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The LOPES experiment

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Cosmic ray particles hit the Earth's atmosphere and induce extensive air showers (EAS). These EAS mainly consist of electrons and positrons that produce radio emission due to their interaction with the Earth's magnetic field. Measuring this radio emission is the purpose of the LOPES (LOFAR Prototype Station) experiment.
LOPES is located at Campus North of the Karlsruhe Institute of Technology at the same site as the EAS particle detector KASCADE-Grande. Since the first measurements in 2003, LOPES was improved by various experimental setups and could establish the radio technique. By now, detailed studies of the measured radio signal are performed, like the behaviour of the lateral distribution or the polarization of the electric field. Furthermore, with LOPES the dependence of the radio pulse on properties of the incoming cosmic ray, like primary energy, primary mass, or incoming direction is investigated. In this article we describe the different LOPES setups, next we explain our standard analysis procedure and then we discuss some highlights of our recent results.

1. Introduction

The first discovery of radio emission from cosmic ray air showers was already in the 1960s [1]. But due to the lack of digital electronics and the huge progress of particle detector techniques the radio measurements played a minor role for some decades. Over the last years the capability of the radio detection of cosmic ray air showers had been rediscovered and the LOPES experiment [2] is playing a pioneering role. LOPES is located at the Campus North of the Karlsruhe Institute of Technology, at the same site as the air

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shower detector KASCADE-Grande [3,4]. This is the main advantage of LOPES over other radio experiments like CODALEMA [5], because KASCADE-Grande provides a trigger and high-quality per event air shower information.

LOPES is an array of radio antennas used as a digital interferometer. The experiment was rebuilt several times to study different aspects of the radio emission of cosmic ray air showers and to test the capability of the radio technique to measure air shower properties like primary mass, primary energy or the arrival direction.

2. Experimental set-up

The experimental setup of LOPES changed several times to address different scientific questions. Fig.1 shows an overview of the different phases. LOPES is based on the design of LOFAR [6], a digital radio observatory for astronomy. The deployed antennas are inverted v-shaped dipole antennas and only in the latest setup, LOPES 3D, a different antenna type has been used. In Fig.2 the antenna positions are shown, exemplarily for LOPES 30 pol. For all setups LOPES is measuring in the frequency range from 40 to 80 MHz with a sampling rate of 80 MHz, that is in the second Nyquist zone. LOPES receives a trigger from KASCADE-Grande for air showers with an energy above $\approx 10^{16}$ eV and the data is read out digitally. Now we describe the unique characteristics and scientific goals of each setup.

LOPES 10 consisted of ten dipole antennas. In this first setup all antennas were east-west aligned because one expects a signal mainly polarized along the east-west direction for a geomagnetic origin of the radioemission. The first idea of the LOPES experiment was to show that it is possible to measure the radio emission of cosmic ray air showers with a digital radio array like LOFAR using digital interferomtery. Besides the delivery of this "proof of principle" it was possible to show a correlation of the radio signal with primary energy and first characteristics of the radio signal could be investigated [2].

The next setup, LOPES 30, was dedicated to measuring the lateral distribution of the radio signal. The number of antennas increased to 30 east-west aligned antennas and therefore also the baseline increased. This led to higher sensitivity and a better angular resolution. During the LOPES 30 period the first absolute amplitude calibration took place and we started with a monitoring of the atmospheric electric field. For the LOPES 30 pol setup half of the antennas have been rotated to measure the north-south polarization. At five antenna positions both polarizations were measured, see Fig.2. Measuring the different polarizations can give further information about the emission mechanism.

The LOPES 3D setup consists of ten antenna stations, each consisting of three dipoles. These so called tripols are able to measure the complete 3-dimensional E-field vector. The LOPES 3D setup was built in February 2010 and by now all calibration steps have been successfully performed and we can start with the first analysis of the new data.

LOPES^{STAR} is an extension to LOPES running in parallel to the other setups. The main challenge for this setup is the research and development for large scale radio experiments, like the Auger Engineering Radio Array (AERA) [7,8]. Different antenna types like the LPDA and the SALLA [9] and a sophisticated digital self-trigger [10] have been developed with this setup. It consists of ten dual-polarized antennas of different types and they are distributed over the whole KASCADE-Grande array, see also Fig.2.

3. Analysis procedure

A big challenge for the LOPES experiment is the high noise level at KIT Campus North. Therefore it is necessary to have a sophisticated analysis procedure. The different steps that are applied to the data in our standard reconstruction are presented in this chapter.

