

# Progress in air shower radio measurements: Detection of distant events

## LOPES Collaboration

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## Abstract

Data taken during half a year of operation of 10 LOPES antennas (LOPES-10), triggered by EAS observed with KASCADE-Grande have been analysed. We report about the analysis of correlations of radio signals measured by LOPES-10 with extensive air shower events reconstructed by KASCADE-Grande, including shower cores at large distances. The efficiency of detecting radio signals induced by air showers up to distances of 700 m from the shower axis has been investigated. The results are discussed with special emphasis on the effects of the reconstruction accuracy for shower core and arrival direction on the coherence of the measured radio signal. In addition, the

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correlations of the radio pulse amplitude with the primary cosmic ray energy and with the lateral distance from the shower core are studied.

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## 1. Introduction

In 1962 Askaryan [1] predicted that extensive air showers (EAS) should generate coherent radio emission. A few years later, in 1965, the phenomenon has been experimentally discovered by observing a radio pulse generated during the EAS development at 44 MHz [2]. In a review by Allan [3] these early studies were summarized. In the pioneering work of Askaryan coherent Cherenkov radiation of the charge-excess was considered as the process responsible for the EAS radio emission. However, the low matter density in the Earth's Atmosphere and the existence of the Earth's magnetic field allow an alternative process for the origin of the radio signals. In an approach based on coherent geosynchrotron radiation [4], electron–positron pairs generated in the shower development gyrate in the Earth's magnetic field and emit radio pulses by synchrotron emission. Detailed analytical studies [5] and Monte-Carlo simulations [6] predict relevant radio emission at frequencies of 10 to a few hundred MHz. During the shower development the electrons are concentrated in a shower disk, with a thickness of a few meters. This leads to a coherent emission at low frequencies up to 100 MHz, where the wavelength is larger than this thickness. For showers above a certain threshold energy one expects a short, but coherent radio pulse of 10–100 ns duration with an electric field strength increasing approximately linearly with the primary energy of the cosmic particle inducing the air shower. I.e., one expects a quadratic increase of the received energy of the radio pulse with the primary particle energy. In addition, the geosynchrotron emission process is expected to be dominant for radio emission during the cosmic ray air shower development. Recently, measurements using the LOPES experiment [7] support these predictions.

A series of recent papers (e.g. [7–9]) report about promising experimental results in detecting radio emission in coincidence with air shower events measured by particle detectors. A rather unique opportunity for calibrating and understanding the radio emission in EAS is provided by LOPES, which is located at the site of the KASCADE-Grande experiment [10,11]. The KASCADE-Grande experiment installed at the Forschungszentrum Karlsruhe is a multi-detector setup which allows precise estimations of charged particle EAS observables in the primary energy range of  $10^{14}$ – $10^{18}$  eV. LOPES-10 is an array of 10 dipole antennas placed inside the particle detector array of KASCADE-Grande. Recently, LOPES-10 was extended with 20 additional antennas to LOPES-30 [12].

The LOPES-10 data set is subject of various analyses addressing different scientific questions. With a sample ask-

ing for high quality events the proof of principle for detection of air showers in the radio frequency range was made [7]. With events falling inside the original smaller KASCADE array basic correlations of the radio signals with shower parameters were shown [13]. Further interesting features are currently being investigated with a sample of very inclined showers [14] and with a sample of events measured during thunderstorms [15]. The focus of the present paper is to display some general features deduced from first measurements of the LOPES experiment for events with primary energies above  $5 \times 10^{16}$  eV which are observed by the large KASCADE-Grande array and LOPES in coincidence, including shower cores at large distances. Special emphasis is put on effects of the applied radio reconstruction procedures, on detection efficiency, and on features of the measured radio signal dependencies on parameters of the primary cosmic particle such as the primary energy and distance of the antennas from the shower axis.

## 2. Data processing

### 2.1. Experimental situation

The KASCADE-Grande experiment [10,11] (Fig. 1, left panel) observes EAS in the primary energy range from 100 TeV to 1 EeV. It enables multi-parameter measurements of a large number of observables of the three main EAS components: electron/ $\gamma$  component, muons, and hadrons. The main detector parts are the original KASCADE array, and the Grande detector stations (Fig. 1, left panel). The KASCADE array consists of 252 scintillator detector stations and measures the electromagnetic and muonic components with 5 MeV and 230 MeV energy thresholds, respectively. The array is organized in 16 quadratic clusters, where the outer 12 clusters contain electron (unshielded) and muon (shielded) detectors, while the inner four clusters contain electron/ $\gamma$ -detectors, only. The 37 stations of the Grande array, covering an area of  $\approx 0.5$  km<sup>2</sup>, take data in coincidence with KASCADE and allow to reconstruct showers with distances between shower core and the LOPES-10 antennas up to 850 m. The Grande array is triggered by a coincidence of seven neighboring stations. The present analysis uses data of the Grande array for reconstructing basic shower parameters: location and direction of the shower axis and the shower size. In addition, data of the original KASCADE array is used to reconstruct the muon number of the individual showers.

