Lateral Distribution of the Radio Signal in Extensive Air Showers Measured with LOPES

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***Abstract*. The lateral distribution of the radio signal in air showers measured with LOPES is studied in detail. The antenna array LOPES is set up at the location of the KASCADE-Grande extensive air shower experiment in Karlsruhe, Germany and aims to measure and investigate radio pulses from Extensive Air Showers. The antennas have an absolute amplitude calibration. This allows us to reconstruct the electric field strength at observation level in dependence of general EAS parameters. The lateral distribution of the measured electric field strengths in individual EAS can be described by an exponential function. The estimated scale parameters describing the slope of the lateral profiles are in the range of 100 m to 200 m, and no evidence for a correlation with shower parameters like azimuth or geomagnetic angle, or primary energy could be found. This indicates that the lateral profile is an intrinsic property of the radio emission during the shower development. For about 20% of the events a flattening towards the shower axis is observed, preferentially for showers with large inclination angle and when measured close to the shower center. The measured lateral distributions are compared on an event-to-event basis with expectations of detailed Monte-Carlo simulations using the REAS2 code.**

***Keywords*: extensive air showers, radio emission, lateral distribution**

I. INTRODUCTION

In the present study we investigate in detail the lateral profile of the radio signal as measured by LOPES [1]. Due to a precise amplitude calibration [2] of each individual antenna and the event information from KASCADE-Grande [3], [4], this is possible on an event-by-event basis with high accuracy. Such investigations are of great interest as the lateral shape defines the optimum grid size for a radio antenna array in a stand-alone mode. Of particular interest is the scale parameter which describes the amount of the signal decrease with distance from the shower axis and the dependence of that parameter on characteristics of the primary particle. In addition, simulations have shown [5], that the lateral shape is related to important physical quantities such as the primary energy or the mass of the primary.

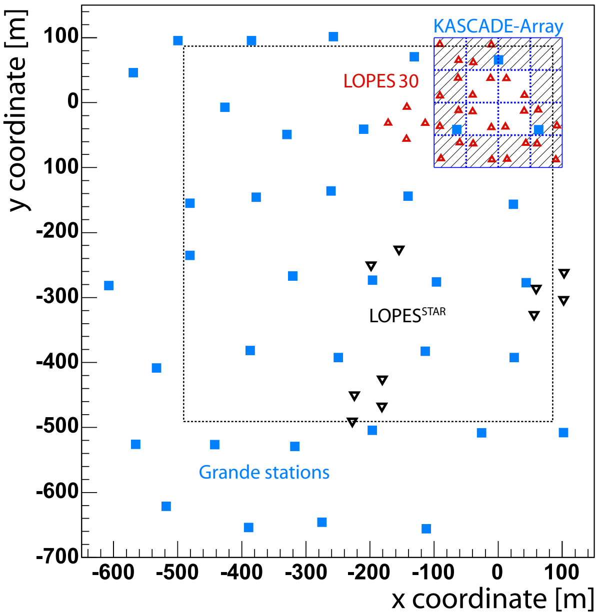

Fig. 1: Sketch of the KASCADE-Grande – LOPES experiments. The dotted line shows the area used for the present analysis.

The LOPES short dipole antennas (LOPES30), positioned within or close to the original KASCADE array (fig. 1), operate in the frequency range of $40 - 80$ MHz and were all (for the period used in this analysis) aligned in east-west direction, i.e. they are mainly sensitive to the linear east-west polarized component of the radiation. This layout was in particular chosen to provide the possibility for a detailed investigation of the lateral extension of the radio signal as it has a maximum baseline of approximately 260 m.

II. Data processing

The data triggered by KASCADE-Grande and recorded by LOPES30 are first generally processed in order to get a calibrated, average field strength value of the received, coherent radio signal, the CC-beam value [6], [7].

The analysis of the data using this CC-beam is based on the RFI cleaned raw data. However, the sampling of the data is done in the second Nyquist domain and a reconstruction of the original 40–80 MHz signal shape is needed to investigate the radio emission properties in more detail, i.e. on basis of single antennas. Therefore, an up-sampling of the data on a single antenna basis is performed (by the zero-padding method applied in the frequency domain) resulting in a band limited interpolation in the time domain [8] to reconstruct the original signal form between the sampled data points with 12.5 ns spacing.

