Refined Lateral Energy Correction Functions for the KASCADE-Grande Experiment Based on Geant4 Simulations


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Abstract. In previous studies of KASCADE-Grande data, a Monte Carlo simulation code based on the GEANT3 program has been developed to describe the energy deposited by EAS particles in the detector stations. In an attempt to decrease...
the simulation time and ensure compatibility with the geometry description in standard KASCADE-Grande analysis software, several structural elements have been neglected in the implementation of the Grande station geometry. To improve the agreement between experimental and simulated data, a more accurate simulation of the response of the KASCADE-Grande detector is necessary. A new simulation code has been developed based on the GEANT4 program, including a realistic geometry of the detector station with structural elements that have not been considered in previous studies. The new code is used to study the influence of a realistic detector geometry on the energy deposited in the Grande detector stations by particles from EAS events simulated by CORSIKA. Lateral Energy Correction Functions are determined and compared with previous results based on GEANT3.

THE KASCADE-GRANDE EXPERIMENT

The KASCADE-Grande Experiment [1] (KArlsruhe Shower Core Array DEtector - Grande) is an extensive air shower (EAS) detector array designed to study cosmic rays in the $10^{16} - 10^{18}$ eV energy range. KASCADE-Grande was built as an extension of the KASCADE experiment - by the means of the Grande array - (Fig. 1). The KASCADE array offers information on the electromagnetic and muonic components of the EAS and the Grande array can detect charged particles that reach the ground, without the possibility of distinguishing between their types.

Meanwhile, the KASCADE-Grande experiment is no longer operational, but a large amount of data is available to be analyzed.

![Figure 1: The layout of the KASCADE-Grande Experiment [1]](image)

EAS RECONSTRUCTION PROCEDURES

The standard reconstruction procedure used at KASCADE-Grande is based on determining the position and arrival direction of the EAS using the Grande array and the estimation of the muon and electron distribution extrapolated from the KASCADE array, with the restriction on the total number of charged particles given by the Grande array. The total number of charged particles correlated with the number of electrons and muons is used for the estimation of the energy and mass of the primary particle.

The charged particle density is calculated from the energy deposited in the detectors by using the lateral energy correction function (LECF). The LECF represents the energy deposited in the detector by all the secondary particles from the shower divided by the number of charged particles and calculated for the position of the detector relative to the shower axis, therefor it accounts for the different energy spectrum of secondary particles in the shower, as well as for the energy deposit of gammas in the simulations.
The standard reconstruction procedure used at KASCADE-Grande is based on an averaged value of the LECF (Fig. 2), without taking into account variations for different energies and angles of incidence of the primary particle.

**FIGURE 2.** The lateral energy correction function used in the standard reconstruction procedure of KASCADE-Grande [1]

The estimation of the primary particle’s energy is done by an EAS observable that is energy sensitive. The charged particle density at 500 m distance from the shower core is such an observable (S(500) parameter). By analyzing CORSIKA [2] simulations (using QGSJet-I) it was determined that the S(500) parameter does not depend on the primary particle’s mass, but only on its energy[3].

CORSIKA simulations also revealed that the charged particle density near the shower axis depends on the mass of the primary particle. The charged particle density in the region 100-200 m from the shower axis is an observable dependent on the mass of the primary particle and can be used for mass discrimination (S(200) parameter) [4, 5].

In order to obtain an accurate description of the charged particle density in the 50 – 800 m distance range by using data from the Grande array, the interaction of secondary EAS particles with the Grande detector stations must be simulated as accurately as possible.

**THE GEANT4 SIMULATION**

Previous studies [6] were done using a simplified geometry of the station implemented in the GEANT3 toolkit. The new geometry of the station includes the sensitive elements (plastic scintillators) and also all the structural elements like the steel frame holding the scintillators, or the structure of the station’s roof, implemented in a Geant4 [7] based program. A new study on the Grande detector’s response to the most common secondary EAS particles (electrons, muons, gamma rays) was presented in [8, 9].