LOPES is an array of radio antennas, which has been installed on the site of the KASCADE-Grande experiment

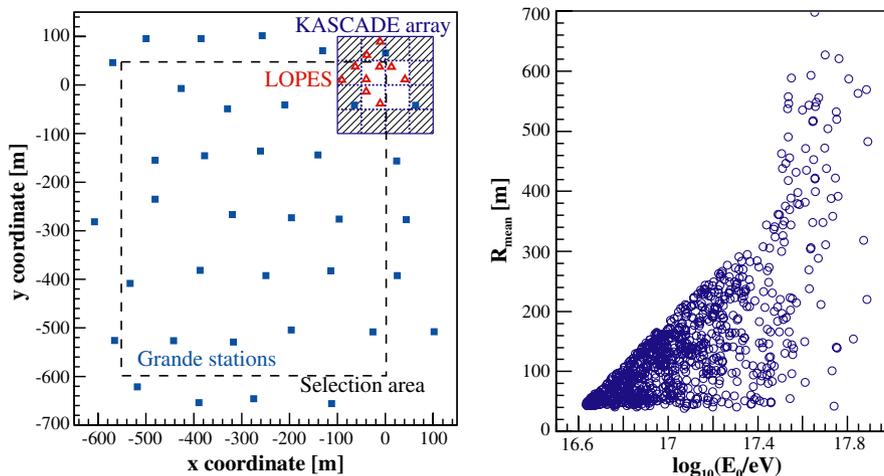


Fig. 1. Left panel: Sketch of the KASCADE-Grande experiment. The main detector components are the KASCADE array and the Grande stations. The location of the 10 LOPES radio antennas is also displayed. Right panel: Distribution of the selected candidate events (862 events) with respect to primary energy (obtained by Grande reconstruction) and mean distance of the shower axis to the radio antennas. The selection is based on cuts of Eq. (2), see text.

in order to demonstrate the feasibility of EAS radio measurements. LOPES is based on prototype developments for the low-frequency-array (LOFAR) [16]. In the current status LOPES (*LOfar PrototypE Station*) operates 30 short dipole radio antennas (LOPES-30); the present analysis uses only data of the first 10 antennas forming LOPES-10 (Fig. 1, left part). The antennas, positioned in the original KASCADE array, operate in the frequency range of 40–80 MHz and are aligned in east–west direction, i.e. they are sensitive to the linear east–west polarized component of the radiation. The read out window for each antenna is 0.8 ms wide, centered around the trigger received from the KASCADE array. The sampling rate is 80 MHz. The logical condition for the LOPES-trigger is at least 10 out of the 16 KASCADE clusters to be fired. This corresponds to primary energies above  $\approx 10^{16}$  eV; such showers are detected at a rate of  $\approx 2$  per minute. The LOPES-10 experiment and its electronics is described in more detail in [8,13].

## 2.2. Selection of candidate events

A sample of 862 candidate events is selected out of 5 months of LOPES-10 data taken in coincidence with the Grande array (Fig. 1, right panel). Selection criteria are

- (i) coincident measurements of the event by LOPES-10, KASCADE field array which has triggered LOPES, and Grande array;
- (ii) a successful reconstruction of the shower observables by the Grande array;
- (iii) zenith angle of the shower less than  $50^\circ$ ;
- (iv) a geometrical cut to ensure the core position to be inside the fiducial area ( $0.358 \text{ km}^2$ ) of the Grande array, see Fig. 1, left panel;
- (v) and, to reduce the amount of data, an energy and distance cut is additionally applied which is motivated by Allan’s formula, as explained below.

The historical measurements of the 1960s were compiled by Allan [3] with the result that the pulse amplitude per unit bandwidth ( $\epsilon_v$ ) of the radio signal induced by an EAS is described by the formula:

$$\epsilon_v = 20 \cdot \left( \frac{E_0}{10^{17} \text{ eV}} \right) \cdot \sin \alpha \cdot \cos \theta \cdot \exp \left( -\frac{R}{R_0(v, \theta)} \right) \left[ \frac{\mu\text{V}}{\text{m} \cdot \text{MHz}} \right] \quad (1)$$

with  $E_0$  the primary particle energy in eV,  $\alpha$  the angle between shower axis and the geomagnetic field,  $\theta$  the shower zenith angle,  $R$  the antenna distance to the shower axis, and the scaling radius  $R_0(v, \theta)$ , which is in the range of 30–300 m with  $R_0 = 110$  m at 55 MHz and  $\theta < 35^\circ$ .

