Restoring the azimuthal symmetry of lateral distributions of charged particles in the range of the KASCADE-Grande experiment

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ABSTRACT

The reconstruction of Extensive Air Showers (EAS) observed by particle detectors at the ground is based on the characteristics of observables like the lateral particle density and the arrival times. The lateral densities, inferred for different EAS components from detector data, are usually parameterised by applying various lateral distribution functions (LDFs). The LDFs are used in turn for evaluating quantities like the total number of particles or the density at particular radial distances. Typical expressions for LDFs anticipate azimuthal symmetry of the density around the shower axis. The deviations of the lateral particle density from this assumption arising from various reasons are smoothed out in the case of compact arrays like KASCADE, but not in the case of arrays like Grande, which only sample a smaller part of the azimuthal variation.

KASCADE-Grande, an extension of the former KASCADE experiment, is a multi-component Extensive Air Shower (EAS) experiment located at the Karlsruhe Institute of Technology (Campus North), Germany. The lateral distributions of charged particles are deduced from the basic information provided by the Grande scintillators – the energy deposits – first in the observation plane, then in the intrinsic shower plane. In all steps azimuthal dependences should be taken into account. As the energy deposit in the scintillators is dependent on the angles of incidence of the particles, azimuthal dependences are already involved in the first step: the conversion from the energy deposits to the charged particle density. This is done by using the Lateral Energy Correction Function (LECF) that evaluates the mean energy deposited by a charged particle taking into account the contribution of other particles (e.g. photons) to the energy deposit. By using a very fast procedure for the evaluation of the energy deposited by various particles we prepared realistic LECFs depending on the angle of incidence of the particles, azimuthal dependences are already involved in the first step: the conversion from the energy deposits to the charged particle density. This is done by using the Lateral Energy Correction Function (LECF) that evaluates the mean energy deposited by a charged particle taking into account the contribution of other particles (e.g. photons) to the energy deposit. By using a very fast procedure for the evaluation of the energy deposited by various particles we prepared realistic LECFs depending on the angle of incidence of the shower and on the radial and azimuthal coordinates of the location of the detector. Mapping the lateral density from the observation plane onto the intrinsic shower plane does not remove the azimuthal dependences arising from geometric and attenuation effects, in particular for inclined showers. Realistic procedures for applying correction factors are developed. Specific examples of the bias due to neglecting the azimuthal asymmetries in the conversion from the energy deposit in the Grande detectors to the lateral density of charged particles in the intrinsic shower plane are given.

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1. Introduction

The analysis of Extensive Air Showers (EAS) generated by interactions of high energy particles entering the Earth's atmosphere from the outer space is one of the standard methods of investigation of the energy spectrum and mass composition of primary cosmic rays, in particular at higher primary energies. Correlated and interwoven with these questions is the study of the characteristics of the interactions of the incident primary particles at energies beyond the energy range accessible to earthbound accelerators [1].

A crucial EAS observable is the lateral distribution of the EAS particles (of various different EAS components) in a plane perpendicular to the shower axis at the observation level. The particle density distributions and their correlations with various EAS components carry important information about the primary particles and are used to determine the energy and mass of the primary. The first step on this way is to deduce the density of particles from the registered detector signals, e.g. in case of scintillation detectors from the energy deposits in the scintillators. Already this step needs careful consideration since the energy deposit of a particle depends on its incidence direction on the detector [2]. Subsequently the reconstructed particle densities are usually parameterised by adequate functions (Lateral Distribution Functions, LDFs) adjusted to the simulated or experimental data deduced from measurements. There are various LDFs, e.g. the well-known NKG form [3] or the Linsley parameterisation [4] and various others which have been tested with simulations and are proven to describe the data generally fairly well for EAS of zenith angles $\Theta < 40^\circ$. When analysing experimental air shower observations or shower simulation output, it is usually assumed that the footprint of an Extensive Air Shower in the observation plane on ground has elliptical symmetry, centred at the shower axis. A simple projection onto a plane perpendicular to the shower axis should restore circular symmetry. Therefore the LDFs are assumed to be dependent only on the radial distance from the shower axis.