To transform the measured ADC counts to the electric field, an absolute amplitude calibration is applied to the data. Therefore, several measurement campaigns with a calibrated reference source took place over the years. As shown in Fig.3 for one antenna the gain stays stable and the remaining systematic uncertainties caused by

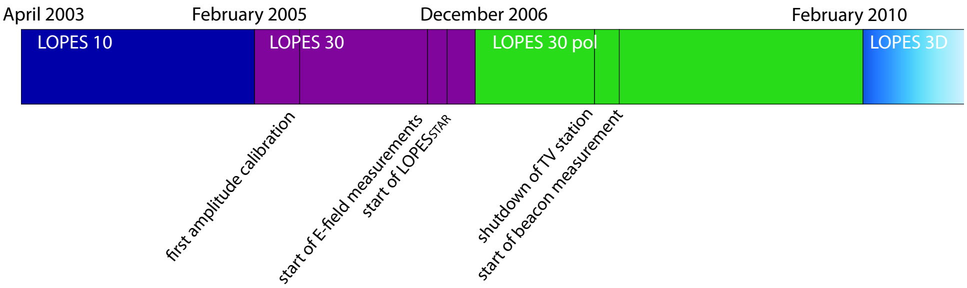

Figure 1. Time-line showing the different phases of the LOPES experiment.

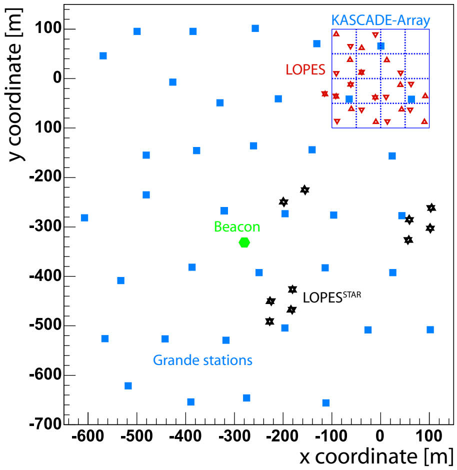

Figure 2. Layout of the LOPES 30 pol setup. Triangles represent either east-west or north-south aligned antennas, stars represent positions with east-west and north-south antennas.

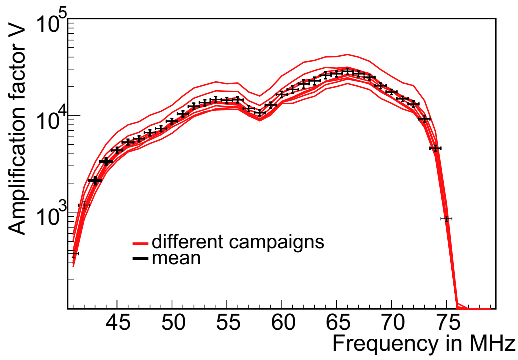

Figure 3. Measured gain over frequency for one antenna. The different campaigns took place during different weather conditions.

environmental conditions like weather are around 13% in the power of the electric field [11]. Although the chosen frequency band does not include the main broadcasting stations there is still narrow-band radio frequency interference that is digitally filtered out.

The next step is the delay and dispersion correction for the individual antennas. The different delays are mainly due to different cable length and the dispersion is caused by the filters. For an interferometric analysis a high precision relative timing between the antennas is needed. This is achieved with a reference signal. In the beginning of the LOPES experiment a TV-transmitter was used. But this was shut down during the LOPES 30 period and a self-made reference antenna, the beacon, has been deployed instead. The achieved timing accuracy is around 1 ns [12].

As already mentioned, LOPES is measuring in the second Nyquist domain. This means that the data can be upsampled, i.e. correctly interpolated, to a higher sampling rate.

Then the beam-forming is performed. The traces of the antennas are rearranged according to the arrival direction of the air shower and the curvature of the radio front. In the next step the calculation of the cross-correlation beam (CC-beam) is done from block averaged data. An example of the upsampled and beamformed trace and the associated CC-beam and Gaussian fit is shown in Fig.4. The last steps are done in an iterative loop at which the arrival direction and the spherical wavefront curvature are varied to maximize the CC-beam.

In addition some quality cuts on KASCADE-Grande reconstructions and radio properties have to be applied to the data. Furthermore we have to take care of the athmospheric electric field: ex-

