29th International Cosmic Ray Conference Pune (2005) **6**, 277–280

Remote event analyses of LOPES-10

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LOFAR (**LO**w **F**requency **AR**ray) [1] will be a new digital interferometer and is an attempt to revitalize astrophysical research by measuring radio wave emission at 10-240 MHz. A "**LO**far **P**rototyp**E** **S**tation" (LOPES) has been built at the KASCADE-Grande experiment in order to test the LOFAR technology and to demonstrate its capability for radio measurements of Extensive Air Showers (EAS). Here we report the analysis performed by correlating the radio signals measured by LOPES-10 with EAS events reconstructed by KASCADE-Grande with remote cores included. Results will be discussed in particular concerning the correlation of the radio pulse amplitude with the primary cosmic ray energy and with the lateral distance from the shower axis.

1. Introduction

KASCADE-Grande [2] is the extension of the multi-detector setup KASCADE [3] and allows a full coverage of the energy range around the so-called "knee" of the primary cosmic ray spectrum ($10^{14} - 10^{18}$ eV). At present, LOPES operates 30 dipole radio antennas in coincidence with KASCADE; for this analysis only the 10 antennas forming LOPES-10 (see Fig. 2, left panel) are relevant. The 37 stations of the Grande extension

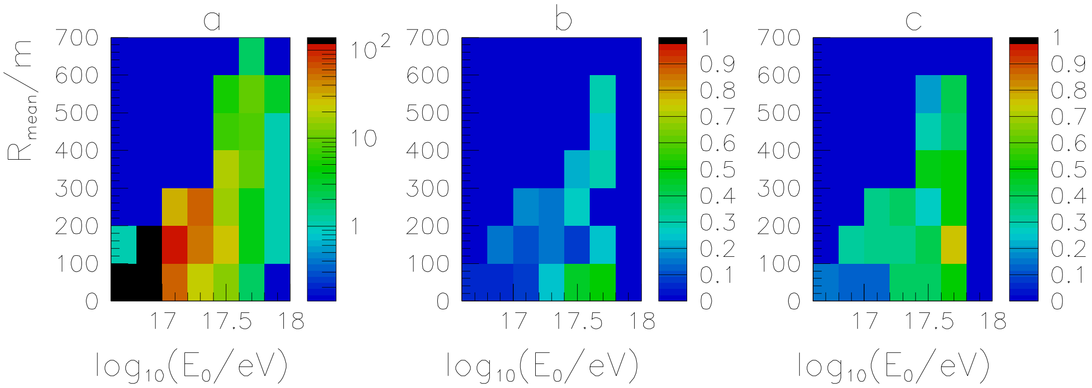

Figure 1. a) distribution of the candidate events on primary energy and distance to the shower axis; b) efficiency of the radio detection after beamforming; c) preliminary efficiency of the radio detection for an optimised beamforming (only performed for half of the sample, yet).