In fact, this is clearly not the case for inclined showers. The cascade continues to develop when the shower hits the ground; particles which strike the ground first represent an earlier stage than those which arrive later and have experienced additional attenuation. Additionally, even for nearly vertical showers, there are asymmetries due to the effects of the geomagnetic field. This is particularly the case for muons, which travel large distances through the atmosphere with minor interaction. Thus, the assumption of circular symmetry may lead to systematic errors in the core location, in the angles of incidence and in the deduced shower parameters. In addition to geometric effects [5–7] arising from the projection from the observation plane onto the plane normal to the shower axis and to effects originating from the attenuation [6–9] of the densities due to different path lengths, travelled by particles at different sides of inclined showers, the Earth's magnetic field also distorts the shape of the lateral distributions. The intriguing effects arising from the geomagnetic field on the lateral distributions have been studied in various papers [10–12]. The geomagnetic field has a stronger effect on showers with very large zenith angles, for which the particles have long path lengths in the atmosphere. This effect also depends explicitly on the geomagnetic angle, i.e. the relative angle between the shower direction and the magnetic field vector. Therefore that means it also depends on the azimuthal angle of the shower [11,12]. Our studies of the asymmetries are based on shower simulations with the CORSIKA simulation program [13], version 6.01, having in mind the motivation to develop feasible methods to restore (at least approximately) the radial symmetry of the lateral distribution in the normal plane.

![Fig. 1. Coordinate system in the observation level (plane $z$) and in the intrinsic shower plane (plane $\beta$). The region BCD located below the shower axis ($SO$) represents the early region of shower development, while the region BAD located above the shower axis represents the late region of shower development. The coordinate systems have the $OY$-axis in common, as the intersection of planes $\alpha$ and $\beta$. The $OX$-axis is in the late region of shower development.](image)

We mainly focus on deviations from the azimuthal symmetry, which arise from an interplay of geometrical features with the attenuation of the shower intensity in the atmosphere. These deviations are of particular interest for a detector configuration like KASCADE-Grande [14], which in general does not allow a complete integration of the lateral density function around the shower core. They are especially important at large distances from the shower axis and for the reconstruction of the muon density from the KASCADE array, which is located in the North-East corner of the Grande area.

In this work we consider the conversion of the experimental signal into the density distribution of the charged particles in the intrinsic shower plane, perpendicular to the shower axis (see the definition of the coordinate systems in Fig. 1). That involves two steps.

In the first step the detector signal, calibrated in terms of the energy deposition, is converted into the number of charged particles that interacted with the detector. The conversion is done using a Lateral Energy Correction Function (LECF) that represents the mean energy deposit in the detector per charged particle. In the second step the number of charged particles that have hit the detector is mapped onto the intrinsic shower plane and the corresponding density of charged particles is obtained. In both steps azimuthal asymmetries have an effect, and they should be corrected for obtaining unbiased results. A feasible procedure for restoring the circular symmetry for practical use is outlined.

