Nuclear Instruments and Methods in Physics Research A 662 (2012) S72–S79

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The LOPES experiment—Recent results, status and perspectives

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ARTICLE INFO

Available online 24 November 2010

Keywords:
Cosmic rays
Extensive air showers
Radio detection
Interferometry

ABSTRACT

The LOPES experiment at the Karlsruhe Institute of Technology has been taking radio data in the frequency range from 40 to 80 MHz in coincidence with the KASCADE-Grande air shower detector since 2003. Various experimental configurations have been employed to study aspects such as the energy scaling, geomagnetic dependence, lateral distribution, and polarization of the radio emission from cosmic rays. The high quality per-event air shower information provided by KASCADE-Grande has been the key to many of these studies and has even allowed us to perform detailed per-event comparisons with simulations of the radio emission. In this article, we give an overview of results obtained by LOPES, and present the status and perspectives of the ever-evolving experiment.

1. Introduction

Forty years after the initial discovery of radio emission from cosmic ray air showers [1], cosmic ray radio detection has once again become a very active field of research. The LOPES experiment [2] in particular has revived the radio detection activities with an innovative approach combining digital radio-interferometry with detailed air shower measurements employing a classical particle detector array. The experiment is situated at Campus North of the Karlsruhe Institute of Technology, at the site of the KASCADE-Grande air shower experiment [3,4]. The close integration of LOPES with KASCADE-Grande, leading in particular to the availability of high-quality per-event air shower parameters, has proven to be the key to many of the successes of LOPES. In comparison, the CODALEMA experiment [5] in Nançay is situated at an observing site with a much quieter radio background, facilitating the detection of radio signals in individual antennas without resorting to interferometric techniques. The CODALEMA experiment, however, does not have access to per-event air shower information of as high a quality as LOPES.

In this article, we first describe the basic properties of the LOPES experiment, followed by an overview of the analysis procedures we apply to our data before we finally discuss the different phases and results of the ever-evolving experiment.

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doi:10.1016/j.nima.2010.11.081

2. Basic properties

LOPES is a digital radio-interferometer measuring in the 40–80 MHz frequency window. This frequency window was chosen to avoid FM radio-transmitters at frequencies above 80 MHz and short-wave and atmospheric noise at frequencies below 40 MHz. All LOPES channels are continuously sampled with 12 bit ADCs and a sampling rate of 80 MHz, i.e., in the second Nyquist zone. The data are stored in ring buffers, and when a trigger arrives from the KASCADE or Grande arrays, 0.8 ms of data are read out and stored for each channel. Events with energies above $\approx 10^{16}$ eV are triggered; the threshold for radio detection lies significantly higher. While these basic properties are universal to all configurations of LOPES, the layout and type of antennas has changed over the course of time.

In Fig. 1, an overview is given of the different phases of LOPES: LOPES 10, LOPES 30, LOPES 30 pol and LOPES 3D. The different phases were tailored to different scientific questions, and will be discussed in some more detail in the following sections.

Although the layout of the antenna array has been changing over the different phases, in all cases the antennas have been placed in a region coinciding with the KASCADE array of KASCADE-Grande, as depicted for the LOPES 30 pol setup in Fig. 2. The antennas used for all phases except LOPES 3D have been inverted-V dipole antennas based, like most of the electronics used, on prototype designs for LOFAR [6]. Further technical details on the hardware of LOPES can be found in Ref. [7].

3. Analysis procedure

The analysis procedure of LOPES data exhibits a high degree of sophistication, which is necessary in particular because of the comparatively high radio-frequency interference background at the "industrial" location of the KIT campus north. Here, we shortly discuss the analysis steps applied in our standard reconstruction.

