EAS RADIO DETECTION WITH LOPES

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Abstract

LOPES is set up at the location of the KASCADE-Grande extensive air shower experiment in Karlsruhe, Germany and aims to measure and calibrate radio pulses from Extensive Air Showers. Data taken during half a year of operation of 10 LOPES antennas (LOPES-10), triggered by EAS observed with KASCADE-Grande have been analysed. We report about the analysis of correlations present in the radio signals measured by LOPES-10. The extended set-up LOPES-30 consists of 30 antennas which now are absolute calibrated. Additionally, LOPES operates antennas of a different type (LOPES$^{\mathrm{STAR}}$) which are optimized for an application at the Pierre Auger Observatory.

1 Introduction

The traditional method to study extensive air showers (EAS) is to measure the secondary particles with sufficiently large particle detector arrays. In general these measurements provide only immediate information on the status of the air shower cascade on the particular observation level. This hampers the determination of the properties of the EAS inducing primary as compared to methods like the observation of Cherenkov and fluorescence light, which provide also some information on the longitudinal EAS development, thus enabling a more reliable access to the intended information (Haungs, Rebel & Roth, 2003).

In order to reduce the statistical and systematic uncertainties of the detection and the reconstruction of EAS, especially with respect to the detection of cosmic particles of highest energies, there is a current methodical discussion about new detection techniques. In this sense the radio emission accompanying cosmic ray air showers, though first observed in 1964 by Jelley et al. (1965) at a frequency of 44 MHz, is a somehow ignored EAS feature. This fact is due to the former difficulties with interferences of radio emission from other sources in the environment and of the interpretation of the observed signals. However, the studies of this EAS component has experienced a revival by recent activities.

This contribution sketches briefly the activities of the LOPES project (Falcke et al., 2005). The main emphasis is put on the calibration of the registered radio signals by measuring in coincidence with the EAS registration of the running EAS experiment KASCADE-Grande (Navarra et al., 2004). KASCADE-Grande is an extension of the multi-detector setup KASCADE (KArlsruhe Shower Core and Array DEtector) built in Germany (Antoni et al., 2003), measuring air showers in the primary energy range of 100 TeV to 1 EeV with high precision due to the detection of all charged particle types at sea-level, i.e. the electromagnetic, the muonic, and the hadronic shower component. Hence, LOPES, which is designed as digital radio interferometer using high bandwidths and fast data processing, will profit from the reconstructed air shower observables of KASCADE-Grande. Since radio emission arises from different phases of the EAS development, LOPES will provide complementary information and help to understand the observables measured with the particle detector array of KASCADE-Grande.

2 Emission process

Recent theoretical studies by Falcke & Gorham (2003) and Huege & Falcke (2003,2005) of the radio emission in the atmosphere are embedded in the scheme of coherent geosynchrotron radiation. Here, electron-positron pairs generated in the shower development gyrate in the Earth's magnetic field and emit radio pulses by synchrotron emission. During the shower development the electrons are concentrated in a thin shower disk ($< 2\,\mathrm{m}$), which is smaller than one wavelength (at 100 MHz) of the emitted radio wave. This situation provides the coherent emission of the radio signal.

Detailed analytical (Huege & Falcke, 2003) and Monte-Carlo simulations (Huege & Falcke, 2005) lead to expectations of relevant radio emission at frequencies of 10 MHz to 500 MHz with a coherent emission at low frequencies up to 100 MHz. For showers above a threshold energy of $\approx 5 \cdot 10^{16}\,\mathrm{eV}$ one expects a short, but coherent radio pulse of 10 ns to 100 ns with an electric field strength significantly above the galactic noise and proportionally increasing to the primary energy of the cosmic particle initializing the air shower. In addition, the geosynchrotron emission process is expected to be dominant for radio emission during the cosmic ray air shower development.

