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First determination of the reconstruction resolution of an EAS radio detector

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LOPES [1] is set-up at the location of the KASCADE-Grande extensive air shower experiment in Karlsruhe, Germany and is a "**LO**far **P**rototyp**E** **S**tation" aimed to measure radio pulses from Extensive Air Showers (EAS). The time shifting procedure of the pulses measured by the LOPES antennas in order to reveal the coherent radio signals induced by the shower in the Earth′s atmosphere is based on the values provided by the KASCADE-Grande [2] reconstruction of shower axis direction and shower core position. It has been found that small variations of the shower position and direction reconstructed by KASCADE-Grande translate into large variations of the estimated radio pulse amplitude. On the other hand, by maximizing the radio coherence the estimate of the shower axis direction and shower core position can be improved.

1. Introduction

The KASCADE [3] experiment (see sketch in Fig. 1a) measures showers in a primary energy range from 100 TeV to 80 PeV and provides multi-parameter measurements on a large number of observables concerning

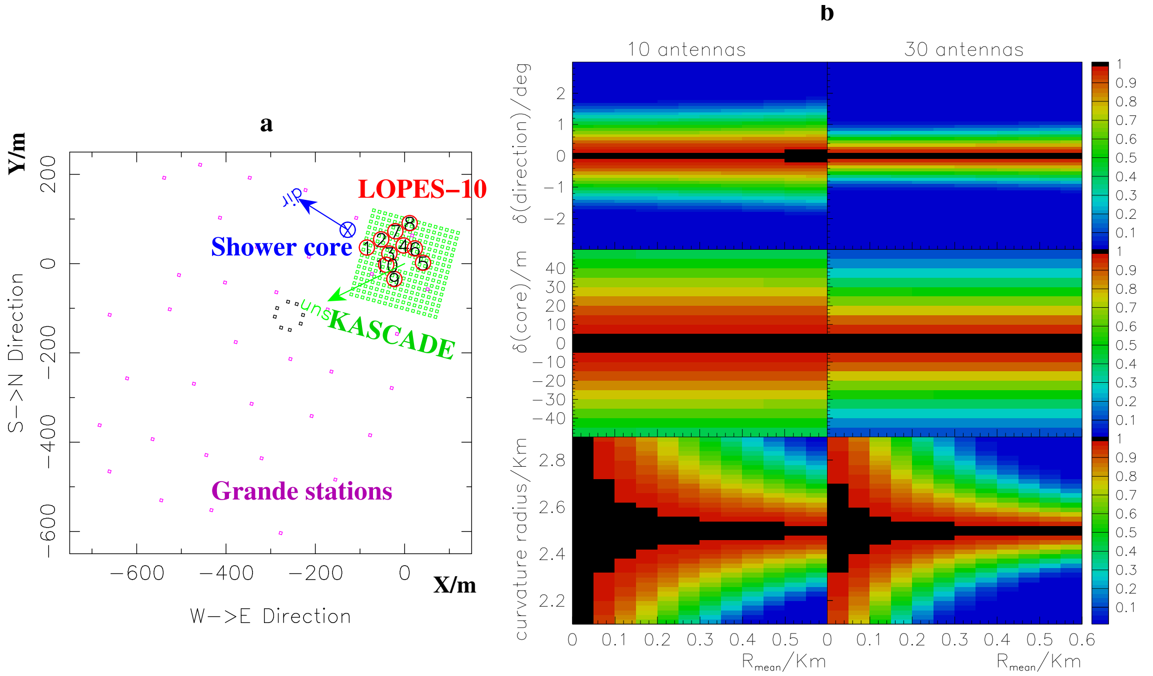

Figure 1. a) sketch of KASCADE-Grande and LOPES-10; b) sensitivity of the (cross correlation) CC-beam estimator to the shower direction, shower core position and curvature radius of the radio front for LOPES-10 and LOPES-30 configurations.

electrons, muons at 4 energy thresholds, and hadrons. The main detector components of KASCADE are Field Array, Central Detector and Muon Tracking Detector. The Field Array consists of 252 stations grouped in 16 clusters, for measuring the electromagnetic and muonic shower component. At present, LOPES operates 30 dipole radio antennas (LOPES-30) positioned inside or nearby KASCADE. In Fig. 1a only the 10 antennas of LOPES-10 are depicted. The radio data is collected when a trigger is received from KASCADE. The logical condition for trigger is at least 10 out of the 16 clusters of the Field Array to be fired. This translates to primary energies above 10^{16} eV; such showers are detected at a rate of 2 per minute. The antennas operate in the frequency range of 40-80 MHz. KASCADE-Grande is the extension of the multi-detector setup KASCADE to cover a primary cosmic ray energy range from 100 TeV to 1 EeV. The enlarged EAS experiment provides comprehensive observations of cosmic rays in the energy region around the knee. Grande is an array of 700 x 700 m^2 equipped with 37 plastic scintillator stations sensitive to measure energy deposits and arrival times of air shower particles. The Grande reconstruction accuracy of shower core position and direction is in the order of 4 m (13 m) and 0.18° (0.32°) with 68% (95%) confidence level for simulated proton and iron showers at 100 PeV primary energy and 22° zenith angle [4].

