Improved radio data analysis with LOPES

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Abstract: The LOPES experiment at the Campus North of the KIT measures radio emissions of high energy cosmic ray air showers. The data set taken with the inverted V-shaped dipoles used in LOPES until beginning of 2010 is now completed and ready for a final analysis. In addition, the Monte Carlo simulation code REAS3 is used for calculating the expected radio signals in individual antennas for individual events. These signals undergo a new detailed detector simulation including instrumental effects like the antenna gain pattern, filter effects, cable delays and correct sampling with an output in the standard LOPES event-file format. For the first time we can process simulated data with the LOPES analysis pipeline that is also used for measured data. This allows us to investigate the accuracy of our reconstruction pipeline itself, the influence of noise on the reconstruction as well as to compare the simulations directly with the measured signals. The goal is to investigate the capability of the radio detection technique in terms of sensitivity to the primary energy, the arrival direction and the primary mass of high energy cosmic rays.

Keywords: LOPES, REAS3, radio

1 Introduction

Over the last years, the radio detection of cosmic ray air showers is on its way to become a coequal detection method with particle or fluorescence detection, and the LOPES experiment [1] is playing a leading role in this process. LOPES was built in 2003 with 10 east-west aligned antennas in a first phase, see Fig. 1. In the next phases, first, the number of antennas was increased and second, half of them were rotated to the north-south direction. For these three phases, inverted V-shaped dipoles were used. In a last phase, the antenna type was changed and now LOPES measures with ten tripoles, each consisting of three crossed dipoles [2]. This allows a measurement of the 3-dimensional E-field vector. The digital electronics and therefore the frequency range from 40-80 MHz is kept for all phases. Since LOPES is an antenna array, it is possi-

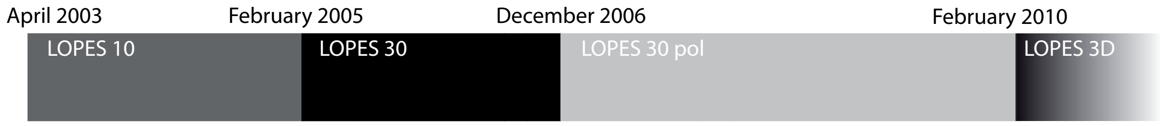

Figure 1: Time-line showing the different phases of the LOPES experiment.

ble to do an interferometric analysis of the measured radio signal.

The main advantage of LOPES is its co-location with the KASCADE-Grande experiment [3, 4] at the Karlsruhe Institute of Technology, Campus North in Karlsruhe, Germany. The KASCADE-Grande experiment provides a trigger on high energy cosmic rays and detailed shower information. This makes LOPES a unique experiment to demonstrate the capabilities of the radio detection technique.

2 Data Set

With the first ten antennas, LOPES could provide the “Proof of Principle” for the measurement of radio emission from cosmic ray air showers by digital interferometry [1]. However, for a detailed analysis of the radio emission the number of antennas was too small. Therefore, the main analysis is based on the “LOPES 30” and “LOPES 30 pol” setups. The “LOPES3D” setup will be analyzed separately since the antenna type has an influence on the reconstruction. With the “LOPES 30” and “LOPES 30 pol” setups, almost 2 million events have been triggered and could be reconstructed by either KASCADE or KASCADE-Grande. This reconstruction includes a cut on the core position, and the zenith angle has to be below 40°. Most of these events have a primary energy below 10^{17} eV and thus are below the LOPES threshold. This necessitates a cut on the primary energy which reduces the number of events to around 3500. However, not all remaining events show a high radio signal in LOPES which requires an additional cut on the quality of the radio signal: We demand a high signal to noise ratio and an highly coherent signal, which means that the maximum of the cross-correlation-beam (CC-beam) is high above the noise and most of the power is coherent (see also Eq. 1 and Sec. 3.1). This results in almost 1000 good-quality radio events for around five years of measurement. They separate into both KASCADE and KASCADE-Grande events, and “LOPES 30” and “LOPES 30 pol” events. The energy distribution for each of these four groups is shown in Fig. 2.

