Simulation study on the performance of the charged particle detector array for cosmic rays at high altitudes from 4300 m to 5700 m


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The observations of very-high-energy (VHE, E > 100 GeV) gamma rays provide an important probe to study the gamma-ray sources, gamma-ray bursts, and AGN. Ground-based extensive-air-shower (EAS) array of charged particle detectors plays a key role in VHE gamma rays due to the large active area, the high duty cycle, and wide field of view. However, the effective gamma-ray detection threshold of existing EAS experiments is limited to 500 GeV ~ 1 TeV because of the low detection efficiency and poor gamma/hadron separation in the energy region below 1 TeV. In order to extend the detection threshold to 100 GeV, the site must be at a higher altitude, at which the maximum EAS shower caused by gamma rays below 1 TeV will be generated. In this paper, we focus on discussing how the observation sensitivity of low energy gamma rays will improve as the altitude of the observation site increases. We have carried out a detailed Monte Carlo simulation to study the performance of the charged particle detector array for cosmic rays at high altitudes from 4300 m to 5700 m. As the main types of particle detector, the Water Cherenkov Detector array (WCD) have been arranged in the Geant4 simulation, and three altitudes of 4300 m, 4900 m and 5700 m have been set in CORSIKA. The detection efficiency, the gamma/hadron separation, the angular resolution, and the energy resolution will be discussed in this work.
1. Introduction

The observations of very-high-energy (VHE, E > 100 GeV) gamma rays provide an important probe to study the gamma-ray sources, gamma-ray bursts, and AGN. Ground-based extensive-air-shower (EAS) array experiment of charged particle detectors, such as the Tibet ASγ [1] (4300 m a.s.l.), the HAWC [2] (4100 m a.s.l.) and the LHAASO [3] (4410 m a.s.l.), plays a key role in VHE gamma rays due to the large active area (> 10^4 m^2), the high duty cycle (> 95%), and wide field of view (∼ 2 sr). However, the effective gamma-ray detection threshold of existing EAS experiments is limited to 500 GeV ∼ 1 TeV because of the low detection efficiency and poor gamma/hadron separation in the energy region below 1 TeV. To extend the detection threshold of gamma rays to 100 GeV, it’s a feasible choice to choose a higher observatory site (> 5000 m a.s.l.), where close to the maximum of the EAS induced by gamma rays below 1 TeV.

In this paper, we have carried out a detailed Monte Carlo simulation to study the performance of the charged particle detector array for cosmic rays at high altitudes from 4300 m to 5700 m. As the mainstream types of cosmic-ray particle detector, the Water Cherenkov Detector array (WCD) have been set in this work. Three altitudes of 4300 m, 4900 m and 5700 m, corresponding to three ideal observations site found in Tibet, China, have been set in our Monte Carlo simulation. The performance of charged particle detector array for cosmic rays, including the detection efficiency, the gamma/hadron separation, the angular resolution, and the energy resolution, will be discussed in this work.

2. The experimental setup

![Figure 1: Left: Schematic view of the Water Cherenkov Detector (WCD) array. The area enclosed by the red solid line indicates the fiducial area, with an area of ∼18,900 m^2, consists of 1336 water tanks. Right: Schematic of a WCD unit. Each water tank is a cylindrical steel structure, 3.0 m in diameter and 2.0 m in height, filled with purified water, and each WCD unit is equipped with one upward-facing 8-inch PMT on the bottom at the center of the tank.](image)
In this work, the charged particle detector array consists of 1624 Water Cherenkov Detector (WCD) tanks has been set up, as shown in Fig.1-Left. The area enclosed by the red solid line indicates the fiducial area of the WCD array, with an area of \(\sim 18,900 \text{ m}^2\), consists of 1336 water tanks. Each water tank is a cylindrical steel structure, 3.0 m in diameter and 2.0 m in height, as shown in Fig.1-Right, filled with purified water. The inner wall and bottom of the water tank are painted black to avoid the reflection of Cherenkov lights, and each WCD unit is equipped with one upward-facing 8-inch photomultiplier (PMT) on the bottom at the center of the tank.

