Radio Detection of High-Energy Cosmic Rays: LOPES

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The detection of radio pulses emitted in the atmosphere during the air shower development of high-energy primary cosmic rays is the task of the LOPES (LOFAR Prototype Station) project. LOFAR (Low Frequency Array) is a new digital radio interferometer under development using high bandwidth ADCs and fast data processing to filter out most of the interference. By storing the whole waveform information in digital form transient events like air showers can be analyzed even after they have been recorded. To test this technology and to demonstrate its ability to measure air showers a LOPES is set up to operate in conjunction with an existing air shower experiment (KASCADE-Grande). The LOPES antennas are operating in the frequency range of 40-80 MHz. For several air-shower events a coincident and coherent signal has been found and a preliminary analysis has already been performed. The main goal of further investigations is to calibrate the radio signal with help of the observables of the individual air-showers given by KASCADE-Grande.

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 [1].

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 Jelly et al. [2] at a frequency of 44 MHz, is a somehow ignored EAS feature. This fact is due 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 [3]. 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 [4].

KASCADE-Grande is an extension of the multi-detector setup KASCADE (KArlsruhe Shower Core and Array DEtector) [5, 6] built in Germany, 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 a different status of the EAS development, LOPES will provide complementary information and help to understand the observables measured with the particle detector array of KASCADE-Grande.

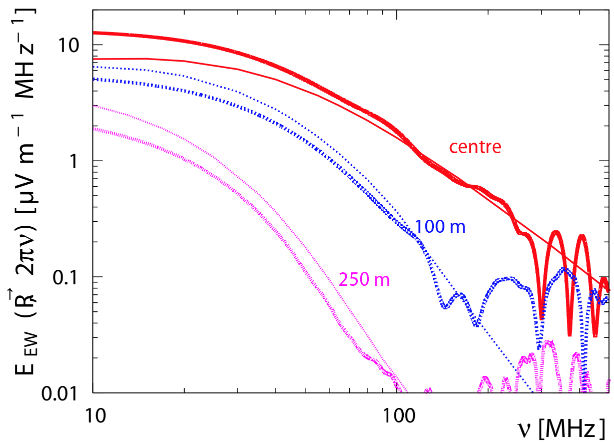

Figure 1: Simulated spectra emitted by a 10^{17} eV vertical air shower for different distances (to north). Compared are the spectral forms of analytic calculations (thin lines [8], scaled down by a factor two) with detailed Monte-Carlo simulations (thick lines [9]).

2. EMISSION PROCESS

Recent theoretical studies of the radio emission in the atmosphere are embedded in the scheme of coherent geosynchrotron radiation [7]. 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 with an average energy of 30 MeV are concentrated in a thin shower disk (< 2 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 [8] and Monte-Carlo simulations [9] 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 $\approx 5 \cdot 10^{16}$ eV one expects a short, but coherent radio pulse of 10 ns to 100 ns with an electric field strength proportional increasing to the primary energy of the cosmic particle initializing the air shower. Figure 1 shows as example the expected frequency spectrum for a vertical air shower of 10^{17} eV primary energy for different distances to the shower axis.

The expected field strength is large enough to be detected by a sophisticated antenna and filter technique such as developed for the large low frequency radio interferometer LOFAR (LOw Frequency Array) [10].

This technique is of interest for air shower measurements, 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. Furthermore, radio detection provide for the first time a calorimetric measurement of the showers with 24 hours duty cycle, and is easy to deploy over a large area.

Figure 2: Photograph of the KASCADE area (upper panel). Bottom: Lookup to one LOPES antenna.