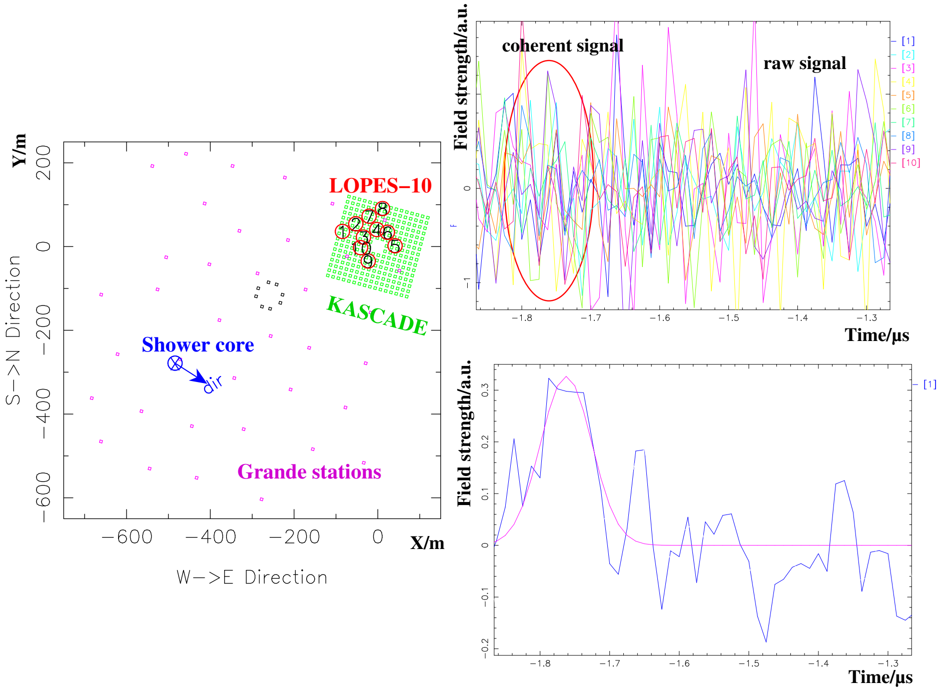

Figure 2. Remote event: mean distance to the shower axis $R_{mean} = 556.0$ m, zenith angle $\theta = 27.2°$, angle to the geomagnetic field $\alpha = 24.3°$, primary energy $E_0 = 10^{17.7}$ eV, curvature radius 2250 m (details in text).

of the KASCADE experiment covering approx. 0.5 km^2 are taking data in coincidence with KASCADE and LOPES and enable to reconstruct showers with primary energies up to 10^{18} eV and with distances between shower core and the LOPES-10 antennas up to 700 m. Due to the extremely low flux of the primary cosmic rays of ultrahigh energies, larger detectors with high acceptance and duty cycle are required. Besides the contribution of KASCADE-Grande to the astrophysics of high-energy cosmic rays, it is also the testbed [4] for the development and calibration of new air-shower detection techniques like the measurement of EAS radio

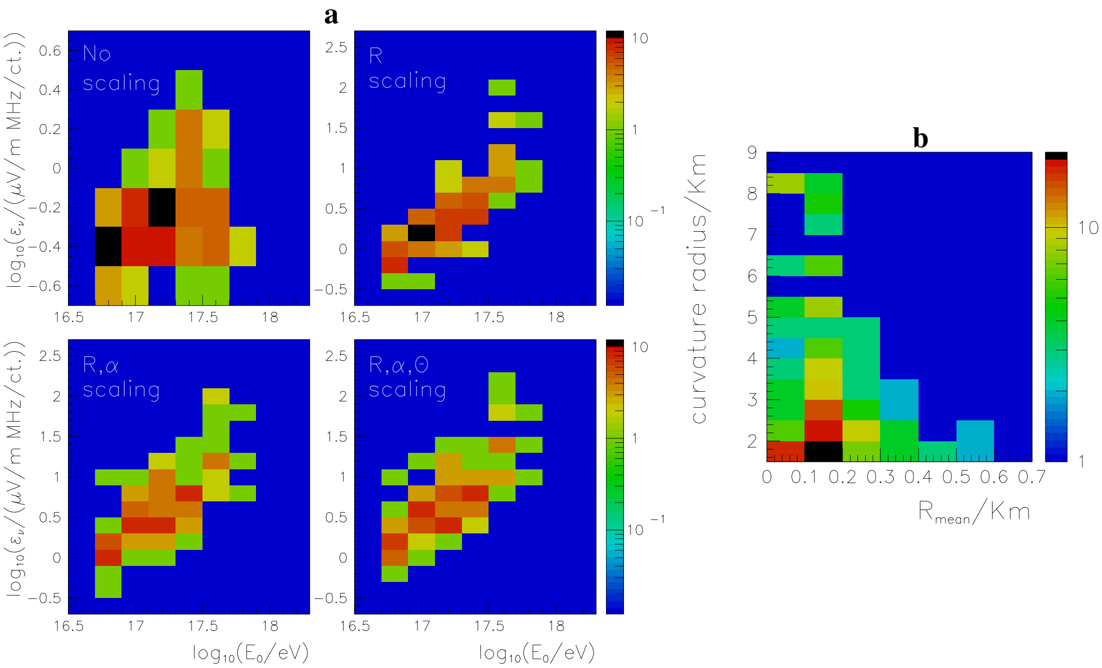

Figure 3. a) correlations of the primary energy and radio signals; b) correlation of the distance to the shower axis and curvature radius of the radio signal.

emission. Radio emission produced by EAS in the Earth′s atmosphere is unaffected by attenuation, has a high duty cycle, is calorimetric and is very sensitive to the direction of the incoming primary cosmic ray [5].