2. Beamforming and coherence of the radio signal; efficiencies

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 radiate incoherently. Fig. 1b, based on analytical calculations for a point source radiating with 60 MHz, placed at 2.5 km along shower axis, gives

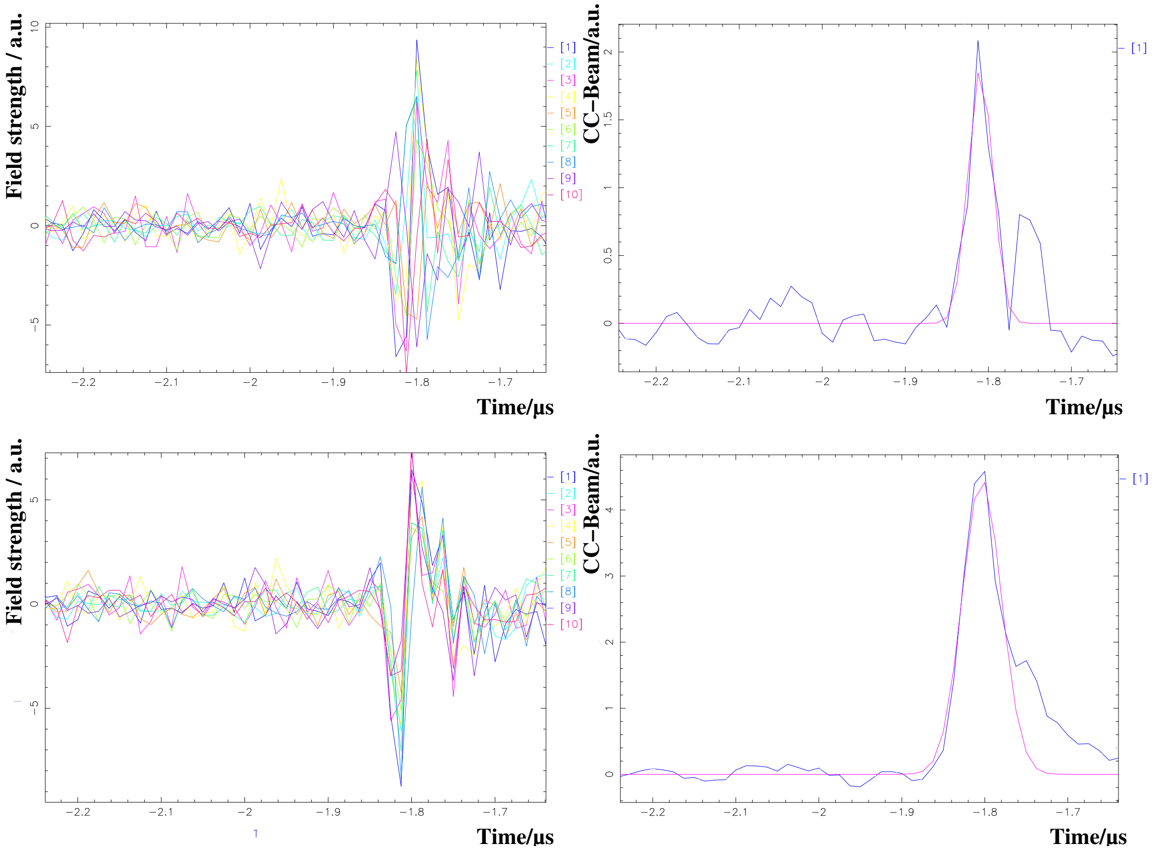

Figure 2. Radio signals in the 10 antennas and the CC-beam coherence estimator after beamforming (upper panels) and after *optimised* beamforming (lower panels).

