. The total number of triggered events which are used for this analysis is given by 959 selected showers. Fig. 2 shows the energy and zenith angular distributions of the triggered, and the radio detected events. For the following studies an energy cut of

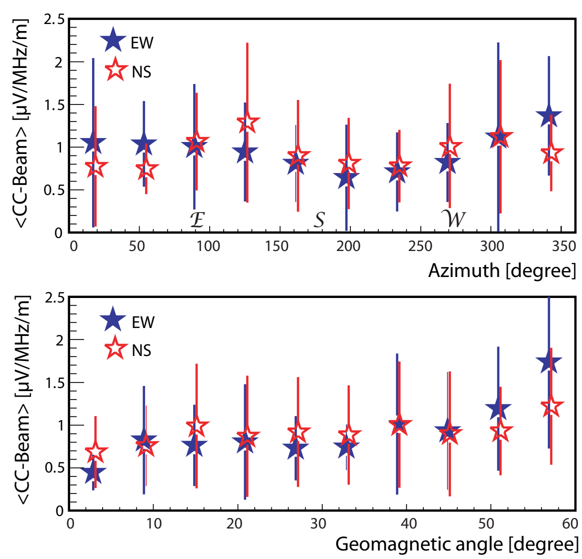

Fig. 3: The normalized CC-Beam values for both polarization components vs. the primary azimuth angle (top panel) and geomagnetic angle (bottom panel). Only events with an estimated primary energy $> 10^{16.9}$ eV are used. Mean values and spread of the distributions are shown.

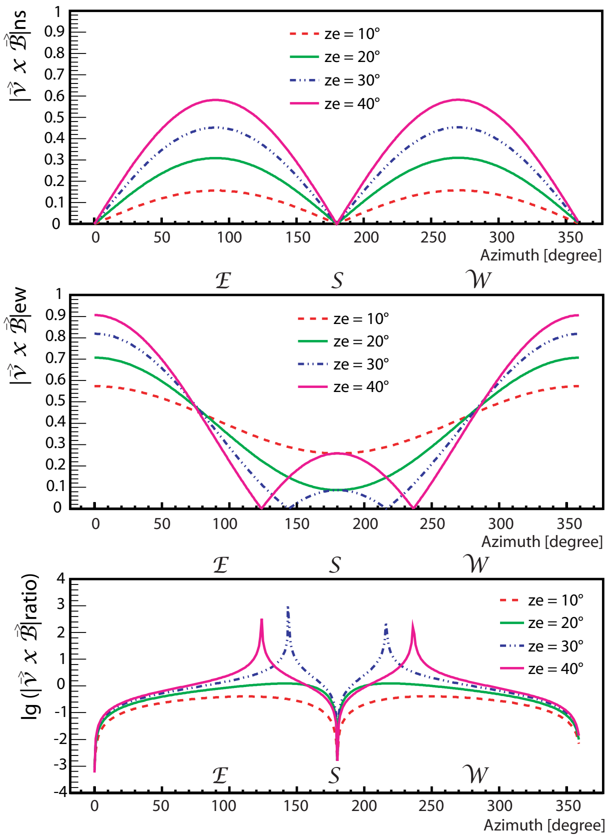

Fig. 4: Relative contributions of the $\vec{v} \times \vec{B}$-vector for the polarization components north-south (top panel), east-west (middle panel), and their ratio (bottom panel) vs. the azimuth angle calculated for different zenith angles.

