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Alborz-I array: A simulation on performance and properties of the array around the knee of the cosmic ray spectrum

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ABSTRACT

The first phase of the Alborz Observatory Array (Alborz-I) consists of 20 plastic scintillation detectors each one with surface area of 0.25 m^2spread over an area of 40 × 40 m^2 realized to the study of Extensive Air Showers around the *knee* at the Sharif University of Technology campus. The first stage of the project including construction and operation of a prototype system has now been completed and the electronics that will be used in the array instrument has been tested under field conditions. In order to achieve a realistic estimate of the array performance, a large number of simulated CORSIKA showers have been used. In the present work, theoretical results obtained in the study of different array layouts and trigger conditions are described. Using Monte Carlo simulations of showers the rate of detected events per day and the trigger probability functions, i.e., the probability for an extensive air shower to trigger a ground based array as a function of the shower core distance to the center of array are presented for energies above 1 TeV and zenith angles up to 60°. Moreover, the angular resolution of the Alborz-I array is obtained.

1. Introduction

Study of the primary cosmic rays provides important information on their origins and acceleration mechanisms. The energy spectrum of cosmic rays follows a power law and shows a bend around 3×10^{15} eV, known as the *knee* region, where the spectral index changes from −2.7 to approximately −3.1 [1]. At these energies, indirect measurements of cosmic rays due to their low flux are performed using ground based arrays of particle detectors. In the last decade, findings of many high-profile experiments confirm the general view which attributes the *knee* to processes of magnetic confinement occurring either at acceleration regions or as diffusive leakage from the Galaxy or both.

Air shower measurements can determine the arrival direction, energy, and mass of the primary cosmic ray. A particle detector array provides statistical samples of secondary particles in the shower disc, and the resolution achieved in the shower reconstruction depends on the sampling fraction of secondary particles from the shower disc [2].

Lowest and highest energies at which cosmic rays can be detected by arrays depend on the distance between neighboring detectors and overall size of detector array, respectively. Therefore geometry and design of an array have an important role to extend the detectable energy range. In this paper, geometrical effects of array layout on the number of detected events, trigger probability and angular resolution are studied by increasing distance between neighboring detectors and also changing configuration of the array.

In order to show dependence of the trigger probability on the primary particle energy (E) and shower core distance from the array center (r), detailed studies on the trigger rate for two rectangular and cluster layouts are carried out. The trigger probability of the simulated array as a function of r and E, known as the trigger probability function $P(r, E)$, is presented as a fundamental parameter to compare different trigger conditions in the both rectangular and cluster layouts. On the other hand, the angular resolution of the array for different trigger conditions and layouts is calculated using a chi-squared minimization algorithm and assuming that the shower front can be approximated by a plane. Two different shower sets simulated by CORSIKA [3], which differ in the distribution of energy and zenith angles, have been applied for these studies.

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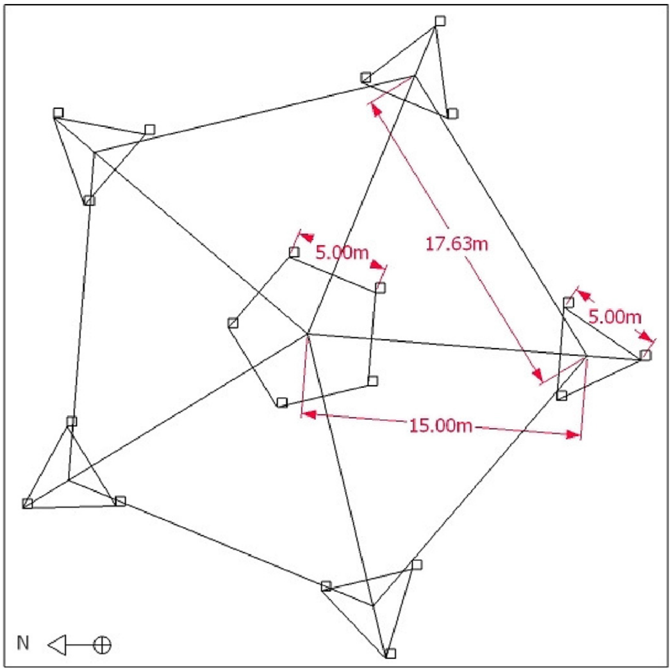

Fig. 1. Cluster layout of the Alborz-I array where 20 SDs will be deployed in a square area. Distance between neighboring detectors in the central pentagon and also in the surrounding triangles around the central pentagon is 5 m.

2. The Alborz-I experiment

The Alborz Observatory Array (AOA) has been designed to measure the flux, arrival direction and energy of the primary cosmic ray around the *knee*. The AOA has been planned to have both Scintillation Detectors (SDs) and Water Cherenkov Detectors (WCDs).

