Performance studies of the CTA observatory

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Abstract: The Cherenkov Telescope Array (CTA), currently in the Preparatory Phase, will study gamma rays in the energy range from a few tens of GeV to >100 TeV with unprecedented sensitivity and angular resolution. In order to cover such a vast energy range, an array of three complementary telescope types is envisaged: a small number of Large Size Telescopes (LST, 23 m-diameter dish) for the low-energy range (below 200 GeV), few tens of Medium Size Telescopes (MST, 12 m dish) for the central energy range (100 GeV - 10 TeV) and a large number of Small Size Telescopes (SST, 4-7 m dish) for the high energy range (above 10 TeV). The optimization of the performance (sensitivity, angular and energy resolutions) of such a complex system requires intensive simulation activities. Some preliminary results in terms of off-axis performance, operation under moonlight conditions and high altitude performance are reported and discussed.

Keywords: CTA, Imaging Atmospheric Cherenkov Telescope, gamma-rays, Monte Carlo simulations

1 Introduction

CTA (Cherenkov Telescope Array) [1] is an international project included in the European roadmap for research infrastructures [2]. The project aims at building a large ground-based gamma-ray observatory for the study of the Universe in the Very High Energy (VHE) range of the electromagnetic spectrum, from tens of GeV to >100 TeV, through the observation of the Cherenkov light emitted by Extensive Air Showers (EAS) of particles initiated by gamma-rays. The goal of CTA is an order of magnitude improvement in sensitivity with respect to the current operating Imaging Atmospheric Cherenkov Telescope (IACT) arrays (HESS, MAGIC and VERITAS), together with expanded field-of-view and dramatically improved angular and energy resolution. The observatory will consist of $\sim$100 Cherenkov telescopes operating from two sites in the northern and southern hemispheres, and will be designed and built by a consortium of scientific institutes belonging in 25 countries worldwide. CTA is currently in a Preparatory Phase, which began in October 2010 and will run for three years; during this phase the project design will be defined and tested through the realization of prototypes. The Monte Carlo working group [1] plays a key role in this phase, as detailed simulations of the development of showers, and their detection and reconstruction, are required to characterise the performance of the instrument.

Presently operating IACTs have a field of view limited to typically $4^\circ - 5^\circ$ in diameter [3, 4]: the planned increase up to $\sim 8^\circ$ could greatly improve the full sky survey capability, the potential for serendipitous source discovery and the analysis of very extended objects. Dedicated Monte Carlo studies are underway to study the off-axis performance of CTA and are critical to the science-based optimisation of the observatory design. Another key input to this process is the duty cycle of the observatory and the array performance under non-optimal conditions. Studies of performance under high Night Sky Background (NSB) conditions are in progress: the nominal duty cycle of $\sim$ 1000 h/y (11%) due to solar, lunar and weather constraints may be significantly extended by operating under moonlight (and twilight) conditions.

2 The Monte Carlo simulations

The simulations performed to optimize CTA performances consist of three major steps: 1. the development of the extensive air shower in the atmosphere and the emission of Cherenkov light; 2. the response of the telescopes; 3. The

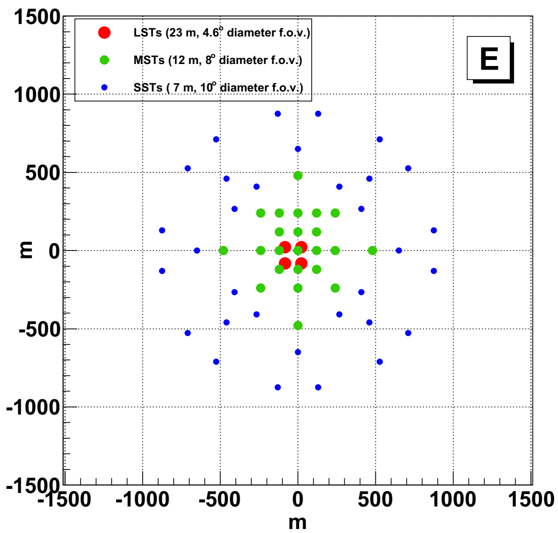

Figure 1: Layout of one of the configurations giving the best sensitivity/cost in the whole energy range (from a few tens of GeV to >100 TeV).