3 LOPES: General layout and data processing

The basic idea of the LOPES (= LOFAR prototype station) project is to build an array of relatively simple, quasi-omnidirectional dipol antennas,

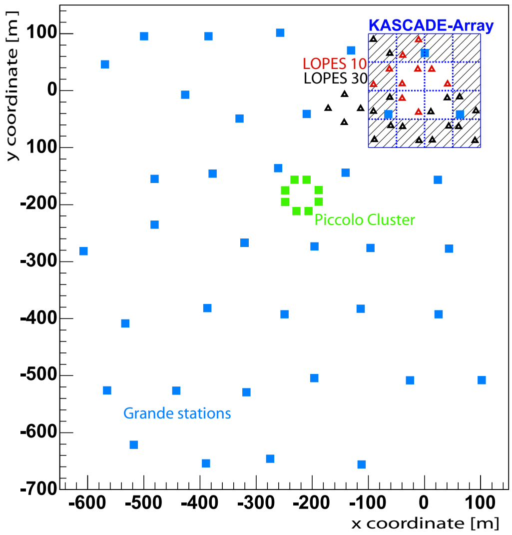

Figure 1: Sketch of the KASCADE-Grande – LOPES experiment: The 16 clusters (12 with muon counters) of the KASCADE field array, the distribution of the 37 stations of the Grande array, and the small Piccolo cluster for fast trigger purposes are shown. The location of the 30 LOPES radio antennas is also displayed.

where the received waves are digitized and sent to a central computer. This combines the advantages of low-gain antennas, such as the large field of view, with that one of high-gain antennas, like the high sensitivity and good background suppression. With LOPES it is possible to store the received data stream for a certain period of time, i.e. at a detection of a transient phenomenom like an air shower retrospectively a beam in the desired direction can be formed. To demonstrate the capability to measure air showers with these antennas, LOPES is built-up at the air shower, experiment KASCADE-Grande. The air shower experiment provides a trigger of high-energy events and additionally with it's direction reconstruction a starting point for the radio data analyses and the beam forming.

In the current status LOPES operates 30 short dipole radio antennas (LOPES-30), data of the first 10 antennas forming LOPES-10 are presently analysed.

The antennas, positioned within or close by the original KASCADE array (Fig. 1), operate in the frequency range of $40-80$ MHz and are aligned in east-west direction, i.e. they are sensitive to the linear east-west polarized component of the radiation what can be easily changed into the opposite polarization by turning the antennas. The read out window for each antenna is 0.8 ms wide, centered around the trigger received from the KASCADE array. The sampling rate is 80 MHz. The shape of the antenna and the steel ground screen gives the highest sensitivity to the zenith and half sensitivity to a zenith angle of 45°, almost independent on the azimuth angle. The logical condition for the LOPES-trigger is a high multiplicity of fired stations of the KASCADE array. This corresponds to primary energies above $\approx 10^{16}$ eV; such showers are detected at a rate of ≈ 2 per minute.

The LOPES data processing includes several steps (Horneffer, 2006). 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 antennas 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 antennas. The geometrical delay (in addition to the instrumental delay corrections) by which the data is shifted, is the

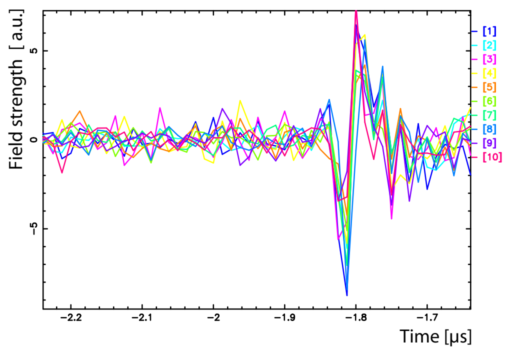

Figure 2: Raw signals of the individual antennas for one event example. The signals at this stage are prepared for the beam-forming based on shower observables reconstructed by KASCADE-Grande.

