Progress in Monte Carlo design and optimization of the Cherenkov Telescope Array

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Abstract: The Cherenkov Telescope Array (CTA) will be an instrument covering a wide energy range in very-high-energy (VHE) gamma rays. CTA will include several types of telescopes, in order to optimize the performance over the whole energy range. Both large-scale Monte Carlo (MC) simulations of CTA super-sets (including many different possible CTA layouts as sub-sets) and smaller-scale simulations dedicated to individual aspects were carried out and are on-going. We summarize results of the prior round of large-scale simulations, show where the design has now evolved beyond the conservative assumptions of the prior round and present first results from the on-going new round of MC simulations.

Keywords: Cherenkov telescopes, Monte Carlo simulations, VHE gamma-ray astronomy

1 Introduction

The Cherenkov Telescope Array (CTA) [1, 2] is planned as the next big step in ground-based very-high-energy (VHE) gamma-ray astronomy, with one installation planned in the southern hemisphere and one in the northern hemisphere. Not only will it enhance the sensitivity by about an order of magnitude over existing instruments but also cover a very large energy range of about four orders of magnitude, the latter at least at the southern site. The most cost-efficient way to achieve these goals is to build CTA with several types of Cherenkov telescopes - a few large-size (and expensive) telescopes (LSTs) for detecting and measuring low-energy showers, a rather large number of mid-size telescopes (MSTs) for the core of the energy range, plus an even larger number of small-size telescopes (SSTs) for energies in the tens to hundreds of TeV. It may eventually be extended with further types of telescopes – currently foreseen are high angular resolution MST-class telescopes of Schwarzschild-Couder type optics (SC-MST) [3].

The evaluation of the expected performance of the different telescope designs, of sub-arrays of equal telescopes (LSTs/MSTs/...) as well as the combined performance of the whole CTA instruments planned for the southern and northern hemispheres is evaluated by the Monte-Carlo simulation method. These simulations are using CORSIKA [4] for the simulation of the particle showers in the atmosphere and `sim_telarray` [5] for the detector simulation. Different analysis methods have been applied to the resulting data. See [6] for more details.

2 Monte Carlo simulations

The simulations for an instrument like CTA require substantial computing resources, in particular for simulating enough background events (mainly proton-induced showers), due to the excellent gamma-hadron discrimination and angular resolution of the instrument. Apart from a small number of initial simulation sets for demonstrating that the expected performance of CTA is not unreasonable and a large number of small-scale simulations for optimization of the individual telescope types, the main effort has gone and is still going into two large-scale simulation sets.

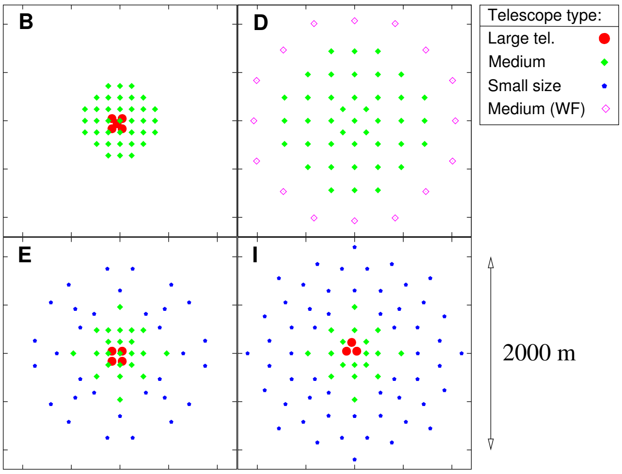

Fig. 1: A selection of layout candidates for a southern CTA site. Top row: Array 'B' (best low-energy performance) and Array 'D' (best high-energy performance). Bottom row: Intermediate layouts with the best overall physics performance, Arrays 'E' and 'I', the latter with 3 LSTs of 412 m^2 mirror area, 18 MSTs of 100 m^2, and 56 SSTs of 37 m^2.

