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LOPES30: A digital antenna array for measuring high-energy cosmic ray air showers

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LOPES, a digital radio antenna array is designed to measure radio emission in extensive air showers (EAS) generated by high-energy cosmic rays. LOPES30 is the extension of an array of 10 antennas, LOPES10, to now 30 inverted V-shaped dipole antennas measuring in the frequency range between 40 and 80 MHz. LOPES operates in coincidence with the KASCADE-Grande air shower experiment, which provides trigger information and well-calibrated parameters of the air-shower properties on a single EAS basis in the energy range from 10 PeV to 1 EeV. The extension of the new antenna field with a maximum baseline of $\sim$270 m will allow to measure the lateral distribution of the radio signal as well as the absolute field strengths and will significantly improve the pointing accuracy compared to LOPES10.

1. Introduction

Due to their stochastic production processes cosmic ray air showers are a complicated phenomenon. Therefore as many observables as possible are needed to reconstruct the shower parameters correctly. There are different approaches to achieve this experimentally. One can detect the particles produced in many interactions forming a cascade of particles on the ground. A more direct way to study EAS is the detection of fluorescence light produced during the shower development. This allows a time resolved investigation of the shower but with the limitation of measurements only in dark, clear, and, moonless nights. There is additionally a third method to investigate high-energy EAS: The detection of radio emission generated by electron positron pairs deflected in the Earth's magnetic field. These radio emission of the EAS particles superimposes to a short coherent radio pulse easily detectable on the ground. The LOPES experiment [1] is measuring this radio emission from EAS.

2. EAS and radio emission

High-energy particles, cosmic rays, arriving at the Earth atmosphere undergo a first interaction with the nitrogen or oxygen nuclei in the upper layers. From this first and the following interactions a cascade of secondary particles arises. The air shower consists of different types of particles, for example hadrons and leptons. The electromagnetic component interacts also with the nuclei of the air by photo pair production and bremsstrahlung. Within these processes relativistic photons, electrons, and positrons are produced were the charged particles are deflected in the Earth's magnetic field. They will emit synchrotron radiation strongly beamed in the forward direction with an opening angle $\propto 1/\gamma$, with the Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$. Theoretical studies of this so called geosynchroton mechanism were published by Huege & Falcke [3]. From all emitting electrons and positrons a beamed coherent short radio pulse is generated. This pulse contains information about the electromagnetic component of the EAS integrated over the whole shower development.

Some properties of radio emission from EAS were obtained by earlier experiments and summarized in a review by Allan (1971) [5]. For a given energy E_p of the primary particle, an angle α to the geomagnetic field, zenith angle θ, and distance R to the shower center an approximate formula for the received voltage ϵ_ν per unit bandwidth can be written as:

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

with a parameter R_0 around 110 m at a frequency ν of 55 MHz. Compared with recent theoretical studies [4] it could be shown that this formula is in the right order of magnitude and describes the observed dependencies rather well. Now experiments like LOPES have to verify the radio emission in EAS by detecting the amplitude of the radio pulse in dependence of the shower parameters.

3. LOPES30 hardware

The hardware design of LOPES is based on the concept of the "**Lo**w **f**requency **ar**ray" - LOFAR which will be an astrophysical research project in the frequency range 10 - 200 MHz. For this radio telescope, a large array of 100 stations with 100 omnidirectional dipole antennas, each is planned to be installed in the Netherlands and partially in Germany. In LOFAR and LOPES the entire data stream can be stored for a certain period of time and therefore transient phenomena like EAS will be detectable.

Using the antenna design from LOFAR, LOPES was built at the site of KASCADE-Grande at the research center Karlsruhe, Germany. It is measuring in the frequency range 40 - 80 MHz, avoiding the short-wave and the strong FM-band. Within this range there are only a few radio transmitters with small bandwidth allowing a relatively good RF suppression. In the first stage of LOPES, ten antennas were running over nearly one year. Since early 2005 LOPES is extended to 30 antennas, fully in data acquisition since March. Analysis results based on LOPES10 data are subject of further contributions at this conference [2, 6].

The inverted V-shaped dipole antenna with an opening angle of 82.5° is connected to a low noise amplifier mounted on top of a pyramidical antenna frame (see Fig.1, left). All antennas are equipped with dipoles in

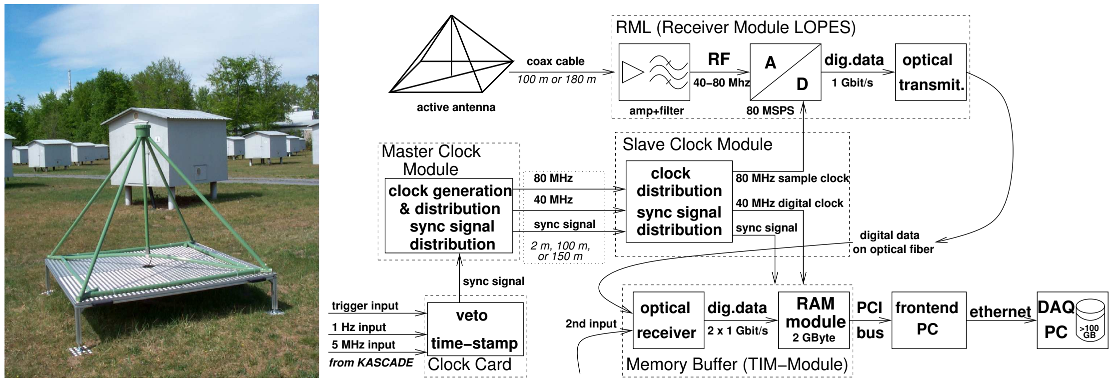

Figure 1. Antenna and scheme of LOPES30. Incoming radio pulses from EAS are transmitted over 100 m to 180 m coax cable to the Receiver Module (RML). Over an optical fiber the digitized signals are sent to a memory buffer. Receiving triggers from KASCADE-Grande a master clock module distributes the synchronization signal to slave clock modules.