3. Monte Carlo Simulations

We have carried out a full Monte Carlo (MC) simulation on the development of air showers in the atmosphere at three altitudes of 4300 m, 4900 m and 5700 m using the EAS simulation code Corsika (Ver. 7.56) [4], with EPOS-LHC [5] for the high-energy hadronic interaction model and FLUKA [6] for the low-energy hadronic interaction model. The gamma ray events are generated according to the Crab orbit with the energy spectrum index of -2.62, while the cosmic rays events are generated based on the primary composition model of “He-rich” mentioned in the Ref. [7]. The kinetic energy cut-off of electrons, positrons and photons is set to 1 MeV. The detector responses to shower particles falling on the detectors of WCDs array are calculated using the Geant4 (Ver. 4.10.01) [8]. The Cherenkov photon emission of particles that reach the WCDs in the water is simulated, the photons are collected by a 8-inch PMT on the bottom at the center of the tank, where the number of photoelectrons is counted and the time of photon hit the PMT is recorded. The quantum efficiency of 8-inch PMTs used by WCDs is also taken into account in the simulation as a function of the wave length of the Cherenkov light [9].

4. Results and Discussion

4.1 Information of secondary particles

To study the performance of the cosmic-ray detector array at three different altitudes, firstly, it’s important to investigate the characteristics of the secondary particles of extensive-air-shower (EAS) at three altitudes of 4300 m, 4900 m and 5700 m. As mentioned above, package of Corsika (version 7.56) is employed to simulate the air shower development through the atmosphere, with EPOS-LHC for the high-energy hadronic interaction model, and FLUKA for the low-energy hadronic interaction model.

As shown in Fig.2, the total number of secondary particles has significantly improved as the altitude increases, especially for the energy regions below 1 TeV. The average total number of secondary particles at 5700 m altitude is about 2~2.5 times of that at 4300 m, which implies that the EAS array at higher altitude could have a lager detection area and a lower detection threshold. Meanwhile, as the altitude increases, for a fixed detection area (for example, \(r_0 \leq 80 \text{ m}\)), the ratio of total energy of secondary particles within radius \(r_0\) to the total particle energy at the corresponding altitude, also gradually increases (about 25%), which means the EAS array at higher altitude would observe more characteristics of secondary particles.
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Figure 2: The average total number of all secondary particles (Left) and the average ratio of total energy of the secondary particles with $r_0 \leq 80$ m to all secondary energy (Right), at three altitudes of 4300 m, 4900 m and 5700 m.

4.2 Angular resolution

With the basic parameters measured by the WCDs, we can reconstruct the information of the air shower we need, including the core position ($x$, $y$) and the arrival direction ($\theta$, $\varphi$) of an air shower, which are reconstructed using the number of photoelectrons and relative timing recorded at each WCD tank, by the methods described in Ref. [10]. The following parameters are also reconstructed with the base measurement of number of photoelectrons:

1. $N_{hit}$, the number of “fired” detectors with the number of photoelectrons $\geq 3$;
2. $\text{sump.e.}$, the total number of photoelectrons recorded by all “fired” detectors, which can estimate the primary energy of an shower;
3. $N_{top}^{iop}$, the maximum number of photoelectrons among the fired detectors with $r \geq r_i$ ($r_i = 20$ m, 30 m, 40 m);
4. $\langle R \rangle$, the mean lateral spread, $\langle R \rangle = \frac{\sum r_i}{N_{hit}}$;
5. $\langle N_{pe} R \rangle$, the mean energy-flow spread, $\langle N_{pe} R \rangle = \frac{\sum (N_{pe} \times r_i) / N_{hit}}{N_{hit}}$.

The gamma ray angular resolution of the WCDs at three altitudes of 4300 m, 4900 m and 5700 m with the events select conditions of $N_{hit} \geq 10$ is shown in Fig. 3. The gamma ray angular resolutions (50% gamma rays containment) are estimated to be approximately 0.7° and 0.3° for 300 GeV and 1 TeV at 5700 m altitude, respectively. As shown in Fig. 3, the angular resolutions improve better as the altitude increases, especially for the energy regions below 1 TeV.

4.3 Energy resolution

As the performance of the WCDs is closely correlated with the primary energy, and the primary energy ($E_0$) is related to the total number of photoelectrons recored ($\text{sump.e.}$), as shown in Fig. 4-Left, which shows the scatter plots of $\text{sump.e.}$ recorded by WCD array and primary energy ($E_0$) of gamma rays with zenith angle less than 12 degrees at 5700 m altitude. The primary energy of each selected events could be estimated using the $\text{sump.e.}$ parameter. Therefore, the MC data at
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Figure 3: The gamma-ray angular resolutions of the WCD array at three altitudes of 4300 m, 4900 m and 5700 m under the events select conditions of $N_{hit} \geq 10$.

Three altitudes is divided into many multiplicity intervals by the sum p.e. to study the performance of the WCDs, and the mode energy corresponding to the same sum p.e. data sample decreases with the altitude increases, which implies that the WCD array at higher altitude could effectively lower the threshold of gamma rays.