3. LOPES – GENERAL LAYOUT

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

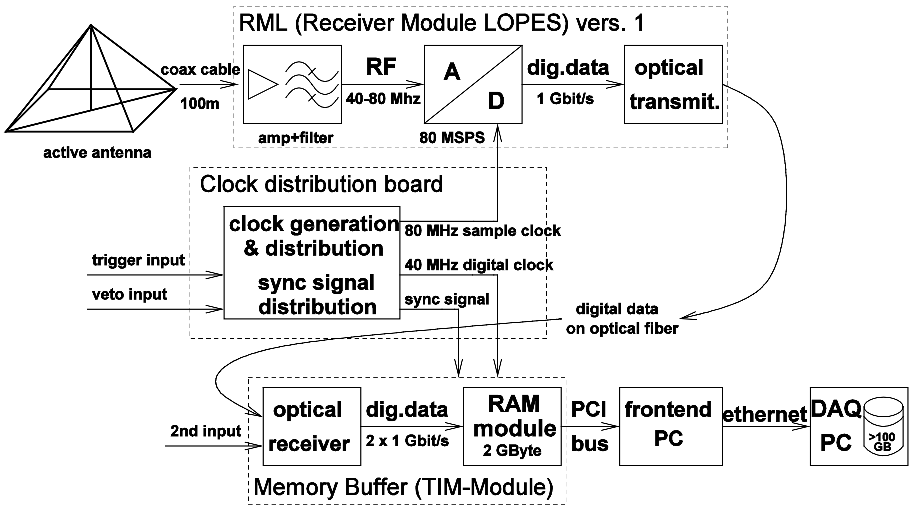

Figure 3: Layout of the LOPES hardware components.

high-gain antennas, like the high sensitivity and good background suppression. This basic concept of LOFAR is for LOPES tailored to detect air showers [3]. With LOPES it is possible to store the receiving data stream for a certain period of time, i.e. at an detection of a transient phenomenom like an air shower retrospectively a beam in the desired direction can be formed.

To test the technology of LOFAR and to demonstrate the capability to measure air-showers with these antennas, LOPES is built-up at a well tested air shower experiment (KASCADE-Grande [4]). The air shower experiment provides at one hand 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.

Figure 2 shows photographs from the experimental setup in Forschungszentrum Karlsruhe, Germany, located at 110 m a.s.l., 49°n, 8°e. The short dipol copper antennas with an inverted 'v'-shape are setup in two opposite edges of the shown pyramid, only. By choosing the east-west edges the antenna is sensitive to the east-west polarized component of the radiation, what can be easily changed in the opposite polarization by changing the tubes. Expecting a highly polarized signal from the Monte-Carlo simulations presently for all antennas only the east-west direction is chosen. 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.

At the top of the antennas there is an amplifier tailored to give sensitivity to a wide frequency band and which has a good noise performance.

Figure 3 sketches the LOPES signal path from the antenna to the data acquisition PC. The receiver module (RML) contains a commercially available amplifier, an anti-aliasing filter giving a usable frequency band from 43 MHz to 76 MHz, and an A/D-converter. Used are 12bit-ADCs running at 80 MHz, thus sampling the signal in the 2nd Nyquist domain of the ADCs. The RML contains additionally an optical transmitter for transporting the data via optical fibers to the backend modules. The used memory modules have inputs for two antennas each and can buffer up to 2 Gbyte. This allows to store 6.25 seconds of data from each antenna. The modules can either start to write data after a 'sync'-signal or write data continuously into the memory and stop at a predefined time after a sync-signal is received. A central clock module distributes the sync-signal to all memory modules and generates also the sample clock for the A/D-converters.

The antenna array at KASCADE-Grande is triggered by a special generated 'large-event trigger' of KASCADE, which means that the primary energy is above 10^{16} eV and which leads to an trigger rate of about two per minute. Fore every trigger about 0.8 ms around the trigger signal of the antenna data is readout and stored. On average the trigger signal arrives with a delay of 1.8 μs to the shower front, hence well in between the stored data.

The following data processing includes several steps. 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. Then by time shiftings a peak is searched in direction of the shower axis by summing up either the electric fields or the power, i.e. the square of the electric field, of several antennas. If there is coherent emission at the air shower development, emitted in the moving shower disk, a clear peak should be visible in

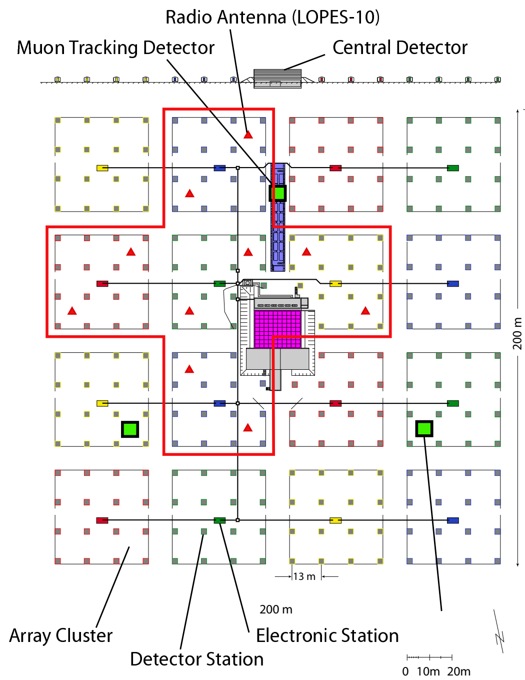

Figure 4: Layout of the LOPES 10 antennas inside the KASCADE array.