2. The KASCADE-Grande experiment

The KASCADE-Grande experiment [14,15] is a multi-detector cosmic ray experiment developed for the study of cosmic rays in the energy range $10^{16} - 10^{18}$ eV. It is located at the Karlsruhe Institute of Technology (Campus North) at 49.1 N, 8.4 E and...
110 m above sea level. The local magnetic field is 47.8 μT, with the vertical component of 43.23 μT pointing downward i.e. the inclination angle with respect to the horizontal direction is 65°. KASCADE-Grande is an extension of the former KASCADE experiment [16,17]. In the KASCADE experiment multiple observables were simultaneously evaluated by a sophisticated detector system, including field detectors (liquid scintillators, threshold energy 5 MeV) for the e⁻/γ component, muon field detectors (plastic scintillators, threshold 230 MeV), a muon tracking detector (streamer tubes, threshold 800 MeV), and a complex central detector, comprising a hadron calorimeter (liquid ionization chambers, threshold 50 GeV), an electromagnetic top cluster detector (plastic scintillators, threshold 5 MeV), an e⁺/γ top layer detector (liquid ionization chambers, threshold 5 MeV), a muon trigger layer (plastic scintillators, threshold 490 MeV), a set of muon multiwire proportional chambers (threshold 2.4 GeV) and a set of muon limited streamer tubes (threshold 2.4 GeV). The field detectors form a compact array distributed on a rectangular surface of 200 x 200 m². The simultaneous detection of several observables and also of the muons with different energy thresholds provided information for consistent shower reconstruction and additionally allowed to test interaction models and quantify the uncertainty resulting from model dependence. The KASCADE experiment obtained the all-particle energy spectrum of the cosmic rays in the range 5 x 10¹⁴ - 10¹⁷ eV as well as the spectra of individual groups of primary particles [18]. A careful analysis of different sets of data, e.g. pertaining to different zenith angle intervals, proved that the data and the analysis procedures are consistent. As reconstruction of the showers relies on simulations, the data analysis using several high-energy interaction models and low energy interaction models proved that the uncertainty of the results is controlled mainly by the limited knowledge of the high-energy interactions. Concerning the spectra of individual groups of particles, this experiment provided conclusive evidence of a change in the index of the power-law spectrum of the primary cosmic rays around 5 PeV, a feature called the knee, with a steepening of the spectra of light elements [18]. While similar results have been obtained in other high-energy cosmic ray experiments, e.g. the EAS-TOP experiment [19], there are still controversies about the origin of the knee [1] and about the position of the knee in the spectra of different elements. The expected position of the knee of the heavy element component (Fe group) is not well inside of the energy range covered by KASCADE. This situation has motivated the extension of KASCADE to the KASCADE-Grande experiment, which is able to measure the spectrum and the mass composition up to 10¹⁸ eV. The extended energy range encompasses the position where the change in the spectrum is expected to occur for Fe primaries (“iron knee”). The KASCADE-Grande detector system [14,15] includes the KASCADE detectors plus 37 plastic scintillator detectors (called Grande detectors) of 10 m² each, plus a smaller array of scintillator detectors (Piccolo), providing a fast trigger to the KASCADE detectors for showers with the core located outside this array. More recently, the possibility to detect radio signals associated with high-energy showers was provided by mounting radio antenna systems (LOPES) in the field of KASCADE-Grande [20,21]. The Grande detectors, formerly used in the EAS-TOP experiment [19], are unshielded and have an energy threshold of 3 MeV. These detectors cover an area of about 700 x 700 m². For trigger purposes the detectors are grouped in 18 overlapping clusters of seven detectors each; each cluster has a central station and the other six detectors located approximately in a hexagon. A trigger is generated by a cluster if a compact group of four stations (the central station plus three adjacent stations) are fired in coincidence; also any event with coincidence between all the seven stations from a cluster generates a trigger. The analysis procedure of KASCADE-Grande data implies first the determination of the shower core position and of the angle of incidence. In a next step the charged particle density (electrons plus muons) at each detector position is obtained by dividing the energy deposition by the appropriate value of the LECF. While the Grande detectors do not differentiate between electrons and muons, the information on the charged particle density is combined with the extrapolation of the muon density from the KASCADE array to the location of the Grande detectors for obtaining the electron and the muon densities. From these basic observables, using knowledge from detailed CORSIKA simulations of the shower development [22–24] and detector response, the energy and the nature of the primary cosmic rays can be obtained. For example the correlation of the number of electrons and muons can be used as a mass estimator [22]. A combination of the number of electrons and of the number of muons can be used as an energy estimator. The charged particle density at 500 m from the shower core proved to be insensitive to the mass of the primary particle [25] and may also be used as energy estimator [26].

3. Lateral energy correction function (LECF)

The Grande detectors do not differentiate between electrons and muons. These detectors give a single signal, proportional to the total energy deposited by all the particles from a shower that have interacted with the detector. Therefore, the appropriate observable provided by a Grande detector is the number of charged particles (electrons and muons). It is obtained by dividing the calibrated detector signal by the mean energy deposited in a Grande detector per charged particle, i.e. by the appropriate value of the Lateral Energy Correction Function (LECF). The basic idea that makes the LECF useful is the fact that the peaks in the distribution of the energy deposition E_p by shower electrons and by shower muons are located practically at the same energy (Fig. 2). Therefore, the energy deposition depends in the first approximation only on the total number of electrons and muons, and not independently on the number of electrons and on the number of muons.

For a realistic evaluation of the LECF several additional facts should be considered.