A comparison with previous results (Fig. 3) shows a small difference in the energy deposition spectrum for muons, but a noticeable difference in the electron and gamma energy deposition spectra. The presence of more non-sensitive elements in the simulation causes the differences between the GEANT3 and Geant4 energy deposition spectra by creating the possibility for particles that do not interact directly with the scintillators, but scatter secondary particles which can create an additional energy deposit.
If we compare the total energy deposit created by the same incident flux of particles (which is not the case in extensive air-showers) on the Grande station, the total energy deposit is 5% smaller for muons, probably due to changes in the interaction models, but 20% higher for electrons and 50% higher for gamma rays, due to the addition of structural elements in the simulation. However, the energy deposit of single particles (the peaks) for all components is described similarly by both simulations.

Taking into account these differences in single particle energy spectra, the LECF will also be affected by these changes.

**COMPUTING THE LATERAL ENERGY CORRECTION FUNCTION**

In order to improve the quality of reconstruction and to get a better understanding of the energy spectrum and mass composition of EAS [10], a more detailed description of the LECF (relative to the one used in the standard reconstruction procedure) is needed.

The LECF is calculated using a CORSIKA (with QGSJet-II) simulated secondary particle distribution and simulating their interaction with an optimized description of the Grande stations, by using the Geant4 toolkit (Fig.4).

In order to determine the Lateral Energy Correction Function (LECF) for CORSIKA simulated EAS, a new simulation code was developed. The new program uses the secondary particles from the observation level simulated by the CORSIKA code as input and determines the energy deposit they produce in the Grande detectors. An array of 2400 Grande stations (Fig.5) is used to determine the radial and azimuthal properties of the LECF in a range of 0 − 1000m from the shower core. The positions of the stations are represented in Fig.5. The shape of the simulated array was chosen as such in order to be able to study the radial and azimuthal variations in the LECF.
For each particle, the coordinates relative to the closest Grande station are determined and the energy deposit is computed. The total energy deposit (all particle types) and the number of charged particles detected is saved for each station. The LECF is determined by dividing the energy deposit from a station by the number of charged particles (electrons and muons) that deposited energy in the station.

The Lateral Energy Corrections Function obtained for a proton and iron induced EAS simulated with CORSIKA are shown in Fig.6 and Fig.7. The shape of the function is consistent with previous results, but the mean value obtained by using the new realistic geometry of the Grande station is higher due to the higher values for gamma energy deposits, as discussed earlier. The spread of the mean energy deposit per charged particle can be explained by the azimuthal asymmetry of the particle distribution and insufficient statistics, mainly caused by the larger and larger distances between stations of the simulated array at large distances from the shower core. An improved simulation code that includes a $1600 \times 1600 \text{m}^2$ square with 160 x 160 Grande stations is under development in order to obtain a LECF of better quality.

*FIGURE 6. LECF for a proton induced EAS, $E_0 = 1.1 \cdot 10^{17}\text{eV}; \theta = 16^\circ$*
This work summarizes the effects of using a realistic geometry of the Grande station and Geant4.6 instead of GEANT3.2.1 on the energy deposit for different particle types common in EAS and on the LECF.

The new simulation code provides results in acceptance with the GEANT3.2.1 based code, and the differences can be understood and attributed mostly to the addition of non-sensitive elements in the simulation.

This procedure is more time consuming than the previous one and needs more computing power in order to calculate a database of Lateral Energy Correction Functions, but still feasible because of the increase in performance and lower costs for modern CPUs. The aim is to get a new description of the Lateral Distribution Function for charged particles which can be used to determine the energy spectrum using the S(500) parameter and possibly a more precise mass discrimination using the S(200) parameter.

The LECF computing procedure is being upgraded by adding a higher number of Grande stations in the simulations in order to obtain a finer radial and azimuthal description of the LECF. Effects on the main shower observable, the shower size (i.e. the total number of charged particles in the air shower) will then also be studied in details.

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