Compared to  $R$  in the formula, for the present analysis  $R_{\text{mean}}$  is defined as the mean of the distances between the 10 LOPES antennas and the shower core position (reconstructed by Grande) in shower coordinates, i.e. in planes perpendicular to the axis direction. The cut has been applied as

$$\log_{10} \left( \frac{E_0}{\text{eV}} \right) > \log_{10} \left( \frac{E_{00}}{\text{eV}} \right) + 0.4343 \cdot \frac{R_{\text{mean}}}{R_0}$$

$$\text{or } \log_{10} \left( \frac{E_0}{\text{eV}} \right) > 17.5 \quad (2)$$

with  $E_{00} = 10^{16.5}$  eV and  $R_0 = 160$  m, i.e. weaker than Allan’s scaling with radius. The threshold primary energy  $E_{00}$  has been chosen based on the results from Ref. [7] and data reduction considerations. In this selection there are no conditions on the weather situation at the KASCADE-Grande site, i.e. environmental corrections were not applied. There is a known effect of an amplification of the radio signal during thunderstorms [15], but during the discussed measuring time this affects less than 3% of the selected events.

### 2.3. Analysis procedures

The Grande array measures the densities and arrival times of the charged particles, from which shower core position and arrival direction are reconstructed. The reconstruction of the shower size  $N_e$  is also based on data of the Grande array, where the lateral distribution of the measured densities is described by a slightly modified NKG-function [17]. The total muon number is obtained by a likelihood fit of the muon densities measured by the KASCADE muon detectors, located in the outer 192 stations of the KASCADE array [18]. In order to select and investigate the candidate events, the primary energy has been roughly estimated from measured and angular corrected electron and muon numbers by a linear combination where the parameters have been deduced from simulations with fixed energies and five different primary masses by means of a linear regression analysis [17]. These preliminary Grande reconstruction procedures applied to the first year of measurements with Grande lead to accuracies of the shower core position and direction in the order of 10 m and  $0.5^\circ$  with 68% confidence level for simulated proton and iron showers with  $>50$  PeV primary energy and  $22^\circ$  zenith angle. The energy resolution is estimated to be  $\Delta E/E \approx 30\%$  in the relevant energy range which is sufficient for the following considerations.

The main steps to process the measured LOPES radio raw signals of an individual air shower are the following (for a more detailed description see Refs. [13,19]):

- (1) Correction of instrumental delays by monitoring the relative phases of a TV transmitter in the measured frequency band.
- (2) Correction of the data for a frequency dependent gain factor of all electronic components in the signal chain. This factor has been obtained by measuring appropriate amplifications and attenuations in a laboratory environment.
- (3) Removal of narrow band radio frequency interference (RFI). It occupies only a few channels in frequency space, while a short time pulse (e.g. from an EAS) is spread over all frequency channels. So, by flagging the channels with RFI the background is significantly reduced without affecting the air shower pulse significantly.
- (4) The digital beam-forming. It consists of two steps: First, a time shift of the data according to the given direction is done and then the combination of the data is performed calculating the resulting beam from all antennas. The geometrical delay (in addition to the instrumental delay corrections) by which the data is shifted, is the time difference of the pulse coming from the given direction to reach the position of the corresponding antenna compared to the reference position. This shift is done by multiplying a phase gradient in the frequency domain before transforming the data back to the time domain. This step

includes also a correction for the azimuth and zenith dependence of the antenna gain. To form the beam from the time shifted data, the data from each pair of antennas is multiplied time-bin by time-bin, the resulting values are averaged, and then the square root is taken while preserving the sign. We call this the cross-correlation beam or CC-beam:

$$CC(t) = \text{sign}(S(t)) \sqrt{\frac{1}{N_p} |S(t)|} \quad \text{with}$$

$$S(t) = \sum_{i \neq j}^N s_i(t) \cdot s_j(t) \quad (3)$$

with  $N$  the number of antennas,  $N_p$  the number of antenna pairs,  $s_i(t)$  the field strength of antenna  $i$ , and  $t$  the time-bin index. The radio wavefront of an air shower is not expected to arrive as a plane wave on the ground, it should have some curvature. During the reconstruction procedures the radius of this curvature is taken into account by iterating a free parameter until the CC-beam is maximal. To some extent, however, the obtained value of this free parameter is degenerated by the uncertainties in the shower direction and due to the fact that the signal is generated in an extended and not point-like source.