1. Other particles, e.g. photons, protons or neutrinos, can interact with the detector. The additional energy deposited by these particles increases the value of the LECF above the mean energy deposited by an electron or by a muon. The relative contribution of these particles depends on the distance from the shower core and therefore the LECF should depend on the radial distance of the detector from the shower core.

2. For inclined showers the average path length of the secondary particles through the scintillation plates is longer and consequently the LECF values should depend on the shower incidence angle.

3. The distribution of the energy deposition by electrons or by muons depends on the energy of the incoming particle. This distribution depends on the distance from the shower core.

4. For vertical showers the angular distribution of shower particles depends on the distance from the shower core, being wider for electrons than for muons. This distribution controls the distribution of the path lengths of the particles through the detector, and hence the energy deposition. This introduces an additional dependence of the LECF on the radial coordinate.

5. For inclined showers the angular distribution of shower particles depends also on the azimuthal coordinate around the shower core; the angles of incidence are smaller in the early region of the shower (located below the shower axis) and
are higher in the late region, above the shower axis (Fig. 3). This introduces an azimuthal dependence of the LECF, with higher energy deposition per particle in the late region of the shower development than in the early region for particles with equal energy.

In what follows the angle of incidence of a particle on the detector will be denoted by $\Omega$, while $\Theta$ will be used for the angle of incidence of the shower.

3.1. Standard LECF used in the analysis of KASCADE-Grande data

The standard LECF applied in the analysis of KASCADE-Grande data is obtained by Monte Carlo simulation as follows. For a specific primary particle, of given energy and direction of incidence, the complete shower development is simulated using CORSIKA [13]; the output of the simulation provides for each shower particle that traverses the observation level the following information: type, position (with respect to a coordinate system with the origin at the shower core, i.e. the point of intersection of the shower axis with the observation level), momentum, and the arrival time (with respect to the first interaction). Then the position of the shower core with respect to the KASCADE-Grande coordinate system is specified (either randomly or not, depending on the purpose of the study) and in this way the positions of the shower particles with respect to the detectors are known. The shower particles that hit the detectors are processed with the CRES program. This program is a specialized code for taking into account the experimental response, based on GEANT 3.21, including all the experimental details in such a way as to obtain simulated data consistent with the experimental data. One step in the flow of CRES processing involves the simulation of the energy deposition in the detectors. The simulation is done by transporting with GEANT 3.21 each particle that hits a detector through the experimental assembly; as a result the energy deposition in that detector is obtained. Dividing this energy by the number of electrons and muons that have hit the detector the value of LECF for the particular location of the detector is obtained. By repeating the complete simulation an average LECF is obtained, using a rather limited number of directly evaluated energy deposition values.

Because CORSIKA simulations are time consuming, the same shower is sometimes distributed with the core at several positions over the area of the KASCADE-Grande array. In this case, depending on the position of the shower core, the detectors sample the particles from various regions of the same shower. Thus, without repeating the shower simulation the values of the LECF for several
positions with respect to the shower core can be obtained. Nevertheless, because particle interaction with the detector assembly carried out with GEANT is time consuming, the final information on the LECF is obtained from only a very small number of the shower particles, representing a fraction of the order of $4 \times 10^{-4}$. The resulting LECF (Fig. 4) is given by the following function [15]:

$$\text{LECF}(r) = \begin{cases} \exp(1-0.1 \cdot r)+7.51+0.02 \cdot r-5.5 \times 10^{-5} \cdot r^2 & r \leq 450 \\ +5.4 \times 10^{-3} \cdot r & r > 450 \\ \text{LECF}(450) & \end{cases}$$

where $r$ is in metres and LECF is given in MeV. As can be seen several of the effects discussed at the beginning of Section 3 are not incorporated or are treated only approximately in the standard computation of the LECF. In what follows a procedure yielding a more detailed evaluation of the LECF will be presented.

3.2. Basic computation of the energy deposition in the Grande detectors

In order to include all the effects listed above in the computation of the LECF it would be necessary to process a larger fraction of the shower particles (e.g. all the particles that hit the area delimited by the Grande array) through the detectors. For this purpose a procedure of evaluation of the energy deposition in the Grande detectors much faster than using GEANT is required. The development of this procedure is based on the fact that for any particle incident with a given energy and angle the energy deposition spectrum in a Grande detector has a relatively simple shape (Fig. 5). This shape can be accurately described as a superposition of some elementary distributions that can be randomly sampled in a very fast computation.