2. Allan′s formula; selection of events

It is believed that the pulse amplitude per unit bandwidth (ϵ_ν) of the radio signal induced by an EAS is described by the Allan′s formula [6]:

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

with E − primary energy, α − angle to the geomagnetic field, θ − zenith angle, R − distance to the shower axis and the scaling radius $R_0 = 110$ m at 55 MHz; the exponential radial factor may play a significant role for remote showers. Due to the significant background encountered at the KASCADE-Grande site inside Forschungszentrum Karlsruhe, present LOPES procedures to analyse radio signals are semi-automatical and, at the end, a final check, by eye, event-by-event, is required. So, it looked reasonable to consider a radius dependent cut on the primary energy in order to reduce the number of (most probable) useless events. It has been considered a primary energy cut described by:

$$\lg\left(\frac{E}{eV}\right) > \lg\left(\frac{E_0}{eV}\right) + 0.4343 \cdot \frac{R}{R_0} \quad OR \quad \lg\left(\frac{E}{eV}\right) > 17.5 \tag{2}$$

with $E_0 = 10^{16.5}$ eV and $R_0 = 160$ m i.e. weaker than Allan′s scaling with radius. Due to the lack of absolute calibration of the radio signal, the threshold primary energy E_0 has been chosen based on the results from ref. [5] and data reduction considerations. Following additional cuts have been considered: period of joint acquisition LOPES + Grande Array + Field Array during 5 months at the beginning of 2004; a Field Array trigger, 10 clusters out of 16, as a necessary condition to have LOPES data; EAS zenith angle reconstructed by Grande Array below 50°; a geometrical cut on the Grande Array reconstructed shower core position: $(X_C/m, Y_C/m) \in (-550, 0) \times (-600, 50)$. After all cuts, 862 candidate events have been obtained, as shown in Fig. 1a.

3. Efficiency of the radio detection; remote radio events; correlations

Fig. 1b shows the efficiency of the detection of radio signals in EAS using beamforming procedures based on the values provided by Grande reconstruction of the shower core and shower axis (SCA). The coherence of the 10 radio signals measured by LOPES-10 antennas is very sensitive to SCA [7]. After an optimised beamforming, searching for maximum coherence by varying the SCA inside the Grande reconstruction uncertainties, the efficiency is displayed by Fig. 1c. The efficiency is even higher because the optimised beamforming has been applied only for half of the candidate events, yet. Fig. 2 shows an example of a remote event with a clear radio signal. The arrow in the left panel points towards the incoming shower direction. The mean distance from the antennas to the shower axis is more than 550 m. After the time shifting procedure of the signals in the 10 antennas a clear coherence may be seen in the upper-right panel with the corresponding peak in the (cross correlation) CC-beam estimator of the coherence (down-right panel). In Fig. 3a all events from Fig. 1c, with good coherent radio signals, have been considered. No correlation between primary energy and the radio pulse amplitude can be seen in the upper-left panel; this is a normal behaviour due to the large surface of the Grande Array. By scaling the pulse amplitude according to the exponential radius factor of Allan′s formula a clear correlation is seen, displayed in the upper right panel. By scaling subsequently with the sine of the angle to the geomagnetic field (down-left panel) and the cosine of the zenith angle, correlation in the down right panel has been obtained, which is comparable with the upper one but more symmetrical. Fig. 3b is a plot of the curvature radius of the radio front as function of the mean distance from the antennas to the shower axis. It appears an anticorrelation of the curvature radius whit increasing distance to the shower axis.

4. Conclusions

LOPES-10 is able to detect radio signals induced by remote Extensive Air Showers even at distances from the shower axis of more than 500 m, for primary energies above $10^{17.7}$ eV. Allan's formula seems to be verified at least on the radius correlation. Curvature radius of the radio front decreases with increasing distance to the shower axis.

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