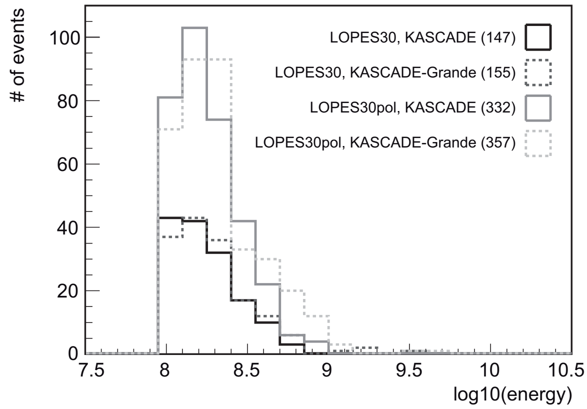

Figure 2: Energy distribution reconstructed by KASCADE-Grande for the selected LOPES events of the four analysis groups. The number given in brackets is the total number of events for this group.

3 Software

3.1 CosmicRay-Tools (CR-Tools)

For an analysis of the LOPES data the LOPES CR-Tools are used [5]. They include an absolute amplitude and time calibration, a filtering of narrow band radio frequency interference and an upsampling procedure. The latter is possible, because LOPES measures with a sampling rate of 80 MHz, and with an effective bandwidth of 40 MHz, i.e. in the 2nd Nyquist domain [6]. Furthermore, a reconstruction of the direction using digital interferometry is applied to the data: Starting with the arrival direction given by KASCADE-Grande, a geometrical time delay between the antennas based on a spherical wavefront with a typical radius is calculated and corrected for. This procedure requires a timing accuracy of less than 1 ns which can be achieved by using the reference signal of the beacon [7]. In the next step, the CC-beam is calculated with

$$CC(t) = \pm\sqrt{\left|\frac{1}{N_{\mathrm{ant}}}\sum_{i=1}^{N-1}\sum_{j>i}^{N} s_i(t)s_j(t)\right|} \tag{1}$$

where N is number of antennas and $s_{i,j}$ the signal in antenna i/j. Then the data is block-averaged and a Gaussian function is fitted. In an iterative procedure, the fit is maximized by varying the direction and the radius of the wavefront. This results in an arrival direction reconstructed with LOPES and a specified curvature radius for each event.

An analysis of the data can either be done based on the calculated CC-beam or on the signal of individual antennas. Due to the fact that only the shower signal of different antennas – and not the measured noise – is coherent, the signal to noise ratio for the CC-beam is much higher than for single antennas. Therefore, not all events are suited for single antenna analysis.

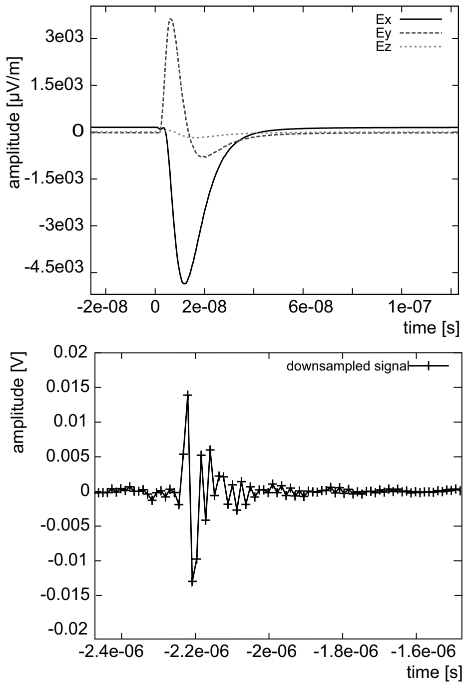

Figure 3: Electric field given by REAS3 (full bandwidth, upper plot) and signal after detector simulation (lower plot) for one antenna