The dependence of the shape of the deposition spectrum on the incident energy is weak (Fig. 2) and the dependence on the incidence angle $\Omega$ is smooth (Fig. 6). Thus, if the parameters corresponding to the elementary distributions and the relative contribution of each such distribution are available for a set of incident energies and angles of incidence, then the values pertaining to any energy and angle can be easily and precisely evaluated by suitable interpolations. The reference energy deposition spectra can be computed with a detailed GEANT simulation for a set of incident energies and angles, for any type of shower particle of interest.

This procedure was applied earlier [2] but in the simulation of the detector response the Grande hut and the pyramid below the scintillators were neglected. In the present approach all the details of the experimental setup of the Grande detectors that are included in the standard description adopted in CRES were included in the simulation [27,28]. The metal hut of the detector station is especially important in the case of photons and electrons, acting as a radiator increasing the mean energy deposition.

The reference energy deposition spectra for electrons, muons, photons, protons and neutrons were computed by full GEANT 3.21
simulation for a common set of energies above 1.2 GeV: 1.2, 2.5, 5, 50, 500, 5000, 50 000, 500 000 GeV. Below 1.2 GeV the energies selected for the simulations were chosen differently for each type of particle, depending on the rest mass. For each energy the simulations have been done for the following incidence angles: 0°, 40°, 50, 500, 5000, 50 000, 500 000 GeV. Below 1.2 GeV the energies corresponding to the maximum, $\sigma_E$ is the width of the distribution.

In a first step each reference spectrum was fitted with simpler functions, including Landau distributions, Gauss distributions, exponential and linear functions. An example of the quality of the fit is given in Fig. 7. In a next step the parameters characterizing each of the simple distributions have been fitted as functions of energy and angle of incidence, for each type of particle. In Fig. 8 the gradual change in the Landau peak and in its fit with the angle of incidence is represented for muons with energy $E=5$ GeV. In Fig. 9 the dependence of the position of the maximum of the Landau peak and of the width of this peak as a function of angle is shown, as an example.

Finally, after determining the parameters of the simple distribution functions as a function of energy and angle, fast sampling procedures have been developed for obtaining the random energy deposition. On the basis of the relative contribution to the spectrum, one of the simple functions is randomly selected. Next, the energy deposition is sampled with specific procedures, according to the probability density defined by the selected function.

Another question is whether the same LECF is appropriate for each detector. The scintillators are identical, the minor differences in the electronics are corrected in the individual calibration of each Grande station [15], but the position of the scintillator plates inside the hut is not strictly the same for all the detectors; due to the fact that the walls of the hut act as radiators the position of the scintillator with respect to the hut might influence the detector signal. Furthermore, the hut is a parallelepiped and thus lacks azimuthal symmetry. In order to evaluate the uncertainties introduced by these effects, selected simulations were carried out using several modified conditions with respect to the standard simulations. In order to evaluate the sensitivity of the detector signal to the position of the scintillator with respect to the hut, a set of simulations was carried out with the scintillator located off-centre, in extreme realistic positions inside the hut. The energy deposition is practically insensitive to the position of the scintillator for a uniform distribution of the azimuthal angle of the incoming particles. Another set of simulations was carried out with fixed azimuthal angle in a given run. The results for different azimuthal angles were compared among each other and were also compared with the standard simulations (carried out with the
azimuthal angles uniformly distributed); they are slightly different, but the effect (typically less than 4%) is smaller than e.g. the uncertainty of experimental detector calibration [15]. Other effects, such as the presence of buildings in the vicinity of the hut, were not considered, although they will be important for very inclined showers.

3.3. Evaluation of the LECF

In order to evaluate the LECF the fast procedures for the simulation of energy deposition in the Grande detectors were combined with the information concerning the distribution of secondary particles provided by the shower simulation done with the CORSIKA code.