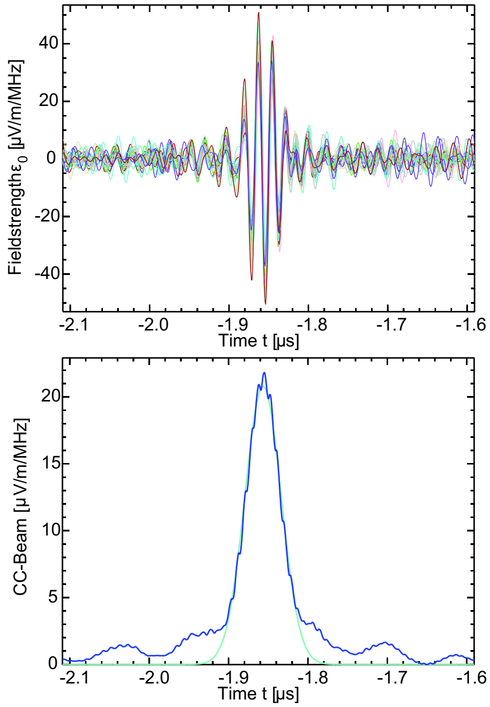

Figure 4. Top: Up-sampled and beam-formed cosmic ray radio pulse for the individual LOPES antennas. Bottom: Calculated CC-beam (dark) and the corresponding Gaussian fit (light).

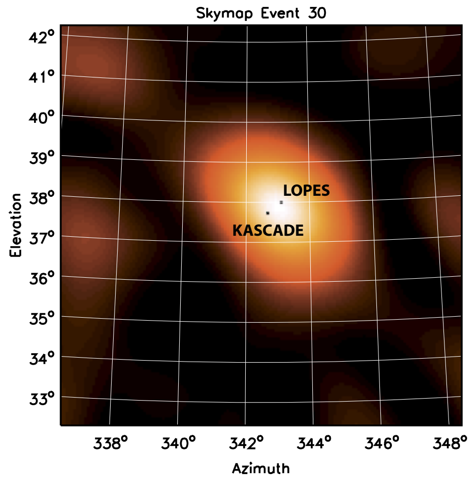

Figure 5. Calculated CC-beam for a section of the sky. The brightest point corresponds to the maximum of the CC-beam and therefore to the arrival direction of the air shower gained with LOPES.

tremely high athmospheric electric fields like during thunderstorms can effect the radio emission and data taken under such conditions have to be analysed seperately [13].

After this procedure we can use either the CC-beam for the data analysis or, for high signal-to-noise events, the maximum amplitude of the individual antennas.

4. Results based on the CC-beam

In this chapter we want to discuss some of the major results achieved with an analysis based on the CC-beam calculations.

Fig.5 shows the measured CC-beam for a section of the sky. The maximum of the CC-beam is the reconstructed arrival direction obtained with LOPES. This fits well with the arrival direction obtained from KASCADE-Grande. We achieve an angular resolution better than 1.5°, limited by the unknown shape of the radio front [14].

Another important result achieved with the LOPES 30 setup is the dependence of the electric field strength of the radio signal on primary energy, distance to the shower axis and geomagnetic angle as presented for the energy in Fig.6 [15]. The electric field can be parametrized with the following formula, where α is the angle between shower axis and the Earth's magnetic field, θ is the shower zenith angle, $\mathrm{R_{SA}}$ is the mean distance of the antennas to the shower axis and $\mathrm{E_p}$ is the primary particle energy.

$$\epsilon_{\mathrm{est}} = (11 \pm 1.)\left((1.16 \pm 0.025) - \cos\alpha\right)\cos\theta$$
$$\exp\left(\frac{-\mathrm{R_{SA}}}{(236{\pm}81)\,\mathrm{m}}\right)\left(\frac{\mathrm{E_p}}{10^{17}\mathrm{eV}}\right)^{(0.95\pm0.04)}\left[\frac{\mu\mathrm{V}}{\mathrm{m\,MHz}}\right] \qquad (1)$$

The errors are the statistical errors of the fit. It is planned to redo the parametrization also for the north-south polarized electric field.

The investigation of the different polarizations of the electric field is still ongoing. These investigations can give additional information on the emission mechanisms of the radio signal. First investigations show a dependence on the azimuth and zenith angle [16]. For a simplified geomagnetic model we can calculate the ratio of the polarizations from the Lorentz force, the so-called vxB model [17]. Fig.7 shows a comparison of the

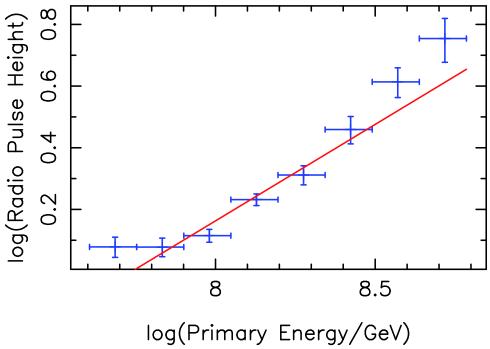

Figure 6. Correlation of the LOPES 30 normalized electric field strength with primary energy.

expected ratio from the simplified model - for the individual geometry of each event - with the measured LOPES data - from the same event - over the azimuth angle. For the Earth's magnetic field in Karlsruhe one expects low signal in both polarizations for showers coming from the south, that means less events can be seen. Although the main characteristics are similar, a deviation is visible, mainly for showers coming from the north. This might be due to an additional emission mechanism but further studies are needed to draw a final conclusion.

