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Recent results of the LOPES experiment

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LOPES measures radio pulses from extensive air showers and aims to calibrate the emitted signal in the primary energy range of $10^{16} - 10^{18}$ eV. LOPES, a digital radio interferometer using high bandwidths and fast data processing, is set up at the location of the KASCADE-Grande extensive air shower experiment in Karlsruhe, Germany and profits from the reconstructed air shower observables of KASCADE-Grande. We report about recent analysis results of the radio signals measured by LOPES.

1. Introduction

The main goals of the LOPES project [1] are the investigation of the relation between the radio emission from extensive air showers with the properties of the primary particles, and the development of a robust, autonomous, and self-triggering antenna set-up usable for large scale applications of the radio detection technique [2,3]. In addition, within the frame of LOPES a detailed Monte-Carlo simulation program package is developed. The emission mechanism utilized in the REAS code (see [4] and references therein) is embedded in the scheme of coherent geo-synchrotron radiation. This paper sketches briefly recent results from LOPES, where the emphasis is put on investigations of signal characteristics (lateral extension, frequency spectrum, and polarization)

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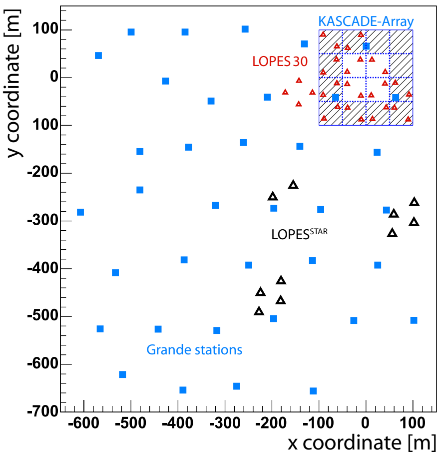

Figure 1. Sketch of the experimental layout of the LOPES experiment.

and of correlations of the registered radio signals with the properties of the primary cosmic particles (arrival direction and energy) by measuring in coincidence with the EAS experiment KASCADE-Grande [5].

2. LOPES layout and data processing

In the current status LOPES operates 30 short dipole radio antennae (LOPES30, fig. 1) having an absolute amplitude and a time calibration [6]. In addition, LOPES runs a field of logarithmic-dipole-antennae (LPDA) which are optimized for operation at the Pierre-Auger-Observatory, and for developing a self-trigger system (LOPES$^{\mathrm{STAR}}$ [3]). All the antennae operate in the frequency range of $40-80$ MHz. The read-out window for each LOPES30 antenna is 0.8 ms wide, centered around the trigger received from KASCADE. The sampling rate is 80 MHz.

The LOPES30 data processing includes several steps [7]. First, the relative instrumental delays are corrected using a known TV transmitter visible in the data. Next, the digital filtering, gain corrections and corrections of the trigger delays based on the known shower direction (from KASCADE) are applied and noisy antennae are flagged. Then a time shift of the data is done and the combination of the data is performed calculating the resulting beam from all antennae. This digital beam forming allows to place a narrow antenna beam in the direction of the air shower. To form the beam from the time shifted data, the data from each pair of antennae is multiplied time-bin by time-bin, the resulting values are averaged, and then the square root is taken while preserving the sign resulting in the so-called CC-beam. Finally, there is a quantification of the radio shower parameters by fitting a Gaussian to the smoothed data. The obtained field strength, ϵ, is the peak height of the Gaussian divided by the effective bandwidth. This value is then compared with shower observables from KASCADE-Grande, e.g. the angle of the shower axis with respect to the geomagnetic field, the electron or muon content of the shower, the estimated primary energy, etc.

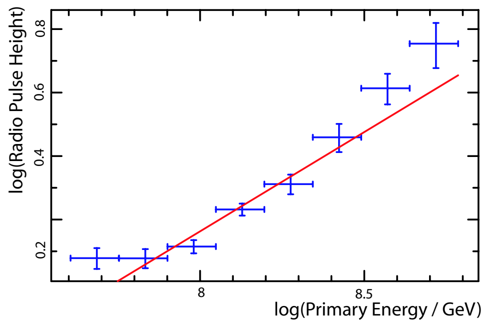

Figure 2. Average radio pulse height plotted versus the estimated primary particle energy [8].

3. Correlation with primary energy

The correlation of the radio pulse height (CC-beam) measured by LOPES30 with the primary particle energy calculated from KASCADE-Grande data [8] is analyzed. The fits of the dependencies of averaged pulse heights with the EAS parameters geomagnetic angle, distance to the shower axis, and primary energy are made iteratively and result in specific relations, e.g. with the primary energy to $\epsilon_{\mathrm{EW}}/[\mu\mathrm{V/m/MHz}] \propto (\mathrm{E_p}/10^{17}\mathrm{eV})^{(0.95\pm0.04)}$ (fig. 2). The found power-law relation with an index close to one (linear dependence of the field strength with the primary energy) serves as proof of the coherence of the radio emission during the shower development.

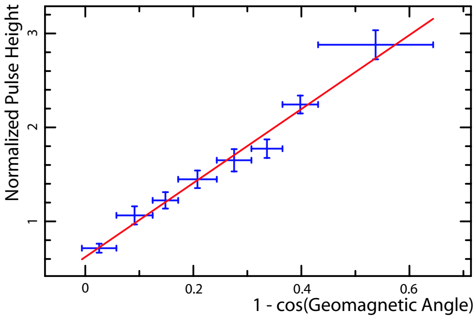

Figure 3. Averaged radio pulse height plotted versus the the angle to the geomagnetic field [8].