analysis of the simulated raw data. The EAS development is calculated using the CORSIKA program [5], while the *sim_telarray* [6] program implements the ray-tracing, photon detection, and the electronics for trigger and signal processing. Finally different analysis programs perform: image cleaning, image analysis (in the standard pipeline based on second-moment Hillas parameters [7]) and stereoscopic event reconstruction (see e.g. [8]). The aim of the simulation is to optimize the array sensitivity over the whole energy range, keeping close to optimal angular and energy resolution. In order to reach this goal about 2.5×10^9 γ-ray events and a factor 20 more background events (hadrons and electrons) have been simulated using several different array layouts. In addition to those presented here, many activities are currently in progress concerning, for instance: the optimization of the LST design, the impact of field of view, pixel size and Schwarzschild-Couder optical design for the SST, the trigger strategy, the digitization sampling rate and the dynamic range, and the optimization of analysis algorithms. Fig. 1 shows the configuration used for the sensitivity curves which are presented in the following sections.

3 The off-axis performance

A key goal for the CTA observatory will be to perform surveys of a significant fraction of the sky. The southern array will be used to perform a Galactic plane survey as well as targeted observations of Galactic and extragalactic objects and will cover the full energy range, and the northern array is optimized for lower (from a few tens of GeV to a few TeV) energies, and will be focussed on the study of extragalactic sources. For each telescope type in these arrays, a wide field of view (f.o.v.) will benefit the survey capability, both in terms of producing a relatively flat off-axis response at higher energies, and by improved determination of the residual cosmic-ray background through the selection of more off-source background-control regions.

We investigate the off-axis performance of CTA by using simulated diffuse gamma-ray showers, that have been produced at off-axis angles up to 10°. The data are analyzed for the CTA candidate array E [1], that consists of 4 LSTs (4.6° diameter f.o.v.), 23 MSTs (8° diameter f.o.v.) and 32 SSTs (10° diameter f.o.v.). Given that the analysis method used in this study is optimized for on-axis gamma rays, the current off-axis performance estimate may be considered to be conservative.

The off-axis differential sensitivity is estimated by first determining an off-axis cut on the reconstructed direction in each energy bin. This cut is obtained by scaling the corresponding optimum on-axis cut by the relative (with respect to on-axis) worsening in the off-axis angular resolution, which is shown in Fig. 2 for several off-axis angles. The on-axis performance is obtained with an analysis method that delivers marginally better differential sensitivity at the expense of worse angular resolution below ~1 TeV, with respect to the standard analysis pipeline on-axis performance [1]. Optimized on-axis cosmic-ray background rejection and telescope multiplicity cuts are applied to the diffuse gamma, proton and electron data, and relative effective areas (with respect to on-axis) are determined as a function of the off-axis angle for each primary particle type. The off-axis gamma-ray and cosmic-ray background rates for each energy and off-axis angle bin are obtained by scaling the on-axis rates with the corresponding relative effective area and with the relative (with respect to on-axis) difference in reconstructed direction cut efficiency. The minimum detectable flux is then determined by demanding for each energy bin a minimum 5 σ detection, at least 10 gamma-ray events and a minimum gamma-ray excess of at least 5% of the residual cosmic-ray background. Fig. 3 shows the expected differential sensitivity for different off-axis angles. The plot shows, for instance, that at an energy of ~12.6 TeV the differential sensitivity degrades by a factor of ~1.4 at 1.25° off-axis and by a factor of ~4.8 at 3.25° off-axis.

4 The moonlight operations

Traditionally Cherenkov telescope arrays have made observations only during astronomical darkness. The presence of moonlight reduces the observation time and hampers the possibility of observing the entire evolution of transient and variable phenomena. An important example of this is given by the recently discovered (by Agile and Fermi) flare activity from the Crab Nebula, The major flares in September 2010 [9] and April 2011 [10] both happened very close to full Moon. Moonlight observations are possible but the

