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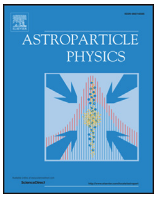

Monte Carlo performance studies for the site selection of the Cherenkov Telescope Array

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ABSTRACT

The Cherenkov Telescope Array (CTA) represents the next generation of ground-based instruments for very-high-energy (VHE) gamma-ray astronomy, aimed at improving on the sensitivity of current-generation experiments by an order of magnitude and providing coverage over four decades of energy. The current CTA design consists of two arrays of tens of imaging atmospheric Cherenkov Telescopes, comprising Small, Medium and Large-Sized Telescopes, with one array located in each of the Northern and Southern Hemispheres. To study the effect of the site choice on the overall CTA performance and support the site evaluation process, detailed Monte Carlo simulations have been performed. These results show the impact of different site-related attributes such as altitude, night-sky background and local geomagnetic field on CTA performance for the observation of VHE gamma rays.

1. Introduction

As a result of the success of current imaging atmospheric Cherenkov Telescopes (IACTs) and the improvement of the different technologies involved, the next generation of ground-based very-high-energy (VHE) gamma-ray detectors is under development. The CTA[1] [1,2] will give deep and unprecedented insight into the non-thermal high-energy Universe scrutinising the gamma-ray sky from 20 GeV to 300 TeV, improving the sensitivity of current instruments by more than an order of magnitude.

In order to achieve these goals, the CTA Observatory will consist of two different sites, one in each Hemisphere, and telescopes of three different sizes: Large-Sized Telescopes (LSTs) [3] sensitive to the faint low-energy showers (below 200 GeV), Medium-Sized Telescopes (MSTs) [4,5] increasing the effective area[2] and the number of telescopes simultaneously observing each event within the CTA core energy range (between 100 GeV and 10 TeV) and Small-Sized Telescopes (SSTs) [6] spread out over several km^2 to increase the number of detected events at the upper end of the electromagnetic spectrum accessible to CTA (up to $\sim$ 300 TeV).

The proposed designs for the Northern and Southern observatories will make the full sky accessible with an improved sensitivity alongside better angular and energy reconstruction. The CTA Southern site, with an ideal location to observe the Galactic cen-

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[1] http://www.cta-observatory.org/.

[2] The effective area of the instrument is defined as the differential gamma-ray detection rate, $\frac{dN_{\gamma,det}}{dE}$, after all analysis cuts (see Section 4), divided by the differential flux of incident gamma rays.

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tre and a big fraction of the Galactic Plane, will be larger in order to measure the extremely low fluxes expected from these sources above 10 TeV. Its baseline design foresees 4 LSTs, 25 MSTs, and 70 SSTs [7]. The Northern site, with a broader coverage of the extragalactic sky, will be more focused on the study of extragalactic objects and transient phenomena. The CTA Northern Hemisphere site is planned to be composed of 4 LSTs and 15 MSTs.

One of the advantages of such an extended telescope layout is that most of the detected events will be fully contained inside the area covered by the array. These so-called *contained events* will be better sampled, providing an improved background rejection, better angular and energy resolution, and reduced energy threshold.

The criteria considered for the scientific site ranking by the CTA Consortium are costs, risks and scientific performance. Costs (including host premiums, available infrastructure, building and operation costs, taxes and fees) and risks (including economic and socio-political risks or environmental hazards) are not considered in the present paper. The scientific performance of a candidate site depends mainly on the average annual observing time (AAOT) and the performance per unit time[3] (PPUT) of the array. The AAOT, mainly dependent on the site's weather conditions, was evaluated for each candidate site using various satellites and weather simulations [8], together with in-situ weather records. The AAOT is also beyond the scope of the paper.

All sites proposed to host such an ambitious project satisfy a list of geographical and atmospheric criteria. Sites were required to be located at medium latitudes, contain enough available area for the deployment of the telescopes layout, have a clean atmosphere with no obstacles blocking significant parts of the sky and tolerable annual ranges of temperature, wind and humidity.

This study focuses on the determination of the scientific performance per unit time of each proposed site, and evaluates through detailed MC simulations the effect of several site attributes like altitude, geomagnetic field and night-sky background (NSB) on the telescope layout performance. These site-related parameters have been widely studied by the current generation of IACTs, and are briefly described in the following section.