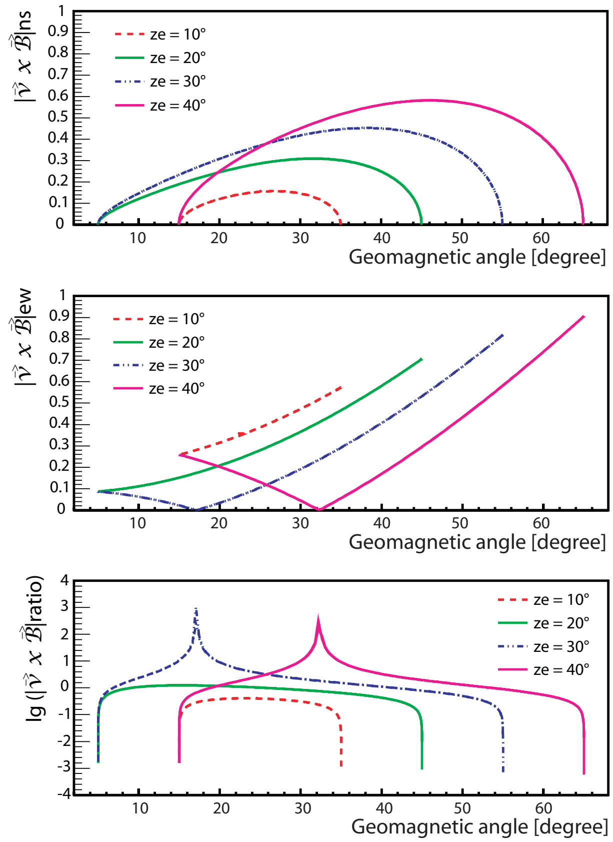

Fig. 5: Same as Fig.4, but vs. the geomagnetic angle.

$E > 10^{16.9}$ eV is chosen in order to avoid any efficiency biased effect on the investigated polarization characteristics. Fig. 3 shows the mean values (and width of the distributions) of the CC-Beam in dependence on shower azimuth and geomagnetic angle (angle between shower axis and the geomagnetic field). The reconstructed CC-Beam value is normalized to the estimated muon number of the EAS and to the mean distance of the antennas to the shower axis in order to minimize the influence of others than directional dependences on the distributions. Slight variations of the radio signal with the azimuth and geomagnetic angles are observed, as well as slight differences between the two polarization directions. A possible origin of these differences is discussed in the following sections.

IV. Polarization characteristics

The radio emission of cosmic ray air showers generated by the geo-synchrotron mechanism is expected to be highly linearly polarized. As predicted by sophisticated Monte Carlo simulations of the radio emission, the signal is usually present in both polarization components whose strengths depend directly on the shower azimuth for a given zenith angle (and therefore also on the geomagnetic angle) [5]. Already in early models of geomagnetic emission mechanisms, the expectation was that, to first order, the emission is polarized in the direction perpendicular to the air shower axis and geomagnetic field, outlined also in [5]. In other words, the polarization characteristics follow a behavior described by a unit polarization vector: $\vec{v} \times \vec{B}$, $\vec{v}$ being the direction of the incoming shower axis and $\vec{B}$ of the Earths magnetic field at the location of the experiment (for Karlsruhe, zenith $= 25°$ and azimuth $= 180°$). Recently, there have been suggestions [6] that, in addition to the polarization characteristics, also the absolute amplitude of the electric field in a first approximation can be considered to be proportional to this Lorentz force. The unit polarization vector is calculated for fixed zenith angles for each individual projection of the polarization, where the north-south part, east-west part, and their ratio (north-south/east-west) are displayed in Figs. 4 and 5. These figures show the dependence of the polarization components of the radio signal on the direction of the shower axis. They emphasize that, in Karlsruhe, considering pure shower geometry the north-south polarized channels are more sensitive to showers coming from east and west directions, and the east-west polarized channels have a higher sensitivity to showers coming from north and south.