3.2 Detector simulation

Until recently, the CR-Tools could not be used for simulated events because the LOPES detector simulation was not available. Now it is possible to do a full detector simulation for an event simulated with the REAS code [8] and to store it in the LOPES file format in the following steps:

Read simulation: The output of the REAS simulation is the 3-dimensional electrical field at a specified antenna position given by the three components E_x, E_y and E_z in the ground system. These are read in and transformed into the shower plane coordinate system. Because there is no radio emission along the shower axis, the electric field reduces to a 2-dimensional vector which is transformed to the frequency domain via FFT.

Apply instrumental effects: Using the gain pattern of the antenna, the total signal measured in each antenna channel is calculated. Filter effects and electronic induced time delays are considered and the absolute amplitude calibration is used to convert the electric field into a voltage. The signal is then resampled to the LOPES sampling rate of 80 MHz.

Apply Noise: Optionally, noise can be added to the signal. It is possible to add narrowband transmitters as well as broadband noise. Narrowband transmitters can be used, e.g., to add a beacon signal. To add the typical broadband noise of LOPES, a measured trace, without an air shower signal, is used.

Generate .event file: In the last step, the voltage is converted to an ADC count and the values are stored in the same binary file format as used for LOPES events. The simulated data can then be reconstructed and analyzed in the same way as measured LOPES data.

In Fig. 3, the electric field given by REAS3 and the voltage after the detector simulation is shown. So far, a comparison of data with simulation was only possible for an analysis based on single antennas, and only the bandwidth of the experiment, and not the full detector influence, had been considered. With the full detector simulation not only an improved comparison for single antennas is possible but also a comparison of the reconstructed CC-beam signal. This allows a more detailed study of data and simulations. Furthermore, the intrinsic accuracy of the reconstruction with the CR-Tools and the influence of noise on this accuracy can be tested.

4 First investigations

For a first investigation, events measured by LOPES have been simulated with REAS3 [9] using the shower information from KASCADE. Around 100 events with a high signal-to-noise ratio in the east-west polarization have been selected. In Fig. 4, the CC-beam of the LOPES data and the simulated event with and without broadband noise is shown. The height of the CC-beam is similar for simulation and data. Also, the signal in the single antennas is comparable, as shown in the lateral distributions in Fig. 4. The CR-Tools also provide the arrival directions reconstructed by maximizing the CC-beam. These are displayed in Table 1 for the same event as in Fig. 4 and also show good agreement.

	KASCADE	simulation w/o noise	simulation with noise	LOPES
φ	294.4	294.4	294.3	294.5
θ	37.85	37.80	37.78	38.07

Table 1: Reconstructed azimuth φ and zenith θ obtained with the CR-Tools for simulation (with and w/o noise) and LOPES data and the arrival direction from KASCADE

To study the intrinsic angular resolution of the CR-tools, the difference between the shower direction from KASCADE, used for the simulation, and the reconstructed direction from CR-Tools is considered. In Fig. 5, this difference is shown for simulations with and without noise. The influence of noise in the east-west polarized signal (EW) is not significant, however, it is relevant in the north-south polarized signal (NS). The reason is the selection criterion: all the selected events show a high signal in east-west but not necessarily in north-south. Therefore, east-west signals always have high signal to noise ratio, while the north-south signal can be quite low. For a high signal to noise ratio, the angle Ω between the simulated and reconstructed direction, i.e. the intrinsic angular resolution of our reconstruction is less than 1°. This is in agreement with former studies on data [10].