2. Site parameters and CTA performance

To optimise the CTA design, detailed Monte Carlo simulations have been performed to estimate its scientific performance [7,9–11]. Throughout this work, the differential sensitivity to point-like sources is the parameter used to evaluate CTA performance per unit time. The differential sensitivity, i.e. minimum detectable flux from a steady, point-like gamma-ray source, calculated for a narrow energy range, depends on the collection area, angular resolution, and rate of background events surviving all gamma selection cuts.

IACTs capture images of the very short flashes (a few ns) of optical Cherenkov radiation caused by the charged particles generated within the extensive air showers (EASs) produced by VHE gamma and cosmic rays. Most of this light is emitted at an altitude of 5–10 km and propagates as a cone with a small opening angle (0.5–1 °). At ground level, the shower results in a pool of light of ~ 120 m radius centreed at the *core position*. As shown in Fig. 1, the lateral distribution of the Cherenkov light emitted within the EASs (i.e. average Cherenkov photon density reaching ground as a function of the distance to the core) changes significantly with the energy of the primary particle. Captured images picture the emitted Cherenkov photons through the atmosphere projected within the line of sight of each IACT as elongated elliptical-shaped images. Then the primary particle is identified (as a gamma ray or background) and original direction reconstructed (with up to sub-arcminute accuracy) using the orientation and shape of all recorded images of the EAS.

The considered CTA candidate sites are listed in Table 1, together with some relevant site-related parameters. These parameters directly affect the performance of IACTs as they influence the development of the EASs [12], modifying the Cherenkov light density at ground level. The main environmental parameters affecting the sensitivity of IACTs are the site altitude, the local geomagnetic field intensity and the NSB level.

2.1. Altitude

The operational altitude of IACTs sets the average stage of development in which EASs are measured [12]. Therefore the altitude of the IACTs influences the quality of the measurements in several ways:

- for a given gamma-ray energy, the intensity of Cherenkov light close to the shower axis (less than ~ 150 m) increases at higher altitudes (see Fig. 1, left panels)
- for gamma-rays with energy above ~ 200 GeV, Cherenkov photon density at large core distances is reduced at higher observational altitudes (see Fig. 1, right panels)
- for a given impact parameter,[4] the centroid (i.e. centre of gravity) of shower images will be shifted towards the camera edge for higher altitude sites. These images get truncated due to the limited field of view of each telescope, therefore limiting the shower distance accessible range
- the contribution from charged particles penetrating to ground level increments the fluctuations of gamma-ray images detected by IACTs close to the shower axis. These fluctuations increase the variance of the shape and total charge of shower images, decreasing background rejection efficiency. This effect increases with altitude

These effects are translated to lower energy thresholds for higher construction altitudes and reduced performance at energies above ~ 200 GeV. Considering the CTA sub-systems individually [7,9]:

- LSTs: at higher altitude sites, more Cherenkov photons reach the telescopes at ground level (see Fig. 1, top panel), providing a lower threshold energy, although angular and energy resolution may be degraded due to the presence of charged particles close to the ground.
- MSTs: telescope spacing is comparable to the crossover point of the Cherenkov light lateral distributions at different altitudes (see Fig. 1, right panels), so modest performance differences are expected for intermediate energies (200 GeV–5 TeV). Higher altitude sites reduce telescope multiplicity (i.e. number of telescope images obtained for each shower) but increase the intensity of the recorded shower images.
- SSTs: telescope multiplicity will be reduced at high altitudes due to the sum of two effects: a reduced atmospheric volume is found within the optical field-of-view of the telescopes (producing bigger images that may be truncated within the IACT camera) and the lower Cherenkov light density emitted by EASs at large impact distances (see Fig. 1, right panels).

As shown in Table 1, there are large differences in altitudes of CTA candidate sites, ranging from 1640 m (Aar, Namibia) to 3600 m (San Antonio de los Cobres, Argentina).

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[3] Throughout this work, the differential sensitivity in 50 h of observation (defined in Section 2) will be used as the main parameter describing an array performance per unit time.

[4] Distance projected on ground between the centre of the Cherenkov light pool and the IACT.