Fig. 4 - Right shows the energy resolution of gamma ray at the energy of $\sim 1$ TeV, and the energy resolution is estimated to be 63%, 80% and 99% around the primary energy of 1 TeV, corresponding to the altitude of 5700 m, 4900 m and 4300 m respectively, which implies the energy resolution improves as the altitude increases from 4300 m to 5700 m.

Figure 4: Left: Scatter plots of the sum p.e. and primary energy (E0) of gamma rays with zenith angle less than 12 degrees at 5700 m altitude. Right: The energy resolution is estimated to be 63%, 80% and 99% around the primary energy of 1 TeV, corresponding to an altitude of 5700 m, 4900 m and 4300 m respectively.
4.4 Effective detection Area

The effective detection area of the WCDs for gamma rays (Crab orbit) at three altitudes of 4300 m, 4900 m and 5700 m is shown in Fig. 5, under the events select conditions of $N_{hit} \geq 10$ (Fig. Left) and $N_{hit} \geq 20$ (Fig. Right). As shown in the Figure, the effective detection area has significantly improved as the altitude increases, especially for energy regions below 1 TeV. For the gamma ray of $\sim 100$ GeV energy region, the effective area at 5700 m is about 5~6 times of that at 4300 m, while about 2 times at 500 GeV.

![Effective Area vs Primary Energy](image1.png)

**Figure 5:** The effective detection area of the WCDs for gamma rays (Crab orbit) at three altitudes of 4300 m, 4900 m and 5700 m, respectively. *Left: $N_{hit} \geq 10$, Right: $N_{hit} \geq 20$.*

4.5 Gamma/hadron Separation

In this work, the separation of the primary gamma rays form hadron nuclei is realized by use of the TensorFlow [11] machine learning method. The parameters reconstructed by the WCDs are very sensitive to the gamma rays and hadron background, including $N_{hit}$, sum.p.e., $N_{top}^{e}$, $\langle R \rangle$, $\langle N_{pe}R \rangle$. An example of the sensitivity parameters is shown in Fig. 6-Left, in which the comparison of mean energy-flow spread ($\langle N_{pe}R \rangle$) distribution of gamma and Hadron is shown by different colors. As shown in the figure, the characteristic parameters used for identification become more effective as altitude increases. Utilizing the parameter ($\langle N_{pe}R \rangle$) only, with 50% of gamma-ray events remaining, the WCDs array could reject $\sim 94.3\%$ background hadron events at $\sim 500$ GeV for 5700 m altitude, while 91.9\% for 4900 m and 88.7\% for 4300 m.

The five parameters mentioned above are input to the TensorFlow. To train the TensorFlow in separating the gamma rays from hadron nuclei, the input patterns for gamma and hadron are set to 1 and 0, respectively. As shown in Fig. 6-Right, at about 500 GeV energy range, with use of the TensorFlow machine learning method, the WCDs array could reject $\sim 96.8\%$ background hadron events for 5700 m altitude, while 95.4\% for 4900 m and 93.1\% for 4300 m. The results above show that the Gamma/hadron Separation has significantly improved as the altitude increases.
Figure 6: Left - The Comparison of mean energy-flow spread ($\langle N_{pe}R \rangle$) distribution of gamma (in red) and Hadron (CRs, in blue); Right - TensorFlow Learning output pattern value (T) distribution of training gamma events and Hadron background, at about 500 GeV energy range, for three altitudes of 4300 m (top), 4900 m (middle) and 5700 m (bottom).

5. Summary

In this work, we focus on discussing how the observation sensitivity of low energy gamma rays will improve as the altitude of the observation site increases, and we mainly analyzed the performance of the WCD array for cosmic rays at three high altitudes of 4300 m, 4900 m and 5700 m. At the 5700 m altitude, for the experimental setup mentioned in this work, the gamma ray angular resolutions (50% containment) are estimated to be approximately 0.7° and 0.3° for 300 GeV and 1 TeV, respectively; the energy resolution is estimated to be 63% around the primary energy of 1 TeV. Most importantly, the effective detection area of the same detector at an altitude of 5700
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m is \( \sim 1000 \) m\(^2\), much larger than that at an altitude of 4300 m, and the WCD array could reject \( \sim 96.8\% \) background hadron events at \( \sim 500 \) GeV, with 50\% of gamma-ray events remaining. The results discussed above show that the performance of WCD array has significantly improved as the altitude increases, especially for the energy regions below 1 TeV (100-1000 GeV), which implies that the EAS array at higher altitude (5700 m) could extend the detection threshold of gamma rays to 100 GeV.

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