Simulation of surface detector arrays at different altitudes to study the second knee energy region

D. Melo1, I. Sidelnik1,2, A. Sedoski1, A. Tapia Casanova1, A. Etche gouen3, J. Figueira1, R. Gamarra1, B. Garcia3, N. Gonzales1, M. Josebachuli4, D. Ravignani1, F. Sanchez1, B. Wundheiler1

1 Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM). Av. Gral. Paz 1499 (1650), Buenos Aires, Argentina
2 Centro Atómico Bariloche and Instituto Balseiro (CONICET, CNEA). Av. Bustillo 9500 (8400), San Carlos de Bariloche, Argentina
3 ITeDA (CNEA, CONICET, UNSAM), Mendoza, Argentina
diego.melo@iteda.cnea.gov.ar

Abstract: In this work we study the effect of altitude on the response of a variety of surface detectors arrays using simulated extensive air showers coming from primary cosmic rays in the second knee energy region, with the aim of assessing the suitability of each configuration. The simulated arrays are all arranged in a square grid, varying the site altitude and the distance between detectors. The explored energy range is from $10^{16.25}$ eV to $10^{18}$ eV, using zenith angles lower than 45°. The spacing between detectors is of 325 m, 425 m and 525 m, at altitudes of 1400 m, 2400 m and 3400 m (a.s.l.). The main parameters used to study the efficiency of the proposed detector arrays are presented and discussed in this paper.

Keywords: second knee, surface detector array, shower simulation

1 Introduction

The region of the spectrum of cosmic rays with energies around $10^{17}$ eV is of great interest in astrophysics, due to evidence of a change in the shape of the energy spectrum, the so-called second knee [1][2][3]. Recently KASCADE-Grande reported results that show a change in the slope of the energy spectrum at $\sim 8 \times 10^{16}$ eV [4], that corresponds to a steepening of the energy spectrum of heavy primary particles as cosmic rays. The structure observed by KASCADE-Grande could indicate the beginning of a transition from galactic cosmic rays to extra galactic cosmic rays. The stringent validation of theoretical models over a transition from galactic to extragalactic cosmic rays requires an understanding of experimental results, for which a correct determination of the mass and energy spectrum of those cosmic rays is mandatory [5].

At energies of $\sim 10^{17}$ eV the extensive air showers originated by these primaries reach their maximum number of particles at high altitudes ($\sim 3.4$ km for vertical Protons and $\sim 4.6$ km for vertical Irons at $10^{17}$ eV). For this reason, the detection of these showers could be influenced by the altitude at which the detectors are placed. To test this effect we investigate the response of a variety surface detector arrays, using simulated air showers with energies ranging from $10^{16.25}$ eV to $10^{18}$ eV at different zenith angles.

2 Monte Carlo Simulations

Atmospheric attenuation plays a key role on the detection of extensive air showers, since the particles produced in the atmosphere are propagated in this medium before reaching the detectors. The electromagnetic component is particularly affected by this effect and as a result a great number of these particles are not detected [6]. Since the attenuation depends on the distance from the point where the particles are originated to the point where the detector is located, the low energy showers are difficult to detect at steep inclinate zenith angles when the detectors are installed at altitudes near sea level. On the other hand the low energy showers produce less particles, leaving a smaller footprint on the ground. The small footprint and the atmospheric attenuation establish limits on the energy threshold of the showers that can be detected by a given array placed on a certain altitude with a given spacing between detectors. A way to improve the detection efficiency of showers with low energy primaries consists in simultaneously placing the detector array a high-altitude site and decreasing the distance between detectors.

In this work we considered three detector arrays arranged over a square grid with a separation between detectors of 325 m, 425 m and 525 m, placed at three different altitudes (1400, 2500 and 3500 m a.s.l.). Using these arrays we evaluate the influence of the altitude and grid size separation in the second knee energy range over the energy threshold and the geometric resolution obtained in the shower reconstructions.

2.1 Air shower simulations

We generated a library of extensive air showers using the AIRE S 2.8.4a [7] package, for each one of the three altitudes proposed. These simulations were carried out considering the high energy hadronic models QGSJET-II-03 [8] and Sibyll-2.1 [9], with a relative thinning of $10^{-6}$, weight factor of 0.2 and ratio between the weight factors (electromagnetic/hadronic) of 88. These simulations were done for Proton and Iron primaries, at eight fixed energies between $10^{16.25}$ eV and $10^{18}$ eV (with step in log10(E/eV) of 0.25), zenith angles of 0°, 15°, 22.5°, 30°, 37.5° and 45°, and azimuth angles uniformly distributed between 0° and 360°. During the AIRE S simulations the secondaries corresponding to gammas, electrons/positrons and muons with energies above the thresholds of 1.286 MeV, 264 KeV and 55 MeV respectively, have been taken into account and stored in the AIRE S output files. For each energy, zenith
angle, primary particle, hadronic model and ground altitude, a total of 300 showers were simulated. With this library we cover the whole spectrum region where the second knee is expected be found.

2.2 Simulation and Reconstruction of Events

After the air shower simulations were done we began the event simulations. We assumed that each array is composed by a number of water Cherenkov detectors similar to those used by the Pierre Auger Observatory [10, 11]. We used arrays of 121, 81 and 49 detectors with spacing of 325 m, 425 m and 525 m respectively, covering a total area of ~10 km².

The simulations of events were carried out using the Auger Offline package [12], modified to consider surface detectors arranged in a square grid. In each case the AIRES output files were used four times in order to generate a total of 1200 simulated events per primary, hadronic model, energy, inclination and ground altitude. To avoid border effects, the impact points of the showers were uniformly distributed inside of array as show in Figure 1.