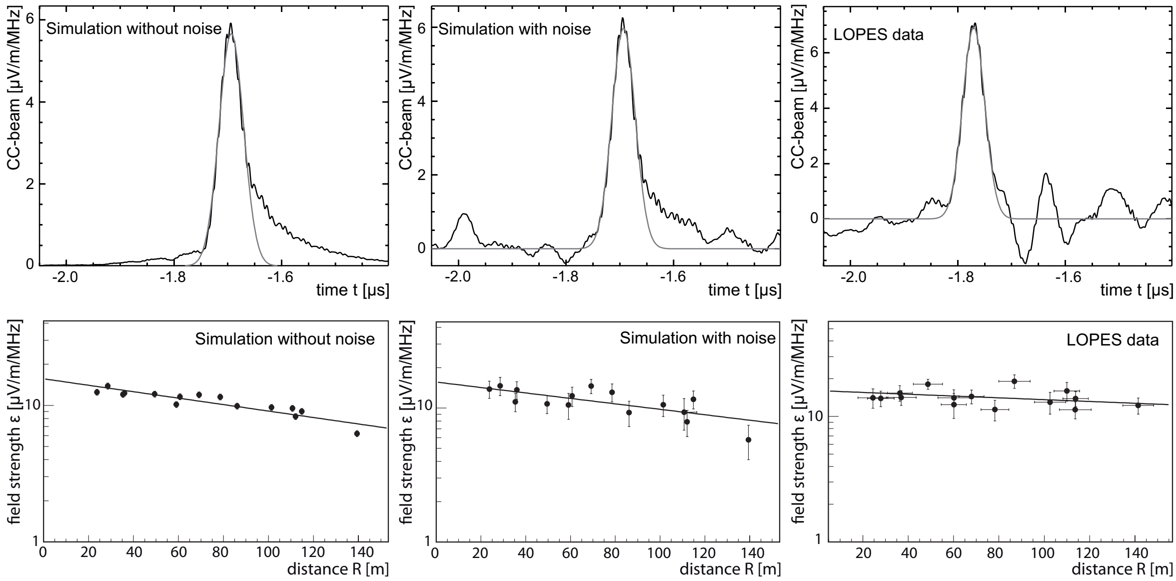

Figure 4: CC-beam (black) and Gaussian fit (gray) in the upper row, lateral distribution and exponential fit in the lower row for simulation (with and w/o noise) and LOPES data. The energy reconstructed by KASCADE is $10^{17.4}$ eV, with the arrival direction given in Tab. 1.

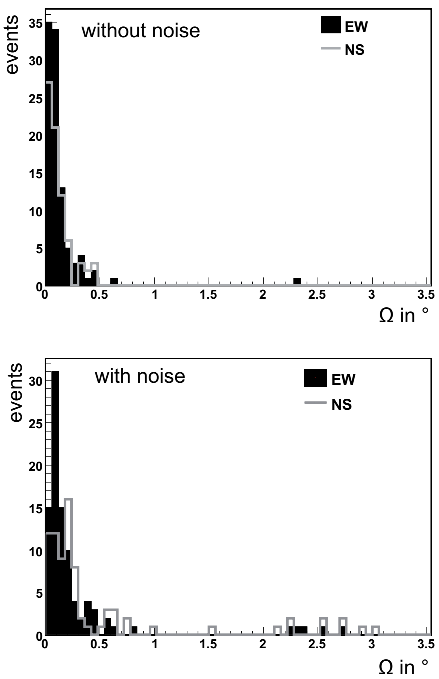

Figure 5: Angle Ω between the simulated and reconstructed direction once for simulations w/o noise and once for simulations with noise

5 Conclusion

With the new detector simulation, it is possible to process REAS3 simulations with the standard reconstruction software of LOPES. This allows to directly compare data and simulations and to do exactly the same analyses with both. First results show comparable signals in data and simulations but so far only a small number of events have been investigated. Studies of the arrival direction shows that our analysis provides an intrinsic angular resolution of less than 1°. This might be improved using a conical shape for the wavefront instead of a spherical one [11]. In the future, studies based on data and simulations like in [11] or [12], which investigate the capability of radio detection on primary mass, can be improved using the new detector simulation. Also, the energy reconstruction can be studied with much higher level of detail. With the complete data set and the corresponding simulations, a final analysis is on its way.

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