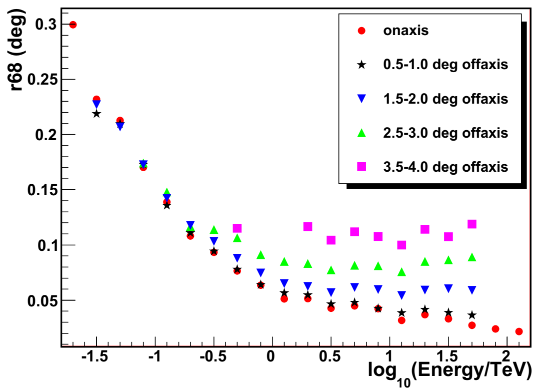

Figure 2: Angular resolution of CTA candidate array E, given as the 68% event containment radius, as a function of estimated energy and off-axis angle. The on-axis angular resolution of the array is also shown. The missing points are due to limited Monte Carlo statistics.

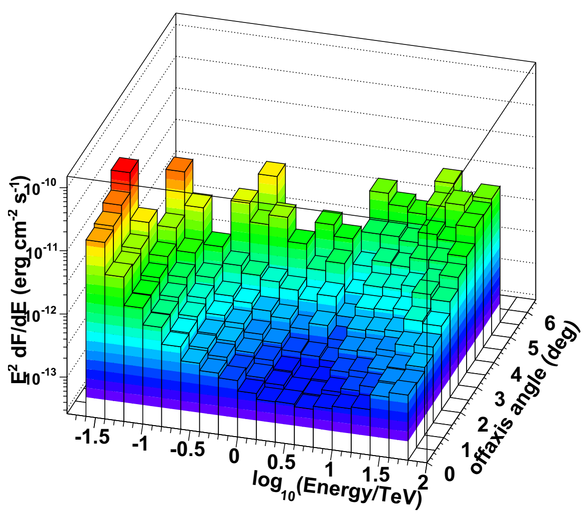

Figure 3: Differential sensitivity (see text for details) of CTA candidate array E calculated as a function of off-axis angle.

increase in NSB during moonlight and twilight conditions leads to a higher trigger and analysis thresholds and to less sensitivity (at least at low energies). Monte Carlo simulations have been carried out to assess the performances of the CTA array under these conditions.
The adopted NSB level simulates a lunar phase of $\sim$60%, with the telescopes pointing in a direction of 90° from the Moon, which corresponds to a NSB level 4.5 times higher than under standard, dark conditions. The performance is

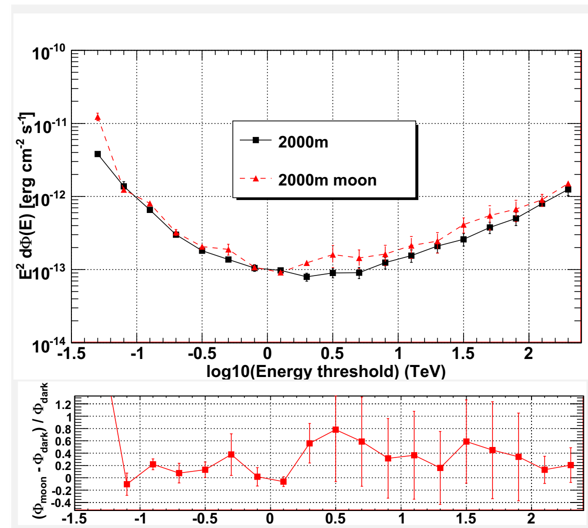

Figure 4: *Top:* Expected sensitivity of CTA candidate array E with (in red) and without moonlight (in black), for 50 h of observations. *Bottom:* Deviation of the sensitivity with moonlight with respect to the one under dark conditions.

computed using the standard moment analysis for γ/hadron separation [7], for 50 h of observations, with 5σ detection per energy bin. The sensitivity under high NSB conditions is presented in Fig. 4 for the array candidate E, compared to the sensitivity without moonlight. For the used analysis algorithm, a pre-cleaning of the camera images is used, based on the amplitude of the signal contained in each pixel. In case of dark condition observations (standard NSB), only the pixels with a content at least 10 times higher than the RMS of the noise ($\mathrm{Amp}_{\mathrm{mean}}$) of the camera surrounded by pixels with a content of 5 $\mathrm{Amp}_{\mathrm{mean}}$ are kept, commonly referred as 5/10 image cleaning. For high NSB observations, the energy threshold implied by the higher value of $\mathrm{Amp}_{\mathrm{mean}}$ appeared to be a too stringent condition. Therefore, a new image cleaning of 4/7 was introduced for the treatment of simulated data acquired in moonlight condition. The corresponding energy threshold is higher compared to dark conditions, at about 80 GeV, however the moonlight sensitivity almost recovers the level under low NSB at higher energies. The expected angular and energy resolutions are roughly not affected by moonlight. Same results are found for other array candidates for CTA. This good performance of CTA with high NSB indicates that it is possible to observe even when the Moon is partially present, increasing the observing time and mainly the continuity of the light curves. The expected gain for the duty cycle is about 30%, corresponding to a total observing time of $\sim$1300 h per year.