1. An absolute amplitude calibration is applied to the data. As of LOPES 30, this is based on a measurement with an external, calibrated reference source [8]. The remaining systematic uncertainty of electric field amplitudes between events is of order 10%.
2. To suppress narrow-band transmitters, a digital filtering algorithm suppressing peaks in the frequency-spectra of each antenna is applied. This hardly affects the broad-band cosmic ray radio signals, and therefore increases the signal-to-noise ratio significantly.
3. The delay of each individual channel (dominated by cable delays and determined in a dedicated calibration campaign) is corrected for.
4. A determination of the relative phases of the beacon transmitter operated in the vicinity of the LOPES antennas (cf. Fig. 2) is used to constrain the relative timing of the LOPES channels to ≈ 1 ns precision [9]. Such a high precision is a necessary prerequisite for a reliable interferometric analysis. Before the availability of the beacon transmitter, a TV transmitter in the LOPES band was used for the phase calibration.
5. Dispersion introduced by the instrumental response (in particular the bandpass filters) is de-convoluted from the signal traces, increasing the signal-to-noise ratio of cosmic ray radio pulses.
6. The 12.5 ns sampled raw data are up-sampled (i.e., interpolated correctly) to a higher sampling rate. This is possible because the data were sampled correctly in the second Nyquist zone and therefore contain the full information in the 40–80 MHz frequency window. Time traces of radio signals at this step of the analysis are depicted in Fig. 3 (left).
7. A digital beam-forming is applied to arrange the time-series data of all channels correctly for radio emission received from the presumed arrival direction. (For the first iteration, the direction reconstructed by KASCADE or Grande is used as a starting point. Likewise, the core position is taken from the KASCADE or Grande reconstruction.)
8. The antenna characteristics (i.e., frequency-dependent gain) for the established arrival direction is corrected for.

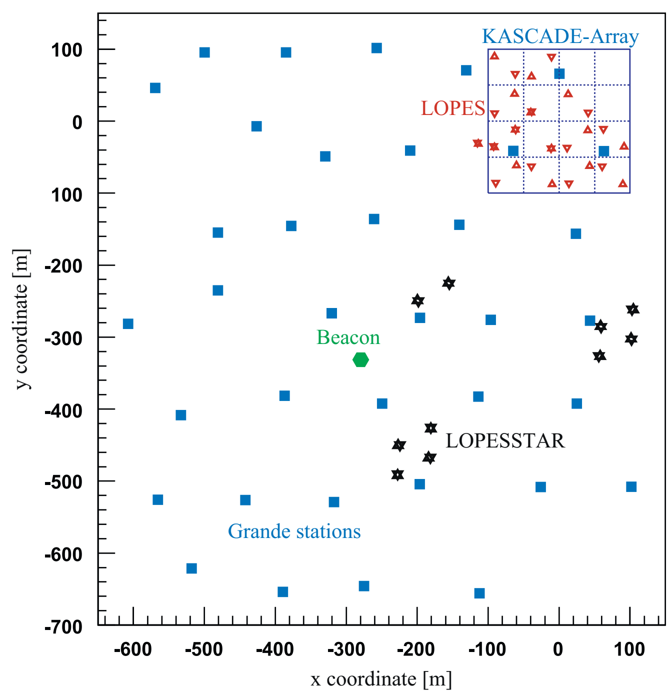

Fig. 2. Layout of the LOPES 30 pol setup. Triangles denote east–west- and north–south-aligned antennas, respectively; stars denote positions with both an east–west and north–south-aligned antenna.

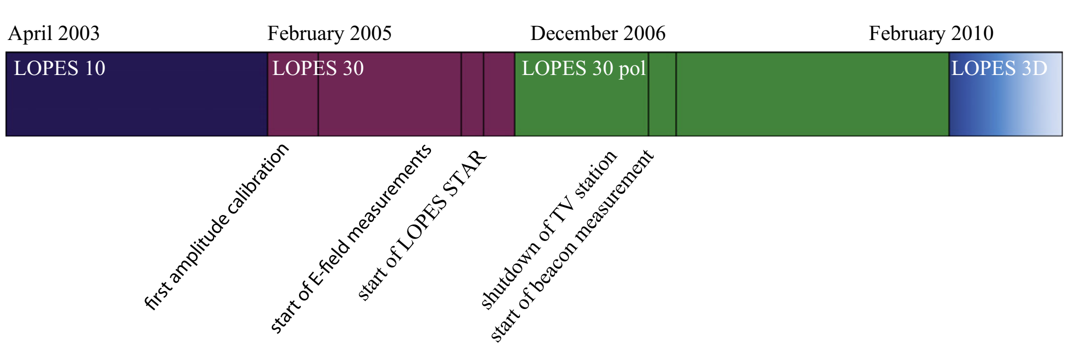

Fig. 1. Time-line of the evolution of the LOPES experiment. LOPES$^{\mathrm{STAR}}$ commenced in late 2005 and runs in parallel with the other phases of LOPES.