After applying the up-sampling the radio signals can be used to reconstruct the electric field strength in each individual antenna. The systematic uncertainty of these field strengths includes a contribution of the noise level, which is estimated by a calculation using a time window (520 nanosecond width) before the actual radio pulse from the shower.

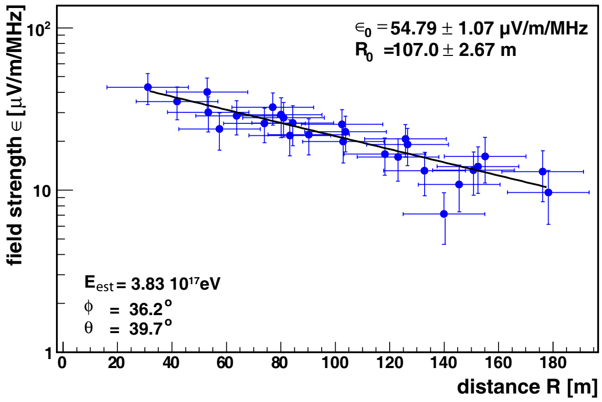

Fig. 2: Lateral distribution reconstructed from single antenna signals, shown for an individual shower.

III. Lateral Distribution of the radio signal

For the analysis of lateral distributions of the radio emission in individual events 110 showers with a high signal-to-noise ratio were selected. The selection requires clear radio signal in all participating antennas and a successful reconstruction of the shower by KASCADE-Grande. To reconstruct the lateral distribution of the radio field strength, the distance of the antennas to the shower axis is obtained with help of the reconstructed shower parameters from KASCADE-Grande. To investigate the lateral behavior of the radio signal an exponential function $\epsilon = \epsilon_0 \cdot \exp\left(-R/R_0\right)$ was used to describe the measured field strengths ϵ. The fit contains two free parameters, where the scale parameter R_0 describes the lateral profile and ϵ_0 the extrapolated field strength at the shower axis at observation level. An example of an individually measured event including the resulting lateral field strength function is shown in figure 2.

For roughly 20% of the events lateral distributions have been found which do not show a clear exponential fall-off. Figure 3 displays an example of such behavior. The shower shows apparently an exponential behavior as others do for larger distances, but there appears a flattening for small distances. There are about 15 events that exhibit such a slope change to a flatter lateral distribution close to the shower axis. In addition, there are a few showers being flat over the whole distance range that could be measured. It should be remarked that at field strengths above 5 μV/m/MHz the ambient noise background cannot affect the measurement. Moreover, no known instrumental effects can explain such shapes, and no strange environmental conditions like a thunderstorm appeared during such events. However, for a statistically reliable analysis, e.g. if two exponential functions with different slopes fit the distribution more reliable, too few of such flat or flattening lateral profiles have been measured so far.

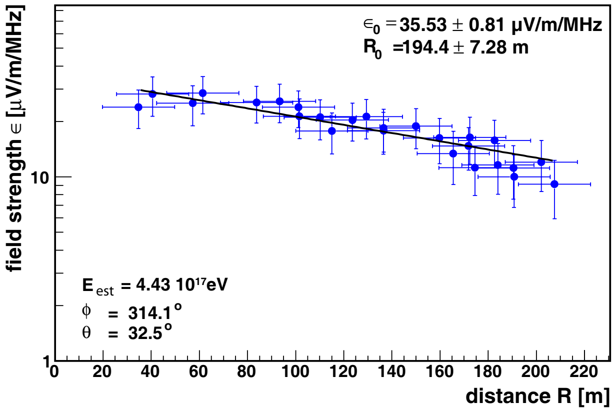

Fig. 3: Lateral distribution reconstructed from single antenna signals, shown for a shower with a clear flattening of the LDF towards the shower center.

