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TANGO Array II – Simulations

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Abstract. The angular and energy resolution of the TANGO Array has been obtained using Monte Carlo simulations. The AIRES code, with the SYBILL hadronic collision package, was used to simulate Extended Air Showers produced by primary cosmic rays (protons and iron nuclei), with energies ranging from 10^{14} eV to 10^{18} eV. These data were fed into a realistic code which simulates the response of the detector stations (water Čerenkov detectors), including the electronics, pick up noise, and the signal attenuation in the connecting cabling. The trigger stage is taken into account in order to produce estimates of the trigger efficiency of the array and to check the accuracy of the reconstruction codes. This paper describes the simulations performed to obtain the expected behavior of the array, and presents the simulated data. These simulations indicate that the accuracy of the cosmic ray primary energy determination is expected to be $\sim$ 60 % and the precision in the measurement of the direction of arrival can be estimated as $\sim$ 4 degrees.

1 Introduction

In order to characterize the behavior of the TANGO Array (P. Bauleo et al. , 2001), detailed simulations were performed to estimate its efficiency for shower detection and its angular and energy resolutions. A special routine, simulating the detector response to the different shower particles, has also been written to provide an input for the reconstruction routines. In the following sections these routines and the reconstruction algorithm are described. All computer programs required for the simulation pipeline (except AIRES) were especially developed in the present work.

2 Extended Air Shower Database

The AIRES program (S. Sciutto , 1998) using the SYBILL hadronic package was used in the first step of the simulation pipeline: the construction of an adequate shower database containing detailed information about the secondary particles at ground produced by primary cosmic rays of the energies of interest. The relative thinning level used was 5.10^{-5}.

To construct the shower database, twenty primary energies ranging from 10^{14} eV to 10^{18} eV were selected, and two nuclear species (protons and iron nuclei) were considered as primary particles. They were injected at zenithal angles from $0°$ to $60°$, in $15°$ steps. To reduce the artificial fluctuations due in part to the thinning method, and also to obtain representative values of the relevant parameters, batches of 100 showers were simulated under the same initial conditions (as described above), and their average and RMS values were used. All these simulations were performed considering a ground level of 15 m.a.s.l. (according to the TANGO Array altitude). The shower database tables contains only particle densities, energies and arrival times (with respect to the core position particles arrival times) for muons, electrons,and gamma-rays.

3 Array Simulation Procedure

In order to predict the response of the array, the information on showers contained in the AIRES database tables was used to simulate “events”, *i.e.* the effect of individual showers falling relatively close to the array.

A simulated event is the set of information about the calculated effect of the shower on the array, taking into account the simulation of the detector, data acquisition hardware, electronics, etc. The procedure to simulate one event is briefly described as follows:

– For each primary energy, 9000 shower core positions were selected landing at random and zenithal and azimuthal angles of the events were chosen as follows: the azimuthal angle was uniformly distributed, and the zenithal angle was cut-off at 45 °. This cut-off was selected accordingly with the atmospheric depth at Buenos Aires, where most EASs arrive within a cone of $\sim 40°$.

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- Once the core position and the angles were established for each particular event, the distances from each detector station to the core were calculated. Then, from the AIRES tables the apropiate mean values and dispersions were extracted and interpolated, to fit the simulated event.

- To include the shower-to-shower fluctuations, uniform random number generators were profiled (using the accept-reject technique) to reproduce the mean value and dispersion of the (fitted) AIRES particle density tables contained in the database, according to the particular secondary particle considered. Then, the number of muons (both charges), electrons (both charges) and gamma-rays hitting each detector, were obtained according with the density (particles/m^2) in each station neighborhood and detector area. The energy and arrival time of every individual particle hitting each detector station were obtained using the same procedure (the accept-reject technique) from the respective (fitted) AIRES Tables.

- Once the number of particles, energies and arrival times of all particle species falling on each station for the event, were obtained, the detector signal was obtained as is described in detail in 3.1.

- The next step was a check to determine whether each particular simulated event produces or not a valid trigger. The simulated traces for each detector station were scanned, searching for the threshold crossing times in each channel. These threshold crossing times, were compared to establish the presence of temporal coincidences between the traces (an EAS).