The Alborz-I as the first phase of the AOA is realized at Sharif University of Technology (SUT), Tehran (35°43′N 51°20′E, 1200 m a.s.l corresponding to an average atmospheric depth of 890 g cm^{-2}), and consists of 20 scintillation detectors (each one 0.25 m^2) covering an area of about 1600 m^2. In the next phase, 10 WCDs will be added to it. The used detectors are optimized by a series of experiments and simulations [4,5].

Each scintillation detector of the Alborz-I has a pyramidal galvanized iron light enclosure with 1 mm wall thickness and diffuse white coated inner surface, housing a 50 × 50 × 2 cm^3 NE102A scintillator. Each detector is embedded in a station with a 5 mm cement ceiling. Scintillation light emitted by the scintillator, when charged particle passing through, is read out by a 5 cm photomultiplier tube (PMT, 9813B) placed at the apex of the pyramidal light enclosure at the height of 20 cm from the scintillator sheet.

Two different array configurations, one cluster and other rectangular grid, are proposed. As shown in Fig. 1, in the cluster layout, 5 out of 20 detectors arranged on an internal pentagon with side length 5 m and the rest set on 5 surrounding triangles with the same side length 5 m which are placed on the corners of an external pentagon with side length about 18 m.

In selection chain of the array properties, such as array layout, trigger condition and energy range of interest, several parameters including the trigger probability function, the number of recorded events and the angular resolution of the array are studied for different implemented conditions in the simulations. The results from study of the array properties are described in the following sections.

3. Monte Carlo simulations

A realistic estimate of the array response and angular resolution, as two main characteristics of an array, requires a detailed knowledge of the physics of shower development and interaction of secondary particles with the detector material.

Two different EAS sets simulated by CORSIKA (version 6.9), which differ in the distribution of energy and zenith angles, have been used. QGSJET-II [6] and GHEISHA ($E \leq 80$ GeV) [7] models have been employed for high and low energy hadronic interactions, respectively. At high energies, the showers have been generated in the High Performance Computing Center (HPCC) of SUT with respect to time consuming simulations. It's worth noting that the cut-off energy of secondary particles kinetic energy in the CORSIKA is chosen 0.3 GeV for hadrons and muons, and 0.003 GeV for electrons and photons, and particles below their energy threshold aren't further tracked. The response of the detectors to secondary particles of showers is calculated by means of GEANT4 detector simulation toolkit [8]. The energy deposition of particles crossing the detectors is computed using simulated air showers which are used as input for detailed GEANT4 simulations. Optical photons, caused by the energy deposition of charged secondary particles in the scintillator, are emitted isotropically and eventually a fraction of photons will reach the photocathode of the PMT. Therefore the output signal of the PMT is proportional to the amount of light reaching the PMT, the photocathode quantum efficiency of $\eta_{QE} \sim 27\%$ for maximum emission of NE102A plastic scintillator in $\lambda_{max} = 423$ nm and the PMT gain G=140 × 10^6. Considering the output signal of the PMT and the anode load resistor and capacitance, the threshold of each detector is considered −200 mV which is correspond to signals of charged particles around 3 MeV. In other words, according to the cut-off energy of secondary particles implemented in the CORSIKA inputs, passage of particles through matter, optical photon processes and PMT response, all charged particles above 3 MeV can be recorded by the detectors in the simulation.

In order to reliable estimate of the trigger probability function, a shower set consists of 3600 extensive air showers with a composition of 88% proton and 12% alpha as primary particles have been simulated. In this set, air showers were simulated with azimuth angles from 0° to 360° and zenith angles between 0° and 60° distributed as $I \propto \sin\theta \cos\theta \, d\theta$ (which the *sine* term respects the solid angle element of the sky, while the *cosine* term takes into account the geometrical efficiency of a flat horizontal detector). The energy of primaries is discretely distributed in a range between 10^{12} eV and 10^{16} eV in steps of 0.5 in log *E*. As mentioned above, cut-off energy of 0.3 GeV and 0.003 GeV are selected for muons and electrons, respectively.

For the both layouts, the core location of each shower is distributed at a discrete square grid of points with maximum number of 2809 square pixels (a 53 × 53 square grid), each one with surface area of 49 m^2 to study the events that falling inside and outside the border of the array and fulfill trigger conditions. The core location is set in the center of each pixel in order to increase the statistics of simulated EASs and also to cover different zones of ground. It should be noted by increasing the energy, events whose cores fall outside the array can trigger it and therefore the array is fired by showers with core located in a larger number of square pixels. Finally, as mentioned above, a more detailed analysis of the array response is carried out using GEANT4 and the trigger probability of the array is estimated as a function of core distance and energy for events falling at ground and fulfill the trigger conditions.

Another set of showers includes 12000 proton and alpha showers, with the same previous composition, distributed over a continuous energy range from 2 × 10^{14} eV to 4 × 10^{14} eV according to a power law with the spectral index of $\gamma = -2.7$ have been generated to estimate the angular resolution of the array. This energy range is selected according to the results of the first simulated showers set which reveal a significant number of recorded events in this range in comparison