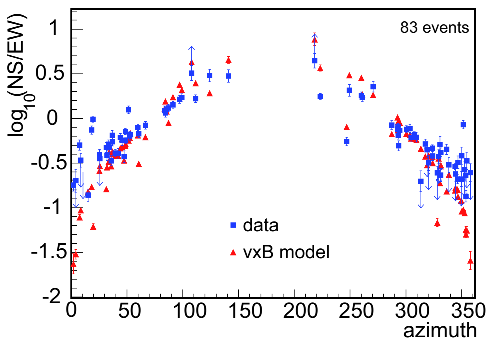

Figure 7. North-south to east-west ratio over azimuth for LOPES 30 pol data compared with the simplified vxB model.

5. Results based on signal of individual antennas

This chapter shows some highlights of our results based on the signal of individual antennas.

For the lateral distribution the field strength of individual antennas is plotted against the distance to the shower axis. Investigations show that 80% of the lateral distributions can be described by an exponential. The other 20% are flat events or events that flatten towards the shower core [18]. The lateral distributions can be compared with simulations of radio emission from air showers, like REAS3 [19]. REAS3 is a Monte Carlo code simulating radio emission from air showers. It includes complex air shower information and has no free parameters. As Fig.8 shows, REAS3 simulations and data are in notably good agreement for most events. This is the first time that simulations can reproduce the absolute field strength. The reason for the deviation of the remaining ones is under investigation.

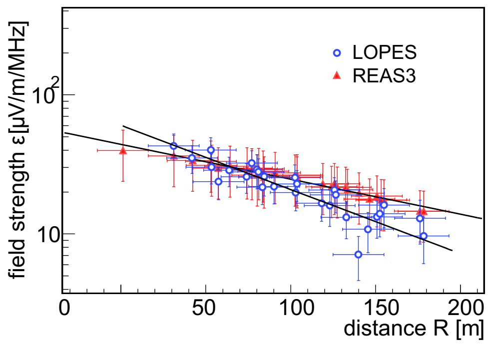

Figure 8. Comparison of the LOPES 30 lateral distribution with REAS3 simulations for one event.

Another important question is the sensitivity of LOPES on the primary mass. From REAS2 simulation we expect a dependence of the lateral distribution on the primary mass [20]. First investigations deal with the slope parameter R_0. KASCADE-Grande provides the ratio of electron to muon number, an estimator for the primary mass. High electron to muon ratios correspond to heavy primaries and therefore should show a large R_0. Fig.9 shows the ratio N_μ/N_e over the slope parameter for LOPES data. A detailed analysis, including a revised noise treatment for the LOPES data [21], is needed before any statement can be made.

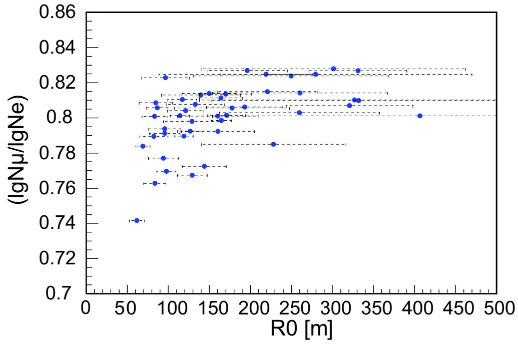

Figure 9. Correlation of the radio lateral slope parameter R_0 with the mass sensitive ratio of muons to electrons measured by KASCADE for the LOPES data.

6. Conclusion and Outlook

LOPES started 7 years ago with the "proof of principle" for digital radio measurements of EAS. Since then this detection method improved and today there exist many radio experiments worldwide. LOPES still plays a major role in the investigation of the characteristics of the radio signal and the capability of the radio measurements on the reconstruction of primary energy, primary mass and arrival direction. LOPES could show that the radio emission of cosmic rays is coherent in the frequency range from 40-80 MHz and as a result the field strength scales quadratically with energy. LOPES also confirms a dependence on the geomagnetic angle and therefore a mainly geomagnetic origin of the radio emission. Investigations show a dependence of the polarization on azimuth and zenith angle and it seems profitable to look deeper into polarization behaviour also with the LOPES 3D setup. The first analysis of the mass dependence of the slope parameter looks promising but still needs detailed systematic studies. The absolute calibrated lateral distributions of LOPES allow accurate comparisons with simulations and there is quite good agreement with REAS3.

LOPES will contribute to further challenges in the field like realizing a self-trigger or the accurate determination of primary energy and mass and will continue to pave the way for large scale experiments like AERA to study high energy cosmic rays.

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