- Finally, a FADC working at 500 Ms/s was simulated (like that used in the DAQ system). An appropriate noise generator has been included. From noise spectrum measurements we concluded that the local AM radio stations are the main noise sources, contributing with $\sim$ 15 to 30 mV to the signal (the typical signal amplitude corresponding to one single particle is $\sim$ 100 mV).

3.1 Detector Simulation

A simple and very fast simulation program was written to emulate the detector response. In this program, instead of simulating in detail the production and transmission of the Čerenkov photons emitted during the passage of charged particles through the water, we used the detailed knowledge of the detector behavior achieved during the previous years of operation of the first detector prototype

In previous experiments (P. Bauleo et al. (1998); C. Bonifazi et al. (2001)), the entrance and exit points of muons on the detector surface have been carefully selected to cover as much as possible all possible situations. As a result of these measurements we have found that the sum of the charges collected in the three PMTs of our WCD is directly proportional to the track length of the particle in the water radiator, and this is valid regardless of the entrance point position or the zenithal angle of the track. We have also found that the rise and fall times of the pulse shapes remain almost constant for the whole range of track lengths.

In addition to the response to fast muons, the response of the WCD to fast electrons and gamma-rays was obtained. Both, electrons and gamma-rays (detected through pair-creation processes), produce also an amount of light proportional to their track lengths. Therefore, the signals due to by gamma-rays are roughly the same as those produced by fast electrons, provided their energy distributions are similar.

In order to include in the simulations the effect of the signal distortions in the cables, we have recorded in a previous work the average pulse shape for vertical muons transmitted through 200 m of RG-213 cable.

By taking into account all this information, the simulation of the surface detector signal was carried out as described below:

- **Muons:** For each muon hitting a detector station, a zenithal angle is selected using a gaussian-shaped random number generator, with its mean value centered in the zenithal angle of the primary particle of the EAS, and a sigma value of 4°(C. Pryke , 1996). Once the zenithal angle is established, the range of the particle in water is obtained according to its energy, and a peak amplitude is found as a function of its range. If the range of the muon exceeds the track length inside the surface detector, then the amplitude is made proportional to the track length. Finally, rise and fall times are selected with a gaussian shaped random number generator (whose mean and sigma values were fitted to the experimental values) and the pulse shape is written to memory.

- **Electrons:** The general procedure is similar to that described for muons. The main difference occurs in the calculation of the range, which, in the case of the electrons, is assumed to be completely contained within the WCD.

- **Gamma Rays:** The track length for a specific γ-ray inside the detector determines the probability of creation of an electron-positron pair (the main interaction channel), according to the mean interaction length. If a pair is produced, the electron simulation routine is called with two electrons, having a total energy balancing the γ-ray energy. The energy of the recoiling nucleus is neglected.

4 Reconstruction Algorithm

The reconstruction procedure is initiated by the obtention of the direction of the shower axis by fitting the arrival times to each detector, asuming a flat shower front. Once the direction is determined, the core position is found through minimization of the lateral distribution function (LDF) using the particle density falling over each station.