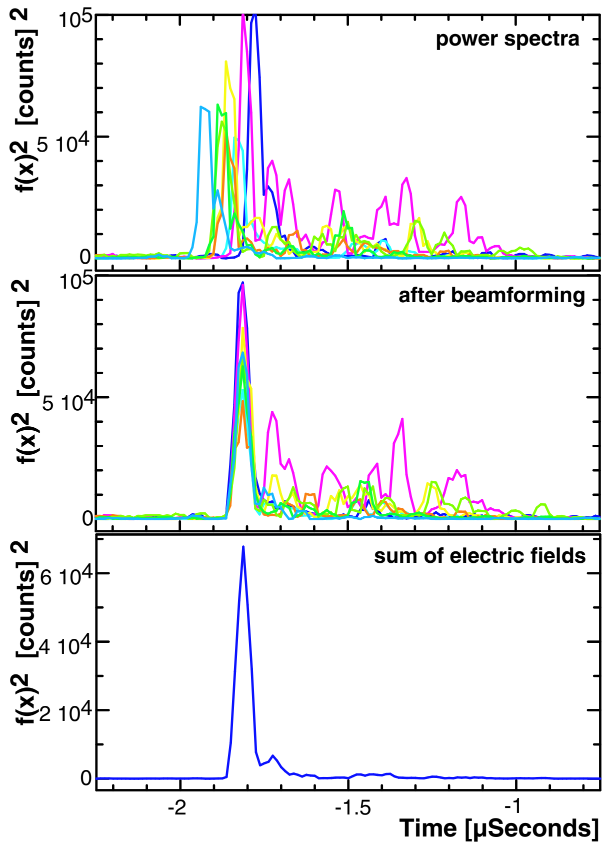

Figure 5: Steps of the reconstruction of a strong air shower event detected by LOPES. In the upper part the received powers (squares of the electric fields) of 8 antennas before beamforming are overlayed. Powers after time shifting using the KASCADE shower direction information are displayed in the second panel. A clear signal is proved by displaying the power after beamforming of the electric field (lower part).

the summed electric field, whereas incoherent noise does not produce a similar peak. The height of the peak one can compare with further shower observables form 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

At present, LOPES operates 10 dipole radio antennas in coincidence with the original KASCADE array [3]. The antennas are positioned in 5 out of the 16 clusters of KASCADE [11], 2 of them per cluster (see Fig. 4). The maximum baseline of the antenna setup is 125 m. The radio data is collected when a large-event trigger is received from the KASCADE array. A preliminary analysis of the first data has already been performed.

4.1. EAS core in KASCADE

Fig. 5 shows a particularly bright event as an example. A crucial element of the detection method is the digital beamforming which allows to place a narrow antenna beam in the direction of the cosmic ray event. This is possible because the phase information of the radio waves is preserved by the digital receiver and the cosmic ray produces a coherent pulse. This method is also very effective in suppressing interference from the particle detectors which all radiate incoherently and which are seen in the raw power spectra of all antennas as a longer period of noise after the real radio peak.

The core of this particular shower lies inside the antenna setup, and the primary energy is estimated to be approximately 10^{17} eV. The shower axis is reconstructed using the KASCADE data to an elevation of $64.5°$ coming from north-east. At that time, 8 antennas were operating and all 8 antennas show a clear signal just shortly before a ≈ 500 ns broad noise distribution arrives. These noise pulses are emitted by the particle detectors of the KASCADE array. However, this emission is not coherent and is reduced in the beamforming process.