time difference of the pulse coming from the given direction to reach the position of the corresponding antenna compared to the reference position. This shift is done by multiplying a phase gradient in the frequency domain before transforming the data back to the time domain. This step includes also a correction for the azimuth and zenith dependence of the antenna gain. Fig. 2 shows a particularly bright event as an example. A crucial element of the detection method is the digital beam forming which allows to place a narrow antenna beam in the direction of the cosmic ray event. To form the beam from the time shifted data, the data from each pair of antennas is multiplied time-bin by time-bin, the resulting values are averaged, and then the square root is taken while preserving the sign. We call this the cross-correlation beam or CC-beam. Finally there is a quantification of the radio parameters: Although the shape of the resulting pulse (CC-beam) is not really Gaussian, fitting a Gaussian to the smoothed data gives a robust value for the peak strength, which is defined as the height of this Gaussian. The error of the fit results gives also a first estimate of the uncertainty of this parameter. The finally obtained value ϵ_ν, which is the measured amplitude divided by the effective bandwidth, is compared with further shower observables from KASCADE-Grande, e.g. the angle of the shower axis in respect to the geomagnetic field, the electron or muon content of the shower, the estimated primary energy or mass, etc.

4 First measurements with LOPES 10

The LOPES-10 data set is a subject of various analyses addressing different scientific questions. With a sample asking for high quality events the proof of principle for detection of air showers in the radio frequency range was made (Falcke et al., 2005).

With events falling inside the original $200 \times 200\,\mathrm{m}^2$ large KASCADE array basic correlations of the radio signals with shower parameters are shown (Horneffer, 2006). More than 220 events with a clear radio signal and with the shower core inside the KASCADE array could be detected. The analysis of these events concentrates on the correlations of the radio signal with all shower parameters, in particular with the arrival direction and with the shower size, i.e. the primary energy of the shower.

Fig. 3 depicts the dependence of the reconstructed radio pulse height with the primary energy of the cosmic particles. The shown correlation supports the expectation that the field strength increases by a power-law with an index close to one with the primary energy, i.e. that the received energy of the radio signal increases quadratically with the primary energy of the cosmic rays. An index of this power-law equal exactly one would serve as a proof of the coherence of the radio emission during the shower development.

Fig. 4 shows the correlation between the normalized reconstructed pulse height of the events with the geomagnetic angle. Normalized here means,

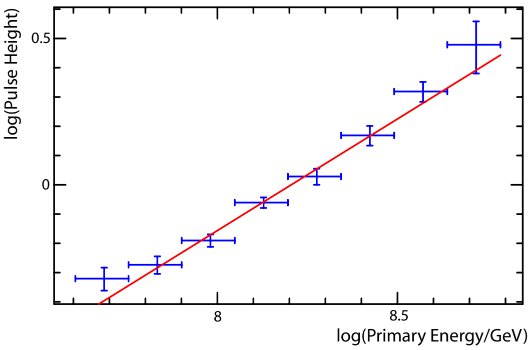

Figure 3: Radio pulse height of the detected events (with shower core inside the KASCADE array) plotted versus the primary particle energy as reconstructed by KASCADE.

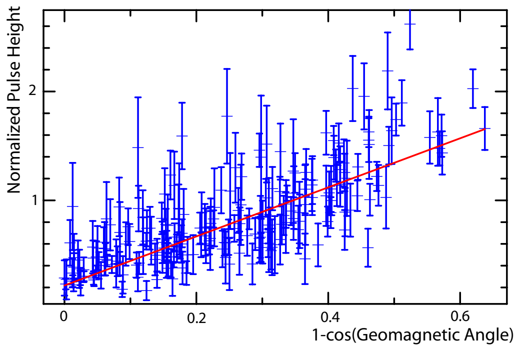

Figure 4: Radio pulse height normalized with the muon number and distance to the shower axis plotted versus the cosine of the angle to the geomagnetic field. The errors bars are the statistical errors.

that the detected pulse height is corrected for the dependency on the muon number, i.e. up to a large extend, the primary energy. The clear correlation found suggests a geomagnetic origin for the emission mechanisms.