Practically, a square of length equal to 2000 m with the centre at the shower core was considered, paved with Grande detectors placed side by side. For each detector every particle that, according to shower simulation, hits the detector was processed and the associated energy deposition was evaluated. As an example in Fig. 10 the mean energy deposited by an electron (the total energy deposition in a detector by all the electrons divided by the number of electrons) is represented for a shower produced by a proton with energy $E = 8.02 \times 10^{17}$ eV and angle of incidence $\Theta = 53^\circ$. In the left panel of Fig. 10 $E_d$ values obtained directly from simulations are represented as a function of the position of the detector described through the distance $R$ to the core and azimuthal angle $\Psi$, while in the right panel the values are smoothed and represented in function of the $(x, y)$ coordinates of the detector in the observation plane (See Fig. 1). In Figs. 11 and 12 results similar to those represented in the right panel of Fig. 10 are displayed for muons and photons. The substantial decrease of the energy deposit per particle as the distance from the core increases from 0 to several tenths of metres in the case of electrons and photons is due to the fast decrease of the energy of the shower electrons and photons in that radial range, implying also a reduced energy deposition. It can be seen that for any type of particle the energy deposition in the late region of the shower (azimuthal angle around 0° or 360°, see Fig. 1) is much larger than in the early region (azimuthal angle around 180°); this is due to the longer path of the trajectory through the detector of the particles that come in the late region, with higher incidence angles, in comparison with particles that come in the early region, with smaller incidence angles.

![Fig. 10](image1.png)

![Fig. 11](image2.png)

![Fig. 12](image3.png)
After processing all shower particles the total energy deposited in each detector was evaluated and then divided by the number of charged particles (electrons and muons) that have hit that detector. In this way the map of the energy deposition per charged particle, i.e. the LECF, as a function of detector position was obtained for the simulated shower. In Fig. 13 the map of the LECF for the same proton shower is displayed. The difference of LECF values between the late region of the shower development, corresponding to azimuthal angles close to 0° and 360° and the early region, corresponding to azimuthal angles around 180° is clearly seen especially at large radial distances.

The procedure was repeated for a set of CORSIKA simulation output files including proton- and iron-induced showers with energy from $10^{16}$ to $10^{18}$ eV and angles of incidence up to 70°. The resulting set of LECF database includes the realistic dependence on the angle of incidence of the shower, on the radial coordinate of the detector with respect to the shower core and on the azimuthal position around the core.

4. Lateral density distribution

The lateral density of charged particles in the observation plane is obtained simply from the energy deposition in the Grande detectors divided by the appropriate value of the LECF. The next step is that of mapping the density from the observation plane onto the intrinsic shower plane. In this step the asymmetry of the density around the shower core should be removed.

The origin of the asymmetry at the observation level is due to geometrical effects, to shower evolution between the early and the late region, and to the effect of the Earth’s magnetic field. The geometrical and the shower evolution effects are present in the case of inclined showers, while the effect of the magnetic field influences all the showers. The basic geometrical effect can be easily understood by considering a very schematic shower model in which the particle density has cylindrical symmetry and close to the observation level the shower particles propagate without interacting on trajectories parallel to the shower axis. In this case equal density contours in the observation plane are elliptical and not circular. It could be expected that a simple orthogonal projection from the observation level to the intrinsic shower plane would restore the symmetry. Clearly this is not the case as illustrated in Fig. 14 for a simulated shower; the simple orthogonal projection onto the intrinsic shower plane does not remove the azimuthal asymmetry [9]. More complex geometrical effects are revealed considering a shower model in which close to the observation level the particles come on conic surfaces. In the absence of shower evolution in this case close to the core, the orthogonal projection would artificially increase the density in the early region of the shower development and decrease it in the late region. Shower evolution further complicates the problem.

