Abstract: The Cherenkov Telescope Array (CTA) is the next generation observatory for very high energy gamma rays. The capability of the array to detect gamma-rays above 10 TeV is going to be achieved with a large number of Small Size Telescopes (SSTs) which will cover a large area. The subarray composed of SSTs has to compromise the number of telescopes (cost) and the large effective area. The separation between the telescopes has to be adjusted to achieve highest sensitivity with the smallest number of telescopes. On the other hand larger separation can worsen the energy threshold as well as the energy and angular resolutions. In our study we have investigated the optimal spacing between the telescopes of the SST array using an analytical approach and the concept of telescope cell consisting of four telescopes as well as Monte Carlo simulations of the sets of cells.

Keywords: CTA, Cherenkov light, SST.

1 Introduction

The current imaging atmospheric Cherenkov telescope (IACT) arrays have provided a tremendous progress in the field of the very high energy (VHE > 100 GeV) astronomy. The latest generation of gamma-ray instruments like H.E.S.S., MAGIC and VERITAS consists of two to five telescopes equipped with analogue cameras based on photomultiplier tubes.

The sensitivity of the current instruments reaches the maximum for energies from 100 GeV to 10 TeV. The best performance in this energy range is obtained by locating the telescopes in the inner light pool of the shower (~120 m from the shower core), where the distribution of Cherenkov light density is relatively flat. The Cherenkov light density at ground level is typically ~10 photons/m² for a shower induced by a 100 GeV γ-ray event. At least 100 photoelectrons (phes) have to be generated to allow for the event reconstruction. With the optical efficiency of the current instruments reaching ~10%, the telescope has to be equipped with at least a ~10 m diameter mirror to collect the required number of Cherenkov photons.

The next generation of IACT arrays, the Cherenkov Telescope Array (CTA) [Actis et al. [2011]], is aimed to improve the sensitivity, as compared to the current instruments, by an order of magnitude in the 100 GeV - 10 TeV energy range and to extend the current sensitivity to lower and higher energies.

The improvement in the lower energy range is going to be achieved by adding telescopes with a large mirror area. Such telescopes will be able to collect enough Cherenkov photons with densities down to ~1 photon/m².

At higher energies above 10 TeV, the Cherenkov light density in the inner light pool is larger than ~1000 photons/m². Therefore, even telescopes with small mirror area (~10 m²) are able to collect enough Cherenkov photons to reconstruct direction and energy of a primary particle. But, since source flux rapidly decrease with energy, such an array must have a very large effective collection area (Aeff).

The CTA, in its design phase, requires the effective collection area to be > 7 km² at energies above 10 TeV. Such a large effective area can be obtained by building dozens of small size telescopes (see e.g. [Rowell et al. [2008]])

The Cherenkov light density for distances above ~120 m from the shower core falls by a factor of ~50 per each 100 m. Despite the large density decrease, VHE γ-ray showers could be seen beyond a distance of ~500 m from the shower core. The Cherenkov light density of the shower induced by a 100 TeV γ-ray is still ~100 photons/m² at a distance of 1000 m from the shower core.

However, the distance between the source position in the camera plane and the image center increases with the impact parameter. An image corresponding to a core distance of 500 m would be displaced by approximately 4°. Therefore, the detection of distant showers requires a camera with a large field of view.

The subarray composed of SSTs has to compromise between the number of telescopes (cost) and the large effective area. At fixed cost, the effective area can be increased by setting the telescopes further apart. On the other hand, larger separation can worsen the energy threshold as well as the energy and angular resolutions.

The simulations of the whole telescope array are time and resource consuming. Therefore, we have used a concept of a telescope cell [Aharonian et al. [1997]]. In our study we have investigated the optimal spacing for the array consisting of four 4m Davies-Cotton Small Size Telescopes.

2 Cell Concept

The cell concept has been introduced to investigate the performance of the IACT array at energies above 100 GeV [Aharonian et al. [1997]]. A cell is system of four IACTs located in corners of a rectangle of a given size. Only events with core distances inside the cell are considered. The sensitivity of an array comprised of N cells is calculated using results obtained for a single cell, except effective area
for γ-rays and protons, which are in addition multiplied by number of cells.

For the larger number of telescopes the relative error of the cell approach becomes smaller. In the case of cells, an effective area of an array is defined as $A_{\text{Teff}} \times N_{\text{cells}} \times d^2$, where $N_{\text{cells}}$ is a number of grid cells, $d$ is telescope separation and $A_{\text{Teff}}$ is an average trigger efficiency in the cell. The required number of cells can be derived for given telescope separation and given effective area. Let's assume for the moment that $A_{\text{Teff}}$ equals 1. In such a case, the number of cells, $N_{\text{cells}}$, is defined as:

$$N_{\text{cells}} = \frac{\text{Req Effective Area}}{d^2}$$

(1)

The number of telescopes, $N_{\text{tel}}$, in the grid built on square cells is:

$$N_{\text{tel}} = (\sqrt{N_{\text{cells}}} + 1)^2$$

(2)

Equations (1) and (2) can be used to derive the number of cells and the number of telescopes for given telescopes separation and required effective area of 7 km$^2$. These numbers are presented in Table 1.

| $d$ [m] | $N_{\text{cells}}$ | $N_{\text{tel}}$ |
|--------|-----------------|-----------------|
| 120    | 529             |                 |
| 200    | 175             | 202             |
| 300    | 78              | 96              |
| 400    | 44              | 58              |

Table 1: Number of telescopes and cells of a given separation required to reach 7 km$^2$ effective area.