4. Correlation with the geomagnetic field

A clear correlation of the pulse height with the geomagnetic angle (angle between shower axis and geomagnetic field direction) was also found indicating a geomagnetic dependence for the emission mechanisms (fig. 3). One issue that has to be kept in mind is that this analysis is only made with the east-west polarized component, which can be the reason for the debatable functional form $(1 - \cos\alpha)$ of the correlation.

5. Lateral extension of the radio signal

For the analysis of lateral distributions of the radio emission in individual events, showers with a high signal-to-noise ratio were selected, and an exponential function $\epsilon = \epsilon_0 \cdot \exp(-R/R_0)$ was used to describe the field strengths measured by individual antennae. The fit contains two free parameters, where the scale parameter, R_0, describes the lateral profile and ϵ_0 the extrapolated field strength at the shower axis at observation level (example event see fig. 4). The distribution of the obtained scale parameters peaks at $R_0 \approx 125$ m but has a tail with very large $R_0 > 1000$ m. Roughly 10% of the investigated showers show very flat lateral distributions with very large scale parameters. These remarkable experimental findings are not understood and require further investigation with higher statistics. The field strength, ϵ_0, exhibits in almost all cases reliable values, i.e. they represent the above mentioned linear behavior with the primary energy.

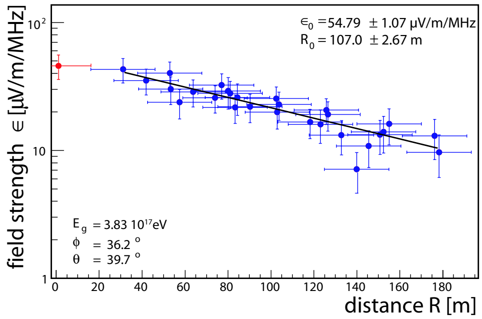

Figure 4. Lateral distribution for an individual shower reconstructed from single antenna signals [9].

6. Polarization characteristics

After measurements of the lateral behavior of the signal of the east-west polarization component by all 30 antennae, the LOPES30 set-up was reconfigured to perform dual-polarization measurements. Half of the antennae have been configured for measurements of the north-south polarization direction. First measurements [10] show a dependency of the CC-beam ratio (North-South polarization pulse height divided by the East-West pulse height) with the azimuth angle of the arriving primary (fig. 5). This dependence in the form of ratio>0 (the North-South polarization component is dominant) for showers arriving from South, respectively ratio<0 (the East-West polarization component is dominant) for showers arriving from North again hints at a geomagnetic dependence of the emission mechanism.

7. Frequency spectrum

For a sample of a few strong events, the radio frequency spectrum received from cosmic-ray air showers in the east-west polarization direction over a frequency band of 40 MHz could be analyzed. The radio data are digitally beam-formed before the spectra are determined by sub-band filtering [11]. The resulting electric field spectra fall off to higher frequencies for all events. But, the spectral slopes depend on the length of the pulse, where longer pulses have more amplitude at lower frequency resulting in steeper spectra. However,

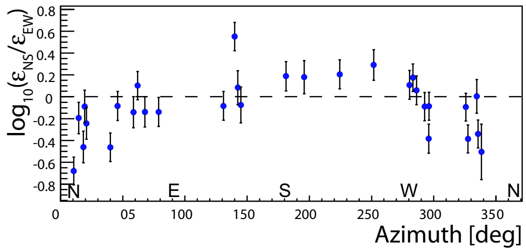

Figure 5. Pulse height ratio (North-South polarization component divided by East-West polarization component) vs. azimuth angle.

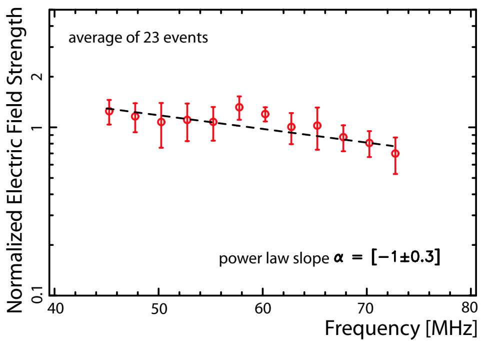

Figure 6. Comparison of average cosmic-ray electric field spectra obtained with 23 events. The frequency bin values determined on the CC-beam are fitted with a power law function (dashed line) [11].

the spectra do not show a significant dependence on the electric field amplitude, the azimuth angle, the zenith angle, the curvature radius, nor the average distance of the antennae to the shower core positions. The average frequency spectrum of the investigated events is shown in fig. 6.

8. Summary

With LOPES the proof-of-principle for the detection of cosmic particles by radio flashes from extensive air showers could be performed. First results obtained by correlating the observed radio field strength with the shower parameters obtained by the KASCADE measurements appear to be very promising for a more detailed understanding of the emission mechanism from atmospheric showers. Most interesting results are the quadratic dependence of the radio-power on energy, the correlation of the radio field strength with the direction of the geomagnetic field, and the exponential behavior of the lateral decrease of the field strength with a scaling parameter in the order of hundreds of meters. Large scaling radii allow us to measure the same field strength at larger distances from the shower core, which will be helpful for large scale applications of the radio detection technique. In addition, the quadratic dependence on energy will make radio detection a cost effective method for measuring air showers. These results place a strong supportive argument for the use of the radio technique to study the origin of high-energy cosmic rays.

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