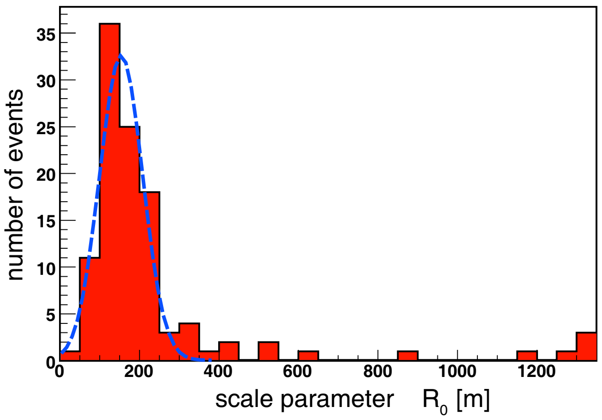

Fig. 4: Distribution of the scale parameter R_0. There are four events set to $R_0 = 1300$ m whose actual R_0 values are higher, i.e. these are very flat events. The dashed line displays a Gaussian fit to the distribution in the range $R_0 = 0 - 300$ m resulting in $\bar{R}_0 = 157$ m with a width of 54 m.

IV. THE SCALE PARAMETER R_0

Most of the showers have a scale parameter smaller than 300 m (figure 4), including the events with a visible flattening to the shower center. As already mentioned, there are some showers with extremely large scale parameter, $R_0 > 1300$ m, those are set to $R_0 = 1300$ m in fig. 4. Fitting a Gaussian function to the distribution of the scale parameter in the range of $0 - 300$ m, i.e. neglecting the flat events, a mean value of $\bar{R}_0 = 157$ m with a width of 54 m is obtained.

For a more detailed study [8] of the lateral distributions the properties of the scale parameter and possible correlations with EAS parameters have been investigated. In case of the LOPES experiment this can be done easily, as the general shower parameters are available from the KASCADE-Grande measurements. The scale parameter has been correlated with the geomagnetic angle, the azimuth angle of the incoming shower, the primary energy, and the shower size, where with none of these parameters a distinct correlation is found. The

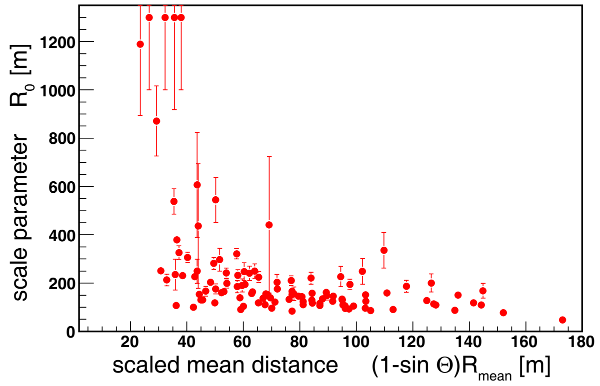

Fig. 5: Relation of the scale parameter R_0 with the mean distance of the antennas to the shower axis scaled with the zenith angle of the axis.

situation is different when the scale parameter has been correlated with the zenith angle of the incoming primary cosmic ray. Here a tendency towards larger values of the scale parameter is seen for inclined events. A clearer feature is even seen, when the scale parameter is analyzed with respect to the corresponding mean distance to the shower axis of all antennas participating in an individual event. It was found that the lateral profile gets flatter when we measure closer to the shower center. In particular, all the very flat events have a mean distance below $R_0 \approx 80$ m.

A strongly pronounced dependence of the scale parameter of flat events is seen when the mean distance is combined with the zenith angle information in the form $R'_{\rm mean} = (1 - \sin\Theta) \cdot R_{\rm mean}$. Figure 5 shows clearly that the probability of a flattening increases when the shower is inclined and when measured closer to the shower axis. But as not all events with small $R'_{\rm mean}$ show a flattening the reason is still unclear and further investigations with larger statistics are required.

V. COMPARISONS WITH REAS2-SIMULATIONS

Because of the performed amplitude calibration of LOPES and the estimate of the field strength at individual antennas a detailed comparison of the measured events with Monte Carlo simulations on an event-to-event basis is possible. Due to the simulation strategy, using realistic air shower models with precise, multi-dimensional histograms derived from per-shower CORSIKA [9] simulations, detailed comparisons are performed [10]. The REAS2 Monte Carlo simulation code (see [5] and references therein) is used to simulate the geo-synchrotron radio emission for all the showers detected in the investigated data set. For each single event a shower that represents best the measured one in KASCADE-Grande estimated parameters is selected. The resulting information and the known shower core position is used in the REAS2 code to calculate the radio emission. The output are unlimited bandwidth pulses, that are digitally filtered with a rectangle filter from 43 to 76 MHz for the known antenna positions