an impression of the sensitivity of the (cross correlation) CC-beam estimator to the shower direction, shower core position and curvature radius of the radio front for LOPES-10 and LOPES-30 configurations. The z-axis is normalised to the value of the CC-beam estimator in case of the ”perfect” coherence i.e. no ”errors” in the guessed position of the radio pointsource (δ(direction)=0, δ(core)=0, curvature=2.5 km). The procedure of time shifting of the radio signals in the antennas is relatively safe when based on the values provided by Field Array reconstruction for shower core and shower axis (SCA); due to the high granularity of KASCADE stations the accuracy in reconstructing SCA is high enough to obtain a good coherence of the radio signals. Of course, this is valid for shower cores inside Field Array and for not too energetic showers which may lead to saturation of the detection. Grande reconstruction of SCA is required for shower cores outside the Field Array. The Grande stations, 10 m^2 of plastic scintillator detectors each, are spaced at $\simeq$130 m and cannot assure a SCA accuracy comparable with Field Array. So, an optimised beamforming, searching for maximum coherence by varying the SCA around the value provided by the Grande reconstruction is required. Fig. 2 shows the result of such an optimised beamforming compared with a normal beamforming for a single event. This radio event corresponds to the shower displayed in Fig. 1a; the arrow points towards the incoming shower direction. An increase of 200% may be seen in the CC-beam estimator after the optimised beamforming. Table 1 contains the values composing SCA (azimuthal angle ϕ, zenith angle θ, X_{core} and Y_{core}) reconstructed by Grande and the corresponding values obtained after maximizing the radio coherence for this event; small shifts in SCA assure an almost perfect coherence of the radio signal (lower left panel in Fig. 2). The maximization of the

Table 1. SCA values from Grande reconstruction and after maximized radio coherence for an example event.

SCA values	Grande reconstruction	maximized radio coherence
ϕ	302.2°	299.3°
θ	41.0°	39.9°
X_{core}/m	-142.8	-139.2
Y_{core}/m	40.3	51.6

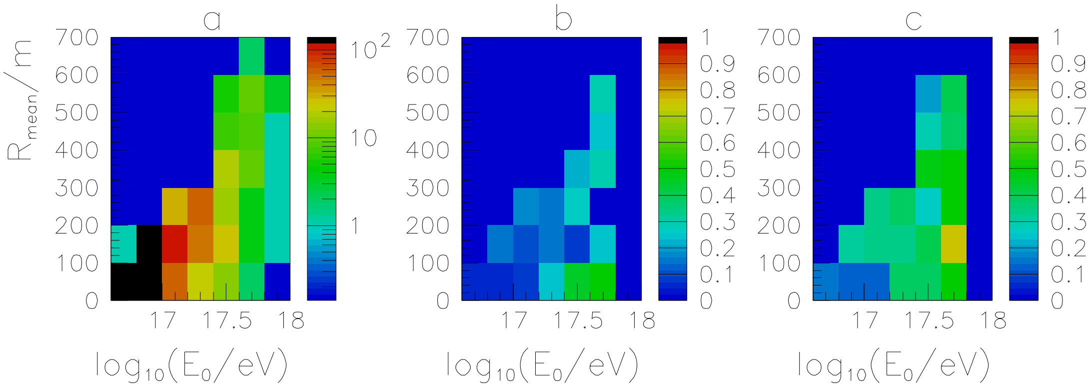

Figure 3. a) distribution of the candidate events on primary energy and distance to the shower axis; b) efficiency of the radio detection for an usual beamforming; c) preliminary efficiency of the radio detection for an optimised beamforming (only performed for half of the sample, yet).

radio coherence (optimised beamforming) plays a key role in establishing the right correlations [5] between the intensity of the radio signal and the other EAS parameters. Fig. 3b shows the efficiency of detecting radio signals for the EAS events in Fig. 3a (for selection conditions see [5]) using normal beamforming procedure based on the values provided by Grande reconstruction of SCA. After an optimised beamforming the efficiency is as displayed in Fig. 1c. The efficiency will be even higher because the optimised beamforming has been applied only for half of the candidate events, yet.

3. Conclusions

The coherence of the radio signal is very sensitive to the shower axis and shower core positions. On one hand, very small fluctuations in the shower observables reconstructed by Grande translate into large fluctuations on the estimated radio pulse amplitude. On the other hand, by maximizing the radio coherence, very precise estimations of SCA can be performed.

References

[1] H. Falcke et al. - LOPES collab., Nature 435, 313 (2005).
[2] G. Navarra et al. - KASCADE-Grande collab., Nucl. Instr. & Meth. A 518, 207 (2004).
[3] T. Antoni et al. - KASCADE collab., Nucl. Instr. & Meth. A 513, 429 (2003).
[4] R. Glasstetter et al. - KASCADE-Grande collab., Proc. of 28th ICRC, Tsukuba, Japan, 781 (2003).
[5] A.F. Badea et al. – LOPES collab., Remote event analyses of LOPES-10, these proceedings.