Besides the analyses of events with the core inside the antenna setup, KASCADE-Grande gives the possibility to search for distant events. For each (large) shower triggering KASCADE, the information from the extension of KASCADE, i.e. from the Grande array, is available. From that information the shower can be reconstructed even if the core is outside the original KASCADE area, and a radio signal can be searched for events which have distances up to 800 m from the center of the antenna setup. Also for this case several hundred events (372 in 6 motnhs data taking) could be detected, where in particular the lateral behaviour of the radio emission is investigated (Apel et al., 2006). The functional form of this dependence and also the lateral scaling parameter is of high interest for the further development of the radio detection technique. After linear scaling of the pulse amplitude ϵ_ν with the primary energy estimated by KASCADE-Grande a clear correlation with the mean distance of the shower axis to the antennas is found (Fig. 5). Following the formula by Allan (1971) an exponential behavior with a scaling parameter of $R_0 = 110\,\mathrm{m}$ is expected for vertical showers. Such an exponential dependence of signal to distance is also expected by detailed simulations of the geosynchrotron effect with a scaling radius of ~ 100 to $\sim 800\,\mathrm{m}$, increasing with increasing zenith angle (Huege & Falcke, 2005). Fitting the present data set by explicitly assuming an

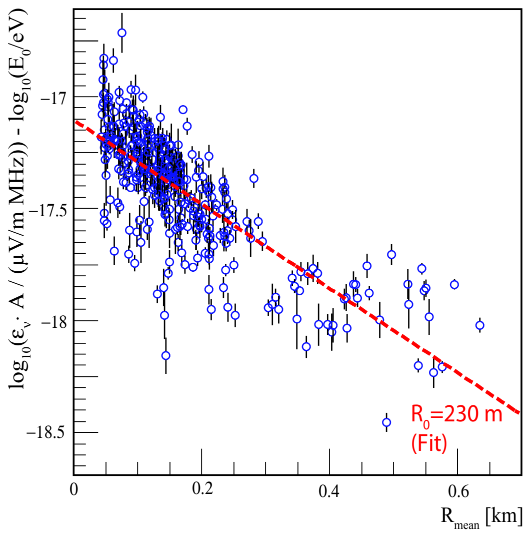

Figure 5: Correlation of the pulse height corrected for primary energy with the mean distance of the shower axis to the radio antenna system. The line show the result of a fit with an exponential function.

exponential function, R_0 results to $230 \pm 51\,\mathrm{m}$, i.e. somewhat larger than Allan's suggestion. One has to note that the missing correction to the zenith angle dependence, as well as the different definition of R_{mean} compared to the definition of the distance R used in Allan's formula surely distorts the obtained scaling parameter.

Further interesting features are currently being investigated with a sample of very inclined showers (Petrovic et al., 2005) and with a sample of events measured during thunderstorms (Buitink et al., 2005). The first one is of special interest for a large scale application of this detection technique, as due to the low attenuation in the atmosphere also very inclined showers can be detected with high efficiency. This is of great importance if ultrahigh energy neutrinos exist. With LOPES one could show that events above 70° zenith angle still emit a detectable radio signal.

The latter sample is of interest to investigate the role of the atmospheric

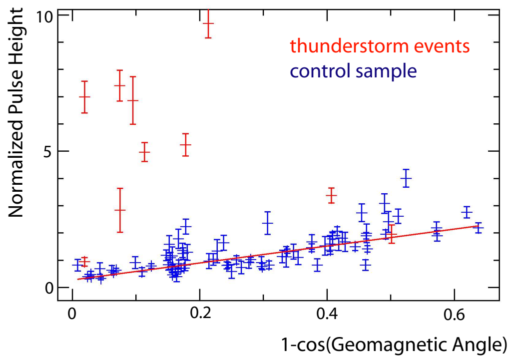

Figure 6: Normalized pulse height of the events taken at fair weather conditions (control sample) and those detected during thunderstorms plotted against the geomagnetic angle.

electric field in the emission process. We examine the contribution of an electric field to the emission mechanism theoretically and experimentally. Two mechanisms of amplification of radio emission are considered: the acceleration radiation of the shower particles and the radiation from the current that is produced by ionization electrons moving in the electric field. We selected LOPES data recorded during thunderstorms, periods of heavy cloudiness and periods of cloudless weather. We find that during thunderstorms the radio emission can be strongly enhanced (Fig. 6). No amplified pulses were found during periods of cloudless sky or heavy cloudiness, suggesting that the electric field effect for radio air shower measurements can be safely ignored during non-thunderstorm conditions.