- (5) Quantification of the radio parameters: Due to the filtering of low and high frequencies, the response of the analog electronics to a short pulse is an oscillation over a short time. Sampling such a signal with an ADC gives a certain fine structure inside the pulse that is not part of the original pulse but is caused mainly by the filter. To suppress this fine structure the data is smoothed by block averaging over three samples in the time domain, where three was found as optimum value not to broaden the pulse too much. Although the shape of the resulting pulse (CC-beam) is not really Gaussian, fitting a Gaussian to the smoothed data gives a robust value for the peak strength, which is defined as the height of this Gaussian. The error of the fit results gives also a first estimate of the uncertainty of this parameter. The uncertainties dependent on the accuracy of the core and direction estimate used as input to the beam-forming are not considered in the following analyses. The obtained value for  $\epsilon_v$ , which is the measured amplitude divided by the effective bandwidth, will be given in units of [ $\mu\text{V}/\text{m MHz}$ ], but has to be multiplied by an unknown quantification factor  $A$  due to the lack of an absolute calibration [19].
- (6) Identification of good events: Not every selected air shower is accompanied by a radio pulse which is detectable by LOPES. There can also be an incoherent noise peak which is as high as a peak induced by the air shower, even in the formed beam. One can therefore not select events with air shower pulses just by the height of the fitted Gaussian, but has to classify events in a further step. The criteria for this selec-

tion are: existence of a pulse, coherence of the pulse, expected position of the pulse in time, and an approximately uniform pulse height in all antennas. Up to now these criteria are verified by hand, where the uncertainties are larger at low signal to noise ratios, i.e. at the threshold of detection.

#### 2.4. Search for maximum radio coherence

The observed radio signal is expected to be sensitive to characteristics of the primary particle inducing the air shower like primary energy and mass. A crucial element of the detection method is the digital beam-forming which allows to place a beam in the direction of the cosmic ray event. Therefore, the measured signal is also expected to be sensitive to the core position, to the shower direction, and to the curvature of the emitted wave front. To investigate such intrinsic capabilities of the beam-forming in case of LOPES-10 a simple simulation has been performed based on analytical calculations.

For a monochromatic point source radiating at 60 MHz, placed at a position of 2.5 km along the vertical shower axis from the ground, the sensitivity of the CC-beam estimator (Eq. (3)) has been calculated. Fig. 2 gives an impression of the relation of the CC-beam to the shower direction, the shower core position and the radius of curvature of the radio front for the geometrical layout of LOPES-10. The  $\delta$ -values denote the differences between the true position/direction of the radio source and the assumed input values for calculating the CC-beam. The  $z$ -axis in the figure are normalized to the value of the CC-beam estimator in case of ‘perfect’ coherence, i.e. no uncertainties in the position of the radio point source ( $\delta(\text{direction}) = 0$ ,  $\delta(\text{core}) = 0$ , and radius of curvature = 2.5 km). Only one parameter is varied at a time, where the other two are set to the true value. The calculations show that one loses (z-value is decreased by 20%) coherence if the start parameters for the CC-beam estimation in the direction are reconstructed with an error of more than  $0.8^\circ$ , and the core position with an error of more than 25 m, respectively. In contrast to direction and core, the distance of the shower axis from the antennas is relevant for the radius of curvature. The

further away from the axis, the more important the precision of the radius parameter becomes.

On the other hand the results shown in Fig. 2 can be interpreted as the intrinsic resolution of the antenna system, i.e. LOPES-10 has a limit in direction resolution of  $0.8^\circ$  and in core resolution of 25 m, and the further away the shower axis is the better the resolution gets as the uncertainty in the radius estimate decreases.

The calculations have also shown that going to lower frequencies the better coherence improves the primary energy estimation, where measuring with more antennas (LOPES-30) improves the reconstruction accuracy of the shower geometry.

As shown in Fig. 2, the procedure of time shifting the radio signals is relatively safe when the shower parameters for core and axis are reconstructed with high accuracy, i.e. provided by the reconstruction of data taken with the original KASCADE field array. Due to the high sampling area the accuracy of the core position and direction is good enough to obtain satisfying coherence of the radio signals. Of course, this is valid only for showers with cores inside KASCADE. A shower reconstruction using data from the Grande array is required for shower cores outside KASCADE. The Grande stations cannot assure an accuracy comparable with the original KASCADE array. This leads to events whose reconstructed radio signals do not fulfill the requirements to qualify as detected in the radio channel. Therefore, a so-called optimized beam-forming is performed, which searches for maximum coherence by varying the core and the direction around the values provided by the Grande reconstruction. I.e., the beam-forming procedures – steps 4–6 as described above – are repeated 50 times per shower, where the core and direction are randomly chosen inside the parameter space given by the KASCADE-Grande reconstruction accuracy. A more detailed discussion of the optimized beam-forming can be found in [20].