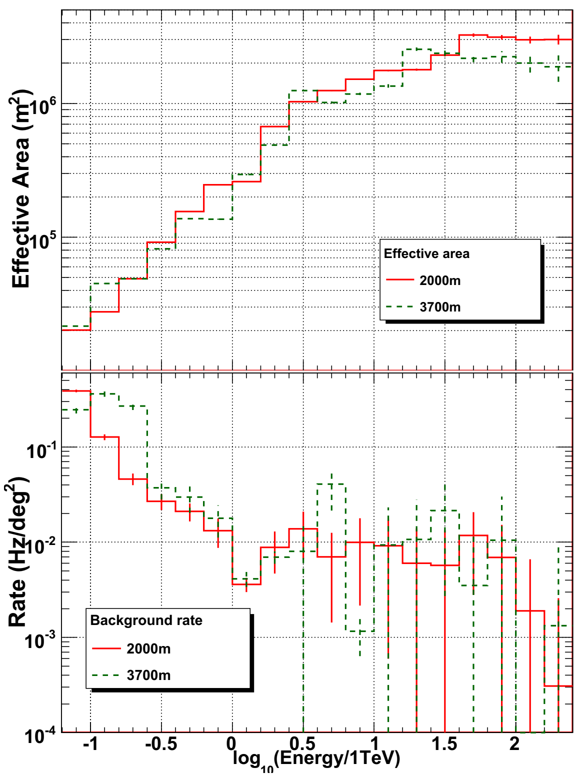

Figure 5: Effective area for the CTA candidate array E of gamma rays (*top*) and background rate (*bottom*) after cuts for standard and high altitude sites.

5 High altitude performance

A consequence of a high altitude site for CTA is to reduce the typical distance to the shower maximum and hence increase the density of Cherenkov light at the observation level and reduce the energy threshold somewhat. This is due to the smaller diameter of the light pool, which in general will also lead to reduced effective area and/or telescope multiplicity, which may degrade performance at high energies. To study this effect in detail and help in the selection of the CTA a set of shower simulations has been performed for a site located at 3700 m above sea level (a.s.l). Data are analyzed using the same 5/10 image cleaning described in the previous section. For energies above few hundred GeV, the results of the high altitude simulations show that for identical array layout, the collection area and background rate follow the same trend of the simulations performed for at 2000 m a.s.l. array (Fig. 5). Consequently, the sensitivities in the energy range between few hundred GeV and few tens of TeV at the two altitudes are comparable within a factor of 2. The angular resolution does not significantly differ from the one for a site at 2000 m. For very high energy showers (E>10 TeV), the energy resolution degrades with respect to the 2000 m altitude performance for some array layouts.

6 Conclusions

Monte Carlo simulations are crucial to define the array and telescope configuration (including number of telescopes, spacing and layout, mirror diameter, optical psf and pixel size) necessary to get the required performance in the relevant energy range. The array design must therefore be driven by simulation results, but with constant feedback on costs and feasibility from the technical work packages. At the moment the Monte Carlo work has helped to define many of the key parameters of the telescopes to be built (in particular for the mid-sized telescope). However, many challenges remain in this area, including the comparison of dual mirror and single mirror designs for the SST and also at intermediate energies. New methods of reconstruction, based on image time gradients or on image fits from a EAS model, advanced gamma/hadron separation methods, using new discrimination variables and Multi Variate Analysis [11, 12], give already significantly better sensitivities and will be used to test of influence of the site altitude on the performance.

Acknowledgements

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