5 Extension to LOPES 30

Presently, 30 antennas are installed at KASCADE-Grande. The 30 antenna setup provides a larger sensitive area to the radio signal at a single event. This will provide the possibility for a detailed investigation of the lateral extension of the radio signal. In addition, the antenna number will be high enough, to configure a part of them for the measurement of the other polarization direction.

Each single antenna is absolute calibrated using a commercial reference antenna. This leads to frequency dependent amplification factors representing the system behaviour in the environment of the KASCADE-Grande experiment. This correction factors will be applied to the measured signal strength resulting in the true electric field strength which can be compared to simulated values.

In addition, during LOPES-30 measurements we place emphasis on the monitoring of the environmental conditions by measuring the static electric field and by recording parameters of a nearby weather stations.

With that data set LOPES-30 is expected to calibrate the radio emission in air showers in the primary energy range from 10^{16} eV to 10^{18} eV.

6 LOPES and the Pierre Auger Experiment

One of the main goals of the LOPES project is to pave the way for an application of this 're-discovered' air shower detection technique in large UHECR experiments, like the Pierre Auger Observatory. Parallel to the measurements at KASCADE-Grande LOPES follows this aim by optimizing the antenna design for an application at Auger (LOPES$^{\mathrm{STAR}}$). Additionally the optimum frequency range, depending on the local noise, and an adapted filtering is investigated. Going in direction of setting up a test array at Auger South, the possibilities of a self-triggering antenna system and an online beam forming are also investigated.

7 Conclusions and Outlook

LOPES is running and takes continuously data in coincidence with the air shower experiment KASCADE-Grande. The first results are very promising with respect to the proof of detection of radio flashes from cosmic rays. With LOPES-30 we will be able to follow the main goal of the LOPES project:

The calibration of the radio emission in extensive air showers. This leads to the possibility to test the formula by Allan (1971)

$$\epsilon_\nu = 20 \left(\frac{E_p}{10^{17}\mathrm{eV}}\right) \sin\alpha \cos\theta \exp\left(\frac{-R}{R_0(\nu,\theta)}\right) \left[\frac{\mu V}{\mathrm{m\,MHz}}\right] \tag{1}$$

expecting a quadratic increase of the emitted radio power with primary energy. In the formula the quantity ϵ_ν describes the electric field of the radio emission, E_p is the primary energy of the cosmic particle, θ the zenith angle of the shower axis, α the angle of the axis relative to the geomagnetic field, and R_0 a distance parameter. Allan achieved his formula by a compilation of several earlier measurements, where no precise coincidence with shower parameters could be obtained.

The quadratic dependence on energy will make radio detection to a cost effective method for measuring the longitudinal development of air showers of the highest energy cosmic rays and cosmic neutrinos.

The LOPES technology can be applied to existing cosmic ray experiments as well as to large digital radio telescopes like LOFAR and the SKA (square kilometer array), providing a large detection area for high energy cosmic rays. First approaches to use the technique at the Pierre Auger Observatory and at a first LOFAR station are under way.

Besides the experimental works done with the present antenna setup the LOPES project aims to improve the theoretical understanding of the radio emission in air showers. Supplementary emission processes like the Cherenkov-Askaryan-effect which plays the dominant role in dense media will be investigated. A further topic is the application of the gained knowledge in detailed Monte-Carlo air shower simulation programs, like the CORSIKA (Heck et al., 1998) tool.

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