The reconstruction of each event was also performed with the Auger Offline package, based on the collected signals and arrival times measured by the water Cherenkov detectors in the event. In the reconstruction was used a Nishimura-Kamata-Greisen[13] function to describe the lateral distribution of particles at ground level. As the slope of the lateral distribution function is unknown, it is necessary to choose the distance in which the effect of the uncertainties in the lateral distribution function is minimized. This distance, so-called optimal parameter, was calculated for each array and altitude, on an event by event basis using an algorithm that is included in the Auger Offline package [14]. The values obtained were 225, 285 and 340 m for the arrays of 325, 425 and 525 m respectively, which are essentially independent on primary type, zenith angle, energy, hadronic model and altitude. For the slope of the lateral distribution function we used a linear parametrization considering the secant of zenith angle (see Equation 1). In the Equation 1 the parameters 'a' and 'b' were determined for each array from events reconstructed with high multiplicity of detectors.

\[ \beta = a + b \sec(\theta) \] (1)

2.3 Data Analysis

The reconstruction efficiency for each array was evaluated as the fraction between the number of reconstructed events and the total number of simulated events. The efficiency was calculated as a function of the primary type, energy, zenith angle, hadronic model, array and altitude. This value was used to calculate the lower energy threshold considered as the lowest energy that gets an efficiency value of one, regardless of primary type. In Figure 2 are shown the efficiency obtained at two zenith angles for the 325 m array placed at 1400 m a.s.l., and for both primary particle types. While the Figure 3 showed the results obtained for the energy threshold.

These results show that, for detector arrays placed at low altitudes, air showers with low energies can only be detected for small zenith angles. Particularly at 1400 m a.s.l. showers of 10^{17} eV can only be detected for zenith angles below 15°.

On the other hand, we evaluated the fraction of saturated events as a function of energy for each array and altitude. At the altitudes contemplated in this study, this fraction increases with the energy and does not depend on the zenith angle. Figure 4 shows the results obtained for events with 15° detected with an array situated at 1400 m.

The accuracy of the geometric reconstruction was studied using the residual distribution of the zenith and azimuth angle (for the arrival direction), and the easting and northing coordinates (for the impact point). In each case these quantities were calculated as the difference between the reconstructed and the simulated parameter. From these distributions were determined the mean value and its RMS. The results indicate that the parameters that define the geometry of the shower are reconstructed without bias. The dispersion indicated by the RMS shows that for any inclination, the uncertainties are reduced when the energy
increases. The uncertainties of the reconstruction of showers started by Proton are slightly greater than those started by Iron, because Proton showers have greater shower-to-shower fluctuation.

We evaluated the distance between the reconstructed and simulated impact point (Equation 2) and later the space angle between the reconstructed and simulated shower axis (Equation 3).

\[
\begin{align*}
    d &= \sqrt{(x_{\text{rec}} - x_{\text{sim}})^2 + (y_{\text{rec}} - y_{\text{sim}})^2} \quad (2) \\
    \delta &= \arccos(Axis_{\text{rec}} \cdot Axis_{\text{sim}}) \quad (3)
\end{align*}
\]

where the subscripts ‘rec’ and ‘sim’ indicate reconstructed and simulated respectively, \(x\) and \(y\) are the easting and northing coordinates, and Axis represents the direction of the shower.

For these distributions, we performed a cut at 68\% of the events in the histograms in order to obtain the resolution. We observe that the resolution of the impact point, at a given energy and array, tends to deteriorate when the inclination of the showers increases. In particular, this is significantly observed for higher zenith angles, where for energies greater than \(10^{17}\) eV the resolution of the core has changed from around 9 m (0\(^\circ\)) to 22 m (45\(^\circ\)). Also we observe that the resolution of the core, at a given energy, tends to deteriorate in a factor \(\sim 2.4\), when the inclination of the showers increases.

Analogously, we evaluated the angular resolution, which (at fixed energy) practically does not change when the inclination of the showers increases. For both resolutions, impact point and angular, we did not find significant differences between the two hadronic models considered.

Finally we obtained the average resolutions, core position and angular, as a function of energy and altitude for each array used, considering events whose energies are above the threshold energy. These results are shown in Figure 5 and Figure 6, respectively. We conclude that the resolution is practically independent of altitude considered, and dependent of the separation between detectors.

3 Conclusions

In this work we have characterized the response of three detector arrays at three altitude levels considering extensive air shower simulations for Proton and Iron primaries using AIRES and the Auger Offline packages, for energies between \(10^{16.25}\) eV and \(10^{18}\) eV, covering the energy region of second knee. In each case the lower energy thresholds were determined as a function of the zenith angle and altitude where are placed the detectors. The geometrical resolution for the impact points and arrival directions were determined for each array. In the full efficiency region, the results obtained show that the detector response is practically independent of the altitude, but dependent of the separation between detectors. An array placed at 1400 m a.s.l with detectors spaced at 325 m is a good option to detect showers around \(10^{17}\) eV.

Acknowledgment: We would like to thank Pierre Auger Collaboration by give us the possibility of use the Auger Offline package in this work.
Simulation of surface arrays

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013

Figure 5: The average resolution corresponding to arrival position obtained with each array as a function of energy and altitude (1400 m in black, 2400 m in red and 3400 m in blue). All events lying above of the threshold energy. We did not find significant differences between the different altitudes considered.

Figure 6: The average angular resolution obtained with each array as a function of energy and altitude (1400 m in black, 2400 m in red and 3400 m in blue). All events lying above of the threshold energy. We did not find significant differences between the different altitudes considered.

References