Fig. 3 shows as an example the result of such an optimized beam-forming for an event with a medium distance between shower axis and radio antennas. In the upper part of the figure the raw time-series of the 10 antennas and the corresponding CC-beam including the fit are shown,

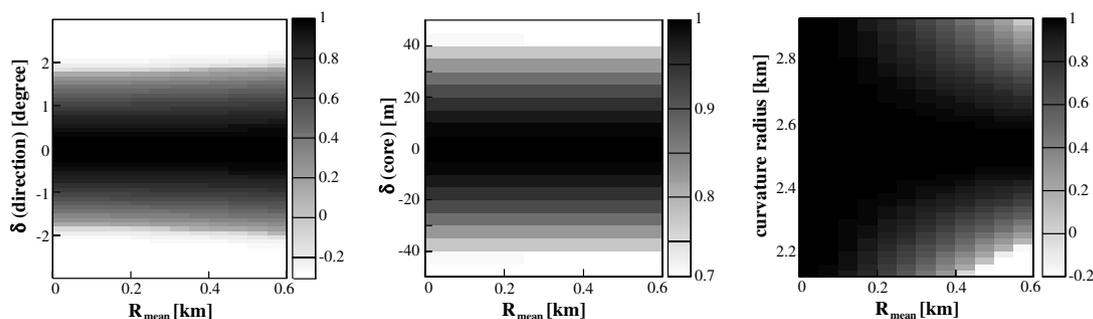


Fig. 2. Analytically estimated sensitivity of the (cross-correlation) CC-beam to the variation of the shower direction  $\delta(\text{direction})$ , the shower core position  $\delta(\text{core})$ , and the radius of curvature of the radio front in dependence of  $R_{\text{mean}}$  for the LOPES-10 configuration, assuming a monochromatic point source emitting at 60 MHz.

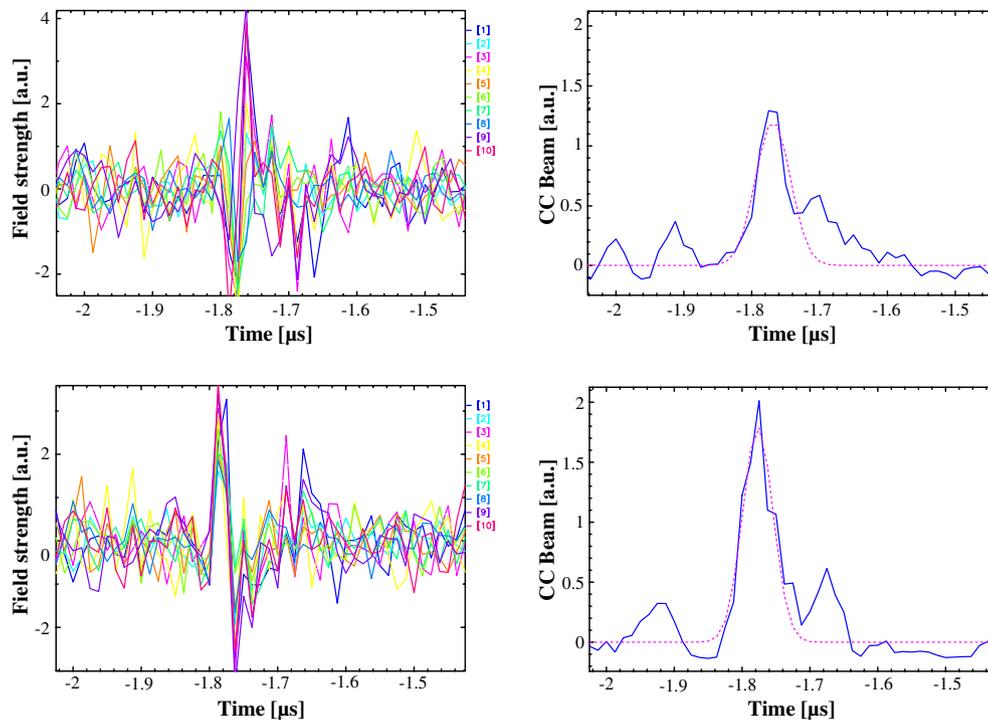


Fig. 3. Event example: Upper panels: Signals of the individual antennas and result of the beam-forming (full line: CC-beam; dotted line: Gaussian fit) based on shower observables reconstructed by Grande; Lower panels: Signals of the individual antennas and result of the optimized beam-forming in order to maximize the radio coherence.

obtained by using the Grande reconstructed parameter set. The lower part shows the same event by choosing those starting parameters for the beam-forming which led to the maximum coherence, i.e. the highest radio pulse. An increase of 50% is seen in the CC-beam estimator after the optimized beam-forming. Table 1 compares the shower parameter values and their changes after achieving maximum coherence.