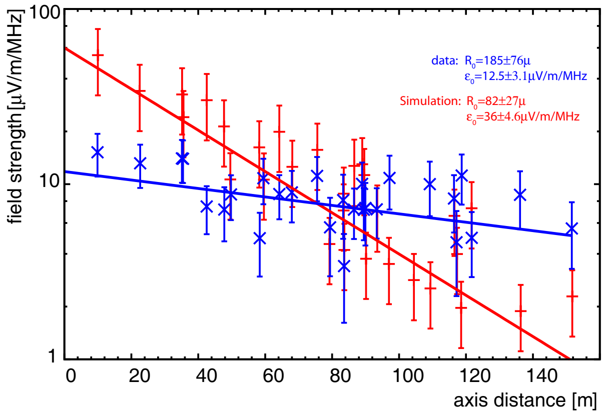

Fig. 6: Lateral distribution obtained for data and simulation for an individual event.

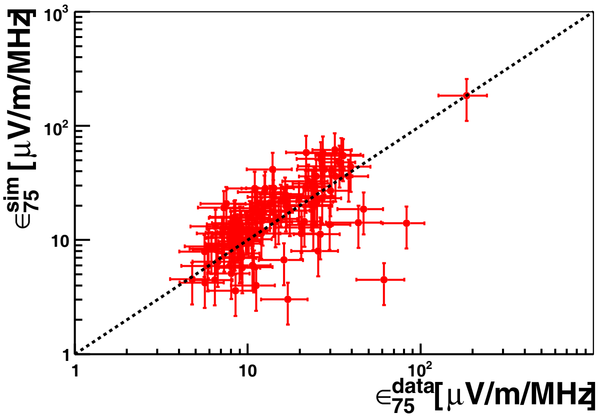

Fig. 7: Comparison of field strength at distance R. Correlations $\epsilon_R^{\mathrm{data}}$ obtained from measurements and $\epsilon_R^{\mathrm{sim}}$ obtained from simulation. The dashed line represents equal values from simulation and measurement.

at ground, which can be directly compared with the measured lateral distribution.

Like in the example displayed in fig. 6, in general the simulations give steeper lateral distributions than measured. The mean for the distribution of the scale parameter from the simulation is $R_0 = 50$ m. Such small values represent a steep lateral decrease of the field strength. In addition, it was derived that the differences between measurements and simulations can be very large and that the unexpected very flat lateral profiles could not be reproduced by the simulations.

The deviation in the scale parameters enters in systematically higher field strengths at the shower axis $\epsilon_0^{\mathrm{sim}}$, compared to the field strengths ϵ_0 obtained from the measured lateral distributions (by approximately factor three). On the other hand we obtain at $R = 75$ m a fairly good agreement between simulations and measurements (fig. 7) for all events. This is a promising result in itself, as such comparisons are performed for the first time for LOPES data.

VI. Conclusions

The lateral distribution of the radio signal in 110 measured LOPES events could be analysed on a single antenna basis. The applied exponential function to these lateral distributions has two free parameters, the field strength ϵ_0 at the shower axis, and the scale parameter R_0. The scale parameter distribution shows a peak value of $R_0 \approx 125$ m and has a tail with very flat lateral distributions. Excluding the flat events a mean value of $\bar{R}_0 \approx 150\,\mathrm{m}$ with a width of $\sigma = 50\,\mathrm{m}$ was obtained. No direct evidence for a dependence on the shower parameters azimuth angle, geomagnetic angle, and primary energy could be found. This indicates that the lateral profile is an intrinsic property of the radio emission and the shower development. Comparing the obtained scale parameter with published values of earlier experiments, a good agreement has been found [8].

Studying the lateral distributions in individual events, approximately 20% of the studied showers show a very flat lateral distribution or exhibit a flattening towards the shower center. Preferably, such showers arrive under larger zenith angle and axes are close to the antennas.

The radio emission observed in EAS was compared with detailed Monte Carlo simulations on an event-to-event basis. The REAS2 simulations exhibit in general a steeper lateral slope, i.e. a smaller scale parameter than the measurements. The absolute field strength, however, agrees quite well at a distance of 75 m to the shower axis. The measured flattening towards the shower center could not be reproduced by the present REAS simulations.

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