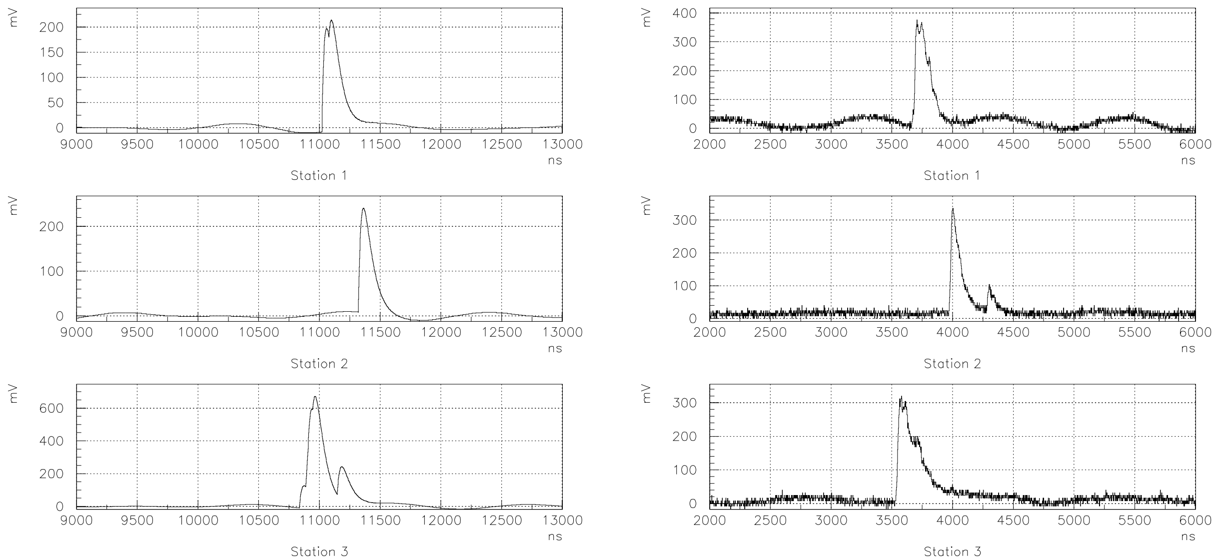

Fig. 1. Simulated event (left) and pulses recorded from a real shower (right). Both events were chosen arbitrarily and are shown only for comparison. The overall zero time for the simulated event is arbitrary and uncorrelated with the zero time for the measured one. Also note the simulated pick-up noise.

Then, using Monte Carlo simulations, it is possible to correlate the shower primary energy with the particle density measured by the detector stations. In the present experiment performed with only 4 detectors, we have used a model where the normalization constant A of the LDF was correlated with the primary energy instead of the particle density at a fixed distance of the core position. The LDF was obtained from (simulated) particle density measurements in each detector station, far away from the core.

The reconstruction algorithm is briefly described below:

– To determine the "trigger time" (t_{10}) of each station, the voltage signal is time-integrated, and the crossing times of charge amplitude values equal to 10% of the maximum charge collected is used to obtain the primary cosmic ray arrival direction. This is achieved for the case of only 3 detectors hitted by the shower front by obtaining a unique, downward-going shower front, which we assume to be a plane, and moves at the speed of light. When all four detectors are hit, then a least squares method is used to find the best fit to this plane shower front.

– The normalization constant of the LDF is found through minimization of the following equation

$$\chi^2 = \sum_{i=1}^{n} \left(\rho_i - \frac{A}{r_i^{\eta + r_i/r_0}} \right)^2 \tag{1}$$

where ρ_i and r_i are the particle density and the distance between the core impact position and the *i*-th station, respectively, and η and r_0 were obtained from simulations as mentioned before.

– The minimization of Equation 1 was performed through a grid search on the simulated events database, yielding the x and y coordinates of the core position, as well as the normalization constant A.

– The normalization constant A has a zenithal angle dependence due to the attenuation of the particle cascade through the atmosphere. By simple geometrical considerations it is possible to propose a functional dependence of the form

$$N = Ae^{[\beta(sec(\theta)-1)]} \tag{2}$$

where N is a conversion factor, proportional to the primary particle energy that includes the atmospheric attenuation correction factor. The average value obtained for β by fitting the simulated data to Equation 2 is ($\beta = 4.1 \pm 0.1$)

4.1 Primary Energy Assignment

Finally, after minimization of Equation 1 and being performed the atmospheric attenuation correction (for which the directional reconstruction is required) it is possible to show the relationship between N -a parameter obtained from the shower reconstruction routine- and the primary energy (obtained from the simulated events database). It should be noted that in this survey over the simulated events database we found that, beyond $\sim 2.10^{16}$ eV, N fails to converge, and the linearity (in logarithmic scale) as a function of the primary particle energy is lost. Therefore, only data at lower energies are shown in Figure 2.