In the sample of the candidate events there are also events which have a very short mean distance to the antennas. Due to this small distance, the particle densities detected by the KASCADE array are relatively high inducing a lot of radio noise (incoherent signals, but still visible in the CC-beam estimation). After optimized beam-forming these incoherent signals cancel out at the CC-beam. Events hitting the KASCADE array can also be reconstructed with KASCADE data independent of the Grande reconstruction, but with better accuracy. It was found [20] that for these events the two independently estimated

parameter sets (Grande plus LOPES after the optimized beam-forming and KASCADE reconstruction) are in better agreement than KASCADE with Grande results alone. Therefore, the optimized beam-forming gives the possibility to improve the accuracy of shower parameters by including the radio information in the reconstruction of the shower with Grande. This concerns the core position and shower direction directly, then iteratively with the new values the reconstruction of the shower sizes and therefore also the primary energy and mass estimation.

For events with very large distances, i.e. around or above 400 m, we also found a significant improvement of the CC-beam detectability by applying the optimized beam-forming. For the reconstruction of such events the expected time shifts, calculated by use of the known core distance, have to be taken into account to find the correct coherent peak. Such shifts serve as an additional constraint on the analysis procedure, especially for events with large distance to the antennas [20].

After applying the optimized beam-forming procedures the obtained shower parameters are compared to the original (Grande reconstructed) parameters. For the angle a mean shift of  $2.3^\circ$  appears, which is still reasonable if we assume an uncertainty of roughly  $1^\circ$  for the present state of Grande reconstruction [17] and also  $\approx 1^\circ$  for LOPES-10 [7]. The mean shift in core position results to 15 m which is also not far off from the reconstruction uncertainties, but for the individual events a systematic shift of the cores in direction to the antenna center was recognized. However, with the available statistics and still partly preliminary cal-

Table 1

Shower observables reconstructed by Grande alone and obtained after optimized beam-forming of LOPES-10 data for the EAS radio event displayed in Fig. 3

Observable	$\phi$	$\theta$	$X_{\text{core}}$	$Y_{\text{core}}$	$R_{\text{mean}}$	$E_0$
Grande	$289.5^\circ$	$41.1^\circ$	-66.0 m	-124.0 m	149.8 m	$4 \times 10^{17}$ eV
LOPES	$292.2^\circ$	$40.6^\circ$	-64.4 m	-123.0 m		

The values of the shower core are given in KASCADE-Grande coordinates (Fig. 1), the mean distance is the mean of the distances from the shower axis to the individual antennas.

ibrations for both the Grande and LOPES detectors, it is premature to investigate any possible systematic shift between the ‘radio’ and the ‘particle’ axis of the shower.

### 3. Results

#### 3.1. Efficiency of the radio detection

As shown in the previous section, the search for a coherent radio signal is very sensitive to the accuracies of reconstructing core position and shower direction. Due to the insufficient resolution of Grande, a lot of radio events fail in the first CC-beam reconstruction. Only 101 of the candidate events could be identified as radio showers. After searching for maximum coherence by varying the core position and direction (i.e. optimized beam-forming), the number of detected radio events increases from 101 to 372 out of 862 candidate events (Fig. 4, left panel). The very small efficiencies visible in the lower-left part of this figure are caused by low primary energies as well as the high radio noise coming from the KASCADE particle detectors. The best efficiency is reached for showers with high energy but not too large distances, where the signal is still strong but the noise from the particle detectors weak.

One of the most interesting results of the current analysis is the presence of clear EAS radio events at more than 500 m distance from the shower axis for primary energies below  $10^{18}$  eV. Concerning the overall detection threshold an increasing efficiency with increasing primary energy reaching approximately 60% for primary energies above  $2 \times 10^{17}$  eV is obtained with LOPES-10 (Fig. 4, right panel). An aggravating circumstance for missing detection even at high energies is the fact that with LOPES-10 only one polarization direction is measured.

In addition, correlations of further shower parameters have to be investigated in more detail to find reasons for low efficiencies, even after applying the optimized beam-forming procedures. Here the direction of the shower axis

plays the main role: By simulations [6] it is expected that the emission mechanism in the atmosphere and therefore also the radio signal strength depends on the zenith, on the azimuth, and as a consequence on the geomagnetic angle. The latter is the angle between the shower axis and the direction of the geomagnetic field. Indeed, detailed analyses of LOPES data have shown [7,13,14] that there are preferred directions for enhanced radio signals, or vice versa, there is no radio signal detection for specific shower conditions, especially at the detection threshold. Again, the fact that only one polarization direction is measured aggravates the interpretation of the data. In addition, for the present analysis there is a selection bias: For large distances mainly showers with small zenith angles are selected due to the fact that the trigger condition requires high particle densities inside the KASCADE array, which is located in a corner of the Grande array. Small zenith angles lead to higher particle densities at KASCADE for same primary energy, and therefore to a worse signal to noise ratio in the antennas. Further on, the probability to detect an air shower in radio might also be influenced by variations of the background noise due to weather conditions or day-night effects in the human dominated environment of LOPES. In summary, events with primary energies even below  $10^{17}$  eV could be detected in the radio domain, which is remarkably low considering the noisy environment at the experimental site and the missing measurements of the second polarization direction.