Several candidates like the shown one are found, and the present analysis concentrates on the correlations of the radio signal with shower parameters, in

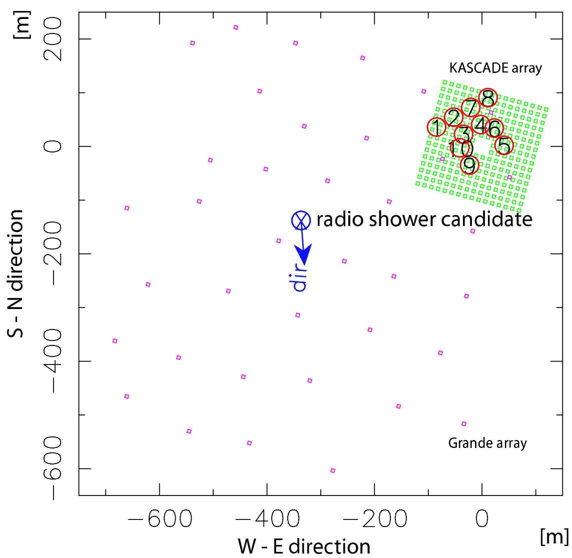

Figure 6: Layout of LOPES 10 in respect to the KASCADE-Grande experiment. The marker denotes core position and direction of a promising radio event.

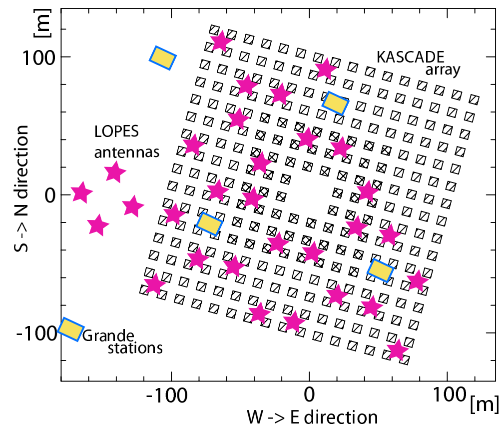

Figure 7: Layout of the LOPES 30 antennas. Four antennas are deployed outside of the KASCADE array to investigate differences in noise obtained by the particle detectors.

particular with the arrival direction and with the size of the shower.

4.2. EAS core in the Grande array

Besides the analyses of events with the core inside the antenna setup, KASCADE-Grande gives the possibility to search for remote events. For each (large) KASCADE trigger, the information from the extension of KASCADE, i.e. from the Grande array (Fig. 6, 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 candidates has been found and are presently analyzed in detail.

5. EXTENSION TO LOPES 30

In the beginning of 2005, 30 antennas will be installed at KASCADE-Grande. For this setup (Fig. 7) a trigger signal also from the Grande array itself will be provided. Hence, the 30 antenna setup provides a larger sensitive area to the radio signal at a single event. It provides also to measure higher primary energies with larger statistics due to the increased sampling area of showers by factor ten. And it will give the possibility for a detailed investigation of the lateral extension of the radio signal. Additionally the antenna number will be high enough, to configure a part of them for the measurement of the other polarization direction. With an amount of 1000 measured events above 10^{17} eV in two years, LOPES 30 in coincidence with KASCADE-Grande will be able to calibrate the radio emission in extensive air showers with high accuracy.

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. Additionally the optimum frequency range, depending on the local noise, and an adapted filtering is investigated. Going in direction of setup a test array at Auger South, the possibilities of a self-triggering antenna system and an online beamforming are also investigated.

7. CONCLUSIONS AND OUTLOOK

The first stage of LOPES consisting of 10 antennas is running and takes continuously data in coincidence with the air shower experiment KASCADE. The first results are very promising with respect to the proof of detection of radio flashes from cosmic rays. Currently the analyses of the already taken data sample is of highest priority.

The second stage of LOPES with 30 antennas, measuring in coincidence and triggered additionally by the large air shower array KASCADE-Grande is under construction. 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 will lead to a proof of the formula by Allan [12]

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

expecting a quadratic increase of the emitted radio power with primary energy. In the formula the quantity ϵ 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 in relative to the geomagnetic field, and R_0 a distance parameter. Allan achieved his formula by a compilation of several former measurements, where no precise coincidence with shower parameters could be obtained.

A quadratic dependence on energy would 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. This would provide an additional detection technique for cosmic neutrinos supplementary to measurements of radio or acoustic signals emitted in dense media like water, ice, or salt [14].

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 of the necessary adoptions to use the technique at the Pierre Auger Observatory 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 [13] 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 [15] tool.

Acknowledgments

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