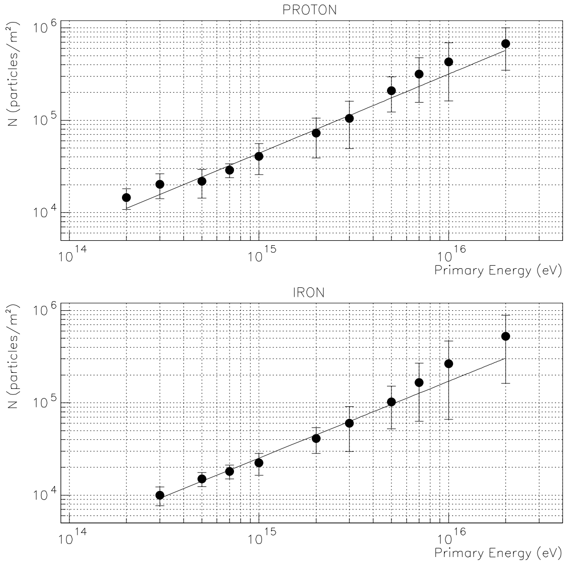

Fig. 2. Relationship between N and primary energy for proton and iron primaries.

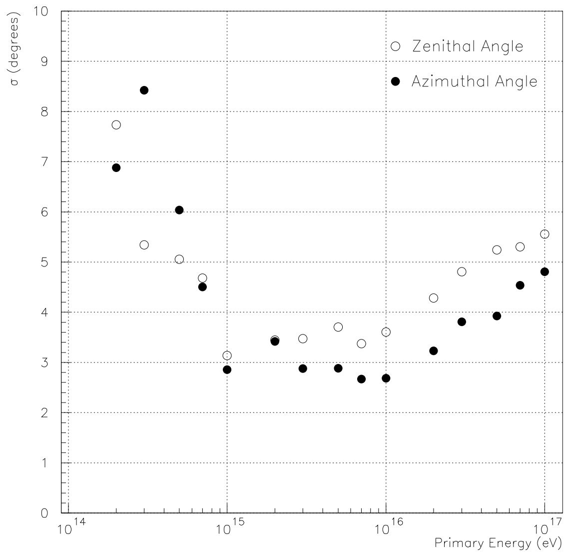

Fig. 3. The energy dependence of the angular resolution (σ) is also shown. Filled dots corresponds to azimuthal angle and open dots to zenithal angle.

From these fits we obtain the following expressions, useful to correlate the parameter N [VEM/m^2] with the primary energy [eV]:

$$E_0 = (4 \pm 1) \times 10^9 N^{1.17 \pm 0.03} \quad (3)$$

and

$$E_0 = (5 \pm 2) \times 10^9 N^{1.20 \pm 0.03} \quad (4)$$

where Equations 3 and 4 correspond to proton and iron primaries, respectively.

According to these results, a knowledge of the primary particle mass would be required to correctly correlate the N parameter with the primary particle energy by choosing the proper expresion. Strictly, this fact prevents us to make an unambiguous assignment of the primary energy. Furthermore, it should be recalled that both Equations 3 and 4, were obtained from surveys performed on the Monte Carlo simulations, which are dependent of the particular hadronic package utilized. On the other hand, however, the results obtained from both expresions are consistent within errors.

5 Conclusions

As described above, the t_{10} values were obtained from the simulated events database and used to obtain the arrival direction of each event. The accuracy in the angular reconstruction is determined by comparing these angles with the “true” angular direction of the particular simulated event, which is read from the events database. As can be seen in Figure 3, the angular resolution (σ) of the array improves progressively with energy in the decade of 10^{14} eV, then remains almost constant in the decade 10^{15} eV and slowly decreases beyond $\sim 10^{16}$ eV.

Regarding energy reconstruction, from Equations 3 and 4 it is possible to estimate the relative error in the energy reconstruction. Those expressions have a dependence on the N value, but its dependence is logarithmic, and the $\Delta N/N$ value was found to be $\sim$ 0.4 from the simulated database. This yields a relative error of 57% and 66% for protons and iron nuclei, respectively, in the energy range from $\sim 10^{14}$ eV to $\sim 10^{16}$ eV.

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