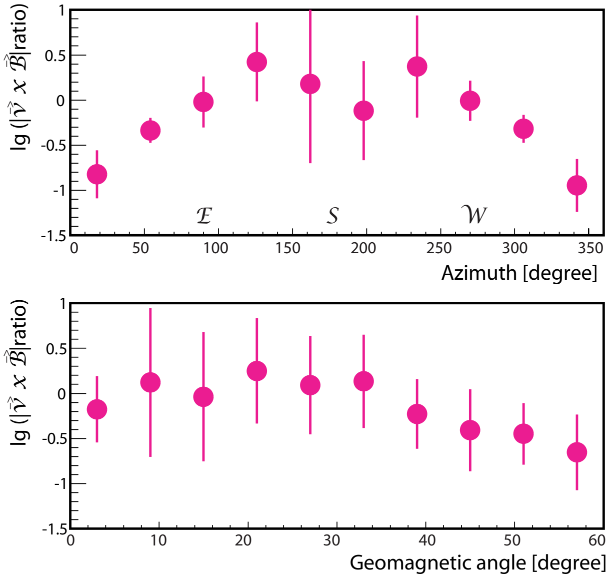

Fig. 6: Ratio of the north-south divided by the east-west component of the $\vec{v} \times \vec{B}$-vector for the measured events taking into account the geometry of the shower axis only vs. the azimuth angle (upper panel) and the geomagnetic angle (lower panel) of the shower. Mean values and spread of the distributions are shown.

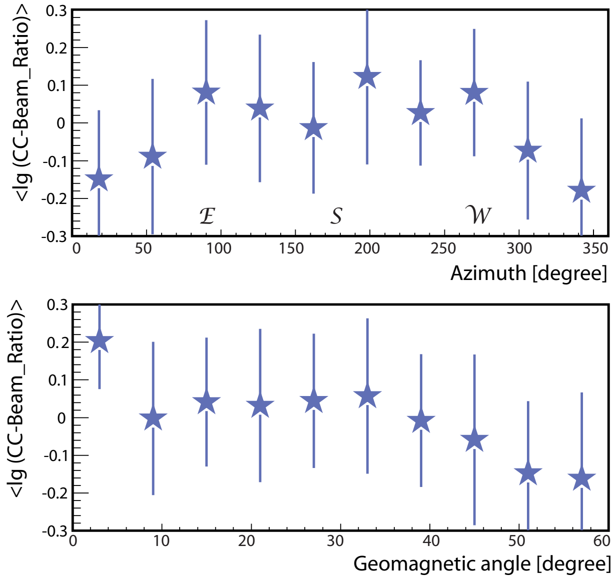

Fig. 7: Ratio of the reconstructed CC-beam values for the north-south and east-west polarization component of the measured events vs. the azimuth angle (upper panel) and the geomagnetic angle (lower panel). Mean values and spread of the distributions are shown.

V. Comparison with Data

To investigate if these expected relations are also seen in the measured data, we calculate the ratio of the north-south and east-west polarization contribution in terms of the $\vec{v} \times \vec{B}$-amplitudes for each individual measured event (Fig. 6) using the geometry of the EAS only. Thus, the displayed distributions reflect the dependencies shown in Figs. 4 and 5 for the sample of the selected radio detected events above a primary energy of $10^{16.9}$ eV. The ratio of the two polarization components is chosen in order to be independent of the energy and distance dependence of the measured amplitudes. It is obvious from figure 6, that there is a characteristic correlation of the ratio on the azimuth and geomagnetic angle expected, if the Lorentz force approximation is applicable. Finally, Fig. 7 shows the distributions of the measured events in their CC-Beam value of the pulse height ratio (north-south/east-west), where the same qualitative behavior is observed in their main characteristics.

VI. Summary and Outlook

Within the current configuration, LOPES is continuously performing polarization measurements since December 2006. The digital antenna array is absolutely amplitude calibrated, and thus we can pave the way for a better understanding of the radio signal as a complementary technique to large cosmic ray experiments. By LOPES-30, the signal is recorded in both polarization directions, east-west and north-south, independently. Meanwhile, a large number of events detected in both polarization directions is at disposal for detailed analysis. In this presentation, the ratio of the radio signal recorded in the north-south polarization direction vs. the signal recorded in the east-west direction was studied. Investigating this ratio in individual showers allows us to study the polarization characteristics of the signal independent of primary energy and distance of the antennas to the shower axis, i.e. in particular the dependence of the polarization on the direction of the incoming primary particle. Correlations of the pulse height ratio of both polarization components with the azimuth, as well as with the geomagnetic angle were compared with predictions of a first order approximation of models based on a geomagnetic origin of the emission. By this, the geomagnetic effect could be verified as a main mechanism in the radio emission process of cosmic ray air showers. Nevertheless, in future, detailed simulations are required for more reliable comparisons with the measurements; full detector simulations included.

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