east-west direction, measuring the east-west polarization of the radio emission. The received voltage is again amplified after transmitting the signals from the field antenna to an electronic cluster dedicated to ten antennas. The radio signal is filtered in a sophisticated bandpass filter and afterwards digitized with 12-bit ADCs. The necessary dynamic range to detect weak pulses while not saturating the ADC with radio interference is achieved with these 12-bit ADCs. They are working with 80 MHz, allowing 2nd Nyquist sampling of the signal and resulting in a 12.5 ns time resolution. The 30 antennas are divided into three clusters having the same sampling clock for the ADCs. The sample clock is generated by a master clock module and is then distributed over slave clock modules to all A/D-boards (see Fig.1, right). This allows to combine data from all antennas as a phased array and thus enhances the sensitivity. After the digitization the signal is converted into an optical signal transferred via fiber optics to a memory module and stored in a front-end PC. From the KASCADE-Grande experiment LOPES30 receives a trigger if a majority condition 10 out of 16 clusters of the KASCADE array detecting an EAS is fulfilled, which requires $\approx$10 PeV primary energy. Under this trigger condition 800 μsec of data from the memory buffer of all antennas are saved on a central DAQ-PC.

4. Status of LOPES30

With LOPES10 the "proof of principal" in detecting radio signals was achieved by comparing relative field strengths in the antenna array [7]. The analysis was done without a precise absolute calibration. For a detailed comparison with theoretical predictions of the expected electric field strengths and polarization of radio emission in EAS an absolute calibration of the LOPES30 antenna system is essential. Therefore a conversion factor for received electric field strengths from EAS and measured voltage amplitudes of the antenna system is determined. In a first step the electronic part is calibrated, including receiver module (RML), optical transmission, and TIM-module (see Fig.1) resulting in a frequency dependent amplification factor. In a second step the whole system will be calibrated, which will be done with a biconical shaped reference radio source mounted on a wooden frame or a stationary balloon. The analysis of the absolute calibration is in progress and will give us a calibrated antenna system to compare theoretical predictions with received voltages of the radio field strength in EAS.

The LOPES30 system is currently triggered by the KASCADE array giving an upper limit in energy of 80 PeV for detecting EAS. By including the KASCADE-Grande trigger this limit is extended to energies of $\approx$1 EeV.

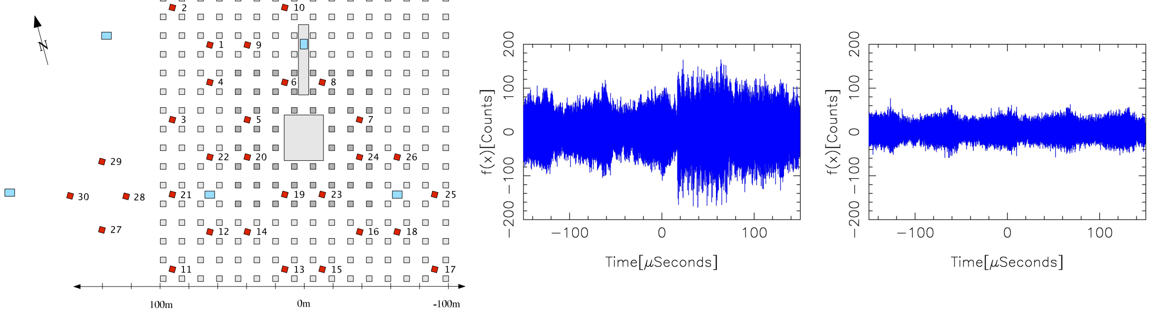

Figure 2. Left: LOPES30 antenna positions (numbered squares) at the KASCADE-Grande experiment. The latter forms a quadratic grid with a central detector and a muon detector. 5 Grande stations are represented by rectangulars. Center and right: Voltage amplitude received in antenna 20 (mid.) and antenna 27 (right) during one event trigger.

The antenna layout of LOPES30 is depicted in Fig.2, left. During a shower detection there are RF interferences generated in the detector huts surrounding an antenna. The RF interference correlates with deposited energy in the huts making it more difficult to distinguish the radio signal from induced noise. Four antennas (27 to 30) are placed outside of the KASCADE array. They were installed to investigate the noise during radio wave detection. For these four antennas on the field the RF interference from the huts is negligible, see an example in Fig. 2. The center and right picture shows the signal of a triggered single event in a time window of 300 μsec for antenna 20 (inside the KASCADE array) and antenna 27 (outside the array). A further noise reduction will decrease the detection limit of LOPES30 allowing to investigate threshold effects of the detection and the lateral distribution of the radio emission. Having a maximum baseline of ~270 m a lateral distribution of the radio signal on single event basis can be seen and comparisons with theoretical predictions will be done. The extension to 30 antennas significantly improves the pointing accuracy compared to LOPES10. This can be used as additional information for the KASCADE-Grande reconstruction of the EAS.

5. Outlook

The LOPES antenna system as a LOFAR prototype showed the possibility to measure radio emission from EAS. With a calibrated system we will be able to verify theoretical predictions about the field strength of radio emission in EAS. Measuring both polarizations of the radio emission will directly verify the geosychrotron effect as the dominant emission process in EAS.

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