#### 3.2. Lateral dependence of the received signal

After linear scaling of the pulse amplitude  $\epsilon_v$  with the primary energy estimated by KASCADE-Grande a clear correlation with the distance is found (Fig. 5). The functional form of this dependence and also the lateral scaling parameter is of high interest for the further development of the radio detection technique. Following Allan’s formula an exponential behavior with a scaling parameter of  $R_0 =$

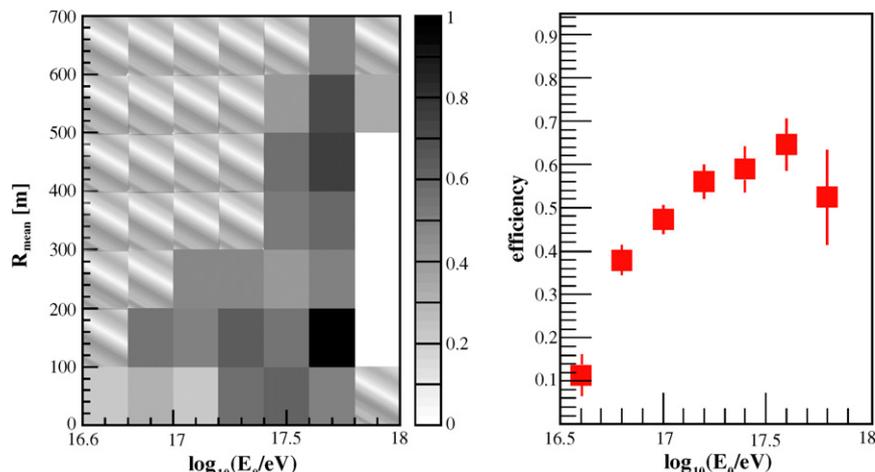


Fig. 4. Left panel: Efficiency of the radio detection after the optimized beam-forming (372 out of 862 candidate events). The hatched areas are bins where no candidates were selected (Fig. 1); Right panel: Efficiency for radio detection versus primary energy.

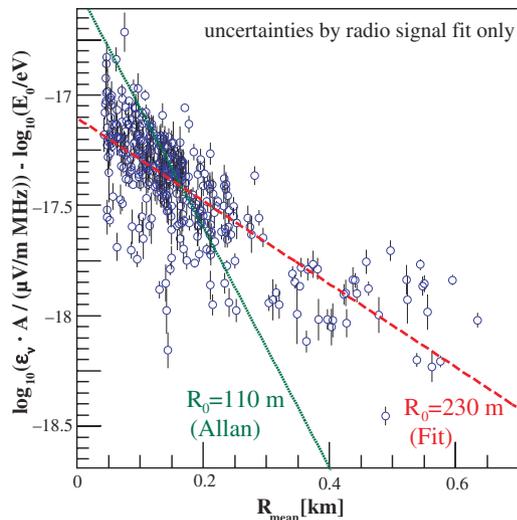


Fig. 5. Correlation of the pulse height corrected for primary energy with the mean distance of the shower axis to the radio antenna system. The lines show results of fits with an exponential function with two free parameters (fit) and with fixed scaling radius as suggested by Allan [3], respectively.

110 m is expected (Eqs. (1) and [3]) for vertical showers. Such an exponential dependence of signal to distance is also expected by detailed simulations of the geosynchrotron effect with a scaling radius of  $\sim 100$  to  $\sim 800$  m, increasing with increasing zenith angle [6]. The CODALEMA experiment does also support such a dependence by a preliminary analysis of a few events ( $R_0$  of a few hundred meters) [21]. Fitting the present data set (Fig. 5) explicitly assuming an exponential function,  $R_0$  results to  $230 \pm 51$  m, i.e. somewhat larger than Allan's suggestion which is also drawn in Fig. 5. One has to note that the initially introduced energy dependent selection cut (Eq. (2)), and the large noise contribution (weak signal) for large distances certainly bias the obtained result on the lateral scaling parameter towards a flatter slope. In addition, the selection cut, the missing correction to the zenith angle dependence, as well as the different definition of  $R_{\text{mean}}$  compared to the definition of the distance  $R$  used in Allan's formula surely distort the obtained scaling parameter.

### 3.3. Energy dependence of the received signal

In Fig. 6 the pulse amplitudes are now scaled according to the exponential radial factor obtained by the fit described in the previous section, without the prior energy correction. By that, a clear correlation between the radio field strength and the primary energy is found.