Besides the practical method of orthogonal projection (Method 1), other different methods have been considered, using the arrival times (Method 2) or the arrival directions (Method 3) of the single EAS particles (which are known only in simulation results). In Method 2 the particle arrival time together with the assumption that the particle was produced practically on the shower axis and that it suffered negligible scattering along the trajectory are used for fixing the particle trajectory and thus the intersection with the normal plane. In Method 3 the direction of the momentum of the particle when it hits the ground together with the assumption of negligible scattering along the trajectory between the normal plane and the observation plane are used for obtaining the intersection of the trajectory with the normal plane. Detailed studies [9] have shown that the geometrical and shower evolution asymmetries can be removed by applying the orthogonal projection combined with an exponential correction function $\exp(-\lambda \cdot d)$, where $d$ is the distance between the corresponding points in the observation and in the intrinsic plane. The attenuation coefficient $\lambda$ turns out to be larger for the electron component than for the muon component of the charged particle density and depends on the shower incidence angle and slightly on the radial coordinate. As an example, in Fig. 15 the result of applying the orthogonal projection plus the correction for the attenuation for obtaining the density at the intrinsic shower plane is displayed. After the density of charged particles is obtained at the positions of the detectors in the observation plane and mapped onto the intrinsic shower plane, it is fitted with distribution functions given by the NKG [3] and Linsley [4] parameterizations. In this way the total number of charged particles or the density at any distance from the shower core can be obtained, in particular at 500 m from the core.
5. Application

As discussed in Section 3, a larger value of the LECF is expected in the late region of the shower development in comparison with the early region, while the density is lower in the late region and higher in the early region. The basic experimental signal, i.e. the energy deposition in the detector, is less affected by the asymmetry, because each of the smaller number of particles hitting the detectors from the late region transfers a bigger amount of energy to the detector, while in the early region the number of particles is higher but each transfers a smaller amount of energy to the detector. Even if the two effects do not compensate perfectly each other, the asymmetry of the energy deposition is less pronounced and more difficult to observe directly. In addition, in order to clearly observe this asymmetry it would be necessary to compare the same shower data for various azimuthal angles in the same radial bin. Due to the limited number of Grande detectors it is impossible to find many detectors in the same radial bin for the same shower; due to the big shower fluctuations it is not easy to compare in a radial bin the data for different azimuthal angles from different showers. However, even if the asymmetry effects are obscured in the direct experimental data by the fluctuations, these effects are systematic and should be taken into account. As an exercise intended to quantify the effects of the asymmetry in the absence of shower-to-shower fluctuations the following analysis was carried out [9,29]. A single shower simulation done by CORSIKA, for a proton primary with energy $E = 3.16 \times 10^{17} \text{ eV}$, $\theta = 45^\circ$ incident from North, was considered. In a first step the shower was positioned repeatedly with the core in the Northern part of the Grande array; thus most of the detectors are located in the late region of the shower development. In the second step the same shower was repeatedly positioned with the core in the Southern part of the Grande array and consequently, most of the detectors are now in the early region of shower development. In both cases the densities were reconstructed, taking into account, or not, the asymmetry corrections. When the corrections are not taken into account important differences between the densities are observed (Fig. 16). For example, the value of the density at 500 m from the core in the case when the core is located in the Southern region of the Grande array, is higher by 23% than the value in the case of the core located in the Northern region. The efficiency of the correction procedure is illustrated in Fig. 17, where the corrected density, computed for the case when the shower core is located in the Northern region of the array, is compared to the density computed for the case of shower core located in the Southern region.

Similar results are obtained repeating the exercise with an iron-induced shower with energy $E = 5.62 \times 10^{17} \text{ eV}$, $\theta = 45^\circ$ incident from North. In this case the uncorrected density at 500 m from the core reconstructed for showers with the core located in the Southern region is higher by 22% than the value reconstructed for the showers with the core located in the Northern region. The correction procedure practically removes the differences between the reconstructed densities based on the locations of the core in the two regions of the KASCADE-Grande array.

6. Conclusions

The lateral particle density in the intrinsic shower plane measured by ground-based EAS arrays like KASCADE-Grande is obtained by first converting the experimental signal into particle density in the observation plane and subsequently mapping this density onto the intrinsic shower plane. The significant azimuthal asymmetries of the resulting lateral distributions, present in both
steps, which appear to be fluctuations of the EAS observations themselves, are rather of systematic origin. They may lead to systematic errors of quantities extracted from lateral distributions of charged particles, in particular for inclined showers with zenith angles greater than 40°. Procedures were developed to remove the effects of the azimuthal asymmetries. The application of these procedures for the reconstruction of the charged particle density in the range of KASCADE-Grande experiment restores the azimuthal symmetry of the density in the intrinsic shower plane.

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