3 Telescope Parameters

The analysis has been performed for a telescope equipped with a 4 m diameter mirror with the focal length of 5.6 m [Molderk et al., 2013]. The camera consists of 1285 Geiger-mode avalanche photodiodes (G-APDs). The physical size of the pixel is 2.32 cm, and the field of view (FoV) of the single pixel is 0.24°. The camera has a diameter of 88 cm and FoV of 9°.

4 Monte Carlo Simulations and Analysis

The Monte Carlo (MC) simulations have been performed to examine the performance of the telescope array. First, the development of the extensive air showers (EASs) caused by γ-rays and protons is simulated. The EASs are simulated with CORSIKA (Cosmic Ray Shulations for Kascade) [Capdevieille et al., 1993] and SIBYLL hadronic interaction model [Pfetche et al., 1994].

The site at an altitude of 2000 m above sea level has been simulated. The simulated primary particles entered the atmosphere at zenith angle of 20°. The events have been simulated in the energy range from 1 TeV to 100 TeV. A standard desert atmosphere has been used.

10 arrays of 4 telescopes have been simulated with a telescope separation ranging from 120 m up to 1000 m. The array layout is presented in Figure 1.

We have divided the CORSIKA simulations into rings of equal area ($1.25 \times 10^5$ m$^2$) and with the same number of events per ring. The outer rings have been simulated up to a radius at which the trigger efficiency considerably decreased. In this simulation the maximum impact parameter was ∼1000 m, which corresponds to 25 rings.

The ring approach has been chosen to ensure sufficient event number at large distances from the array core without a loss of computer resources for simulations of events with negligible event detection efficiency.

Next step, the sim_telarray package has been used to simulate the telescopes array response to Cherenkov photons. The parameters of the simulated telescope have been given in section 3.

Analysis of sim_telarray output has been done using read_hess software, which attempts to reconstruct the events seen by telescopes by applying various image analysis methods, image cleaning etc [Bernlöhfer et al., 2013]. The results presented here are derived using the so-called “standard cuts”: a minimum amplitude of 100 phes has been required, four telescopes had to be triggered, at least 5 pixels in the shower image, images have been cleaned using 7/14 value for tail cuts. The other cuts on energy and angular resolution have been optimized by simulated annealing method to achieve the best sensitivity.

The sensitivity, an angular resolution and an energy resolution have been calculated using definitions given by Bernlöhfer et al. [2013]. A Boosted Decision Trees method was used to distinguish proton and γ-ray events. Errors were estimated by a bootstrap method.

5 Results

In this paper, the results of the analysis of square four-telescope cells with side lengths of 120 m, 200 m, 300 m and 400 m are presented. The results for distances above 400 m have been omitted due to the significantly worse sensitivities. The final sample of simulated events consists of 11.6 mln of γ-ray events and 33.2 mln of proton events.

The results obtained for four-telescope cells have then been used to extrapolate the sensitivity of an array of 64 telescopes corresponding to 49 cells.

Figure 2 shows the effective area of the 49 cells. The simulations imply that almost all γ-ray events inside the cell are triggered. A significant fraction of the events is lost after applying cuts. Figure 3 presents trigger efficiency after cuts.
Fig. 2: γ-ray effective area for array consisting of 49 cells with different separation. Effective area has been obtained considering only γ-ray showers inside the cells. The results correspond to effective area after trigger (trigg) and after cuts (aft cuts).

Fig. 3: Trigger efficiency of all events (also outside the cell) after cuts for different telescope separations: 120 m, 200 m, 300 m and 400 m, respectively. Figures represent γ-ray events with energy ~100 TeV.

Fig. 4: Proton effective area for array consisting of 49 cells with different length sides. Effective area has been obtained considering only proton induced showers inside the cells. The results corresponds to effective area after trigger (trigg) and after all cuts (aft cuts).

Fig. 5: Angular resolution as a function of energy for events inside the cells. Cuts were optimized to get best sensitivity.

6 Conclusions and Discussion

The currently existing analysis methods have been optimized to work well in the energy range from 100 GeV to 10 TeV, and have been widely used by experiments like H.E.S.S., Veritas or MAGIC. New methods optimized for observations above 10 TeV would provide in the future a significant improvement in the array performance.

The study presented here shows that the sensitivity of
SST array can be substantially improved in the regime above 10 TeV through the increased telescope separation. The sensitivity for the SSTs is constrained by proton background for energies below 10 TeV. At higher energies, sensitivity is only constraint by a number of γ-ray events. The improvement in the sensitivity is achieved by enhancing the effective area. The cell approach shows that the sensitivity required by the CTA in energies above 10 TeV is met with 64 SST 4 m DC telescopes, with spacing above 200 m.

Figure 6 shows that a significant fraction of the events with energies below 10 TeV is lost after all cuts. The number of remaining events at the energies above 10 TeV tends to the number of triggered events.

The obtained angular and energy resolutions of the array depend strongly on the detailed analysis method. The cuts used here have been optimized to achieve the best sensitivity despite of energy resolution.

In this study we did not use the timing information. It has been shown by Stamatescu et al. [2011] that the angular resolution can be significantly improved by using timing gradient. The background rejection also can be enhanced by introducing telescope timing characteristic [de La Calle Pérez and Biller [2006].

The adopted cell approach constrains analysis only to events inside the cell. In reality showers will be detected by a larger number of telescopes. The cell concept provides then the “safe” approximation - only the lower limits on the array performance.

The further improvement of the results is going to be achieved by additional proton simulation to increase the statistic. Also γ-rays in the energy range from 100 TeV up to 300 TeV will be simulated. We also plan to improve the analysis methods by adding the timing information. We will investigate the accuracy of the cell approach using ongoing Prod2 simulation. The aim is to compare the results of full SST array with given spacing to an array built of cells with similar spacing to one used in Prod2.

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