By scaling in addition subsequently with the angle to the geomagnetic field, the azimuth, and the zenith angles, an even stronger correlation with less fluctuations would be expected. Due to the low statistics and the discussed systematic uncertainties of the experimental configuration as well as the efficiency behaviour of the detection, these steps are omitted in the current phase of the analysis. In particular, the small detection efficiencies at low energies distort

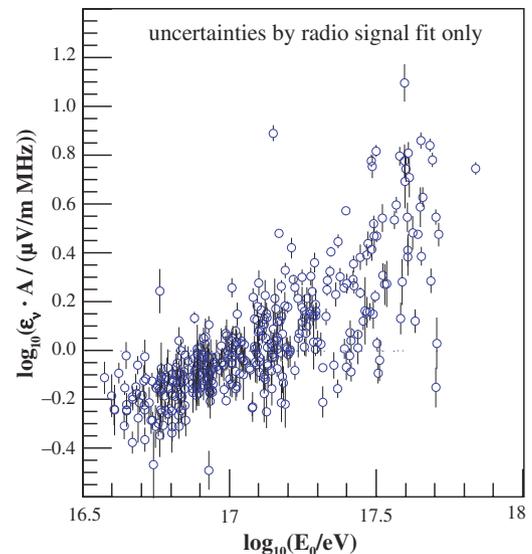


Fig. 6. Correlation of the pulse height (corrected for the lateral mean distance of the shower axis to the radio antenna system) with the primary energy of the showers. No correction for the dependence on the geomagnetic angle, on the zenith angle, or the azimuth angle are applied.

the correlation to a flatter behaviour. Consequently, we omit also to perform a fit to the presented data. Nevertheless, the shown correlation supports the expectation that the field strength  $\epsilon_v$  increases by a power-law with an index close to one with the primary energy, i.e. that the received energy of the radio signal increases quadratically with the primary energy of the cosmic rays. If the index of this power-law were exactly one this would serve as proof of the coherence of the radio emission during the shower development.

## 4. Summary and outlook

A combined data analysis correlating the radio signals measured by LOPES-10 with extensive air shower events reconstructed by KASCADE-Grande was performed. The analyzed showers have their axis in up to 700 m distance from the antenna array and in the primary energy range of  $10^{16.5}$ – $10^{18}$  eV. Some general dependences of the measured radio signal on certain shower parameters were discussed. Missing statistics and experimental deficiencies hamper more detailed investigations in this early stage of air shower radio detection experiments. Nevertheless, the presented first analysis led to some interesting results which can be summarized as follows:

- The most crucial element of radio detection is finding the coherence of the radio pulses. The coherence itself is very sensitive to the shower direction and shower core position. On the one hand, very small fluctuations in the shower observables reconstructed by Grande translate into large fluctuations in the estimated radio pulse amplitude. On the other hand, by maximizing the radio coherence, improved estimations of the core and

direction parameters can be performed. Therefore, the maximization of the radio coherence (optimized beam-forming) plays a key role in detecting EAS radio signals. It increases the efficiency of radio detection and improves the quality of the correlations between the radio signal intensity and the other EAS parameters.

- LOPES-10 is able to detect radio signals (at 40–80 MHz) induced by extensive air showers even at distances of more than 500 m from the shower axis for primary energies above  $10^{17}$  eV.
- For LOPES-10 an energy detection threshold for primary energies below  $10^{17}$  eV was found, which is remarkably low considering the noisy environment at the experimental site and the missing second polarization measurement.
- The dependence of the radio signal strength on the distance of the antennas to the shower axis can be described by an exponential function with a scaling radius in the order of a few hundred meters.
- After scaling with the lateral dependence, a nearly linear increase of the received field strength with the primary energy could be obtained, confirming the coherent character of the emission mechanism during the shower development, as expected by simulations of the geosynchrotron mechanism.

With the measurements of LOPES-10 it was shown that the radio signal in air showers depends on various parameters: The primary energy, the distance to the shower axis, and the direction of the shower axis. Additionally, for all dependences the polarization direction of the measurements plays a role, which was not investigated with LOPES-10. In the present analysis first hints to the lateral structure and to the energy dependence of the radio signal could be derived. With data of the current extension, LOPES-30, consisting of 30 absolute calibrated antennas and the possibility of an additional trigger by Grande, a larger baseline and higher statistics in the measurements will be available. With LOPES-30 one can also use independent subsets of antennas for the CC-beam estimate, and would than have the possibility to estimate the electric field several times, which allows a reconstruction of the lateral extension of the radio emission per single air shower. Additionally, polarization measurements will be performed with LOPES-30. With that data set LOPES-30 is expected to calibrate the radio emission in air showers in the primary energy range from  $10^{16}$  eV to  $10^{18}$  eV.

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