The first one, termed *prod-1*, was based on initial and conservative assumptions of telescope parameters. It was carried out for hypothetical sites at altitudes of 2000 m and 3700 m, respectively. Part of these simulations were set up to correspond to an elevated nightsky background, corresponding to partial moon light. In all of these prod-1 simulations a total of 275 telescopes was simulated, including five different types of telescopes. The performance parameters as evaluated for many different subsets, each matching a given cost envelope, were subjected to many different astrophysical test cases. These tests narrowed down the configurations or layouts with overall best performance to a class of *intermediate layouts*, although individual astrophysical problems could be be better studied with more compact or more widely spaced arrays. The preferred intermediate-layout candidate, 'Array I', is illustrated in Figure 1. See [6] for the overall prod-1 layout, the assumed telescope types, and details of evaluated subsets.

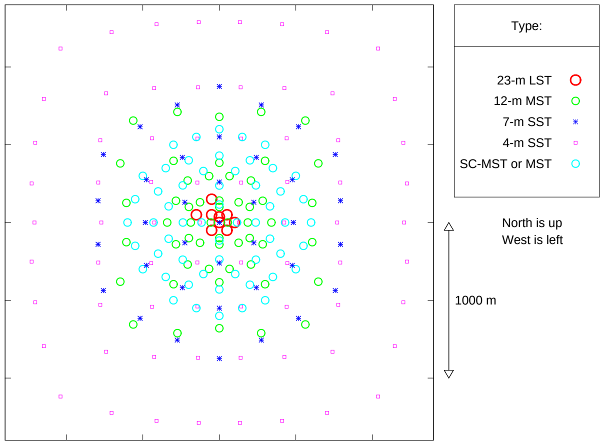

Fig. 2: The layout of telescope positions included in the prod-2 round of large-scale simulations for CTA design and optimization.

The second round, *prod-2*, takes these results into consideration in the layout of its 229 telescope positions, some of them used for more than one type of telescope. A total of seven different types of telescopes are included in the simulations (two different types of MSTs and four different types of SSTs). See Figure 2 for the overall prod-2 layout. Telescope parameters were also adapted to current designs, including optical design, camera design, photosensor parameters, as well as trigger and readout. For several telescope types the simulations handle different kinds of telescope-level triggers in parallel, such that they can be evaluated and compared at the level of final instrument performance – like sensitivity. The prod-2 simulations are currently being carried out for three different candidate sites at altitudes between 1600 and 3600 m. While prod-1 only recorded one ADC sum per read-out channel, the prod-2 data includes traces (samples) of pulses in all pixels, allowing for more advanced signal measurement methods.

3 Analysis

Several sets of analysis tools [6] were used to process the MC data and to evaluate the expected instrument performance. Some of these tools were derived from the analysis tools of current Cherenkov telescope systems like H.E.S.S., MAGIC, and VERITAS, while others were developped mainly for the purpose of CTA MC data analysis. The baseline analysis method is basically following traditional Hillas-parameter based stereo analysis methods, with a few additional gamma-hadron selection cuts. Figure 3 shows the expected sensitivity of the intermediate-layout 'Array I' subset of prod-1 derived with the baseline analysis method, for 50 hours of observation time. Some of the advanced analysis methods make use of additional information like the time gradient along the images or image profiles, some apply simultaneous fits to all images. All of the advanced methods use some machine-learning method like Neural Networks, Random Forrest, or Boosted Decision Trees for gamma-hadron selection. As a result, the advanced methods

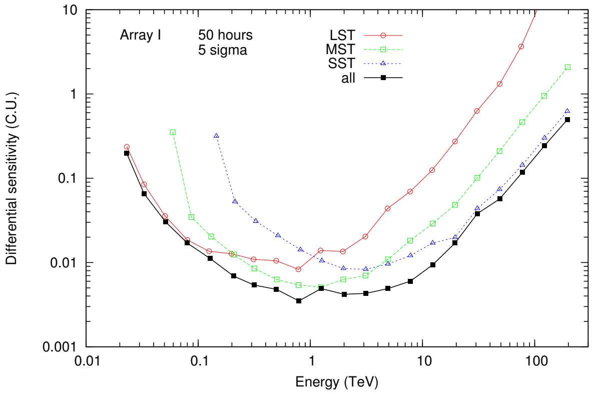

Fig. 3: On-axis differential point source sensitivity of one subset of prod-1 ("Array I", solid black line with filled squares) and its components, 3 LSTs (red, open circles), 18 MSTs (green, open squares), 56 SSTs (blue, open triangles) in 50 hours of observation time, as derived with the baseline analysis method at 20° zenith angle, for a site at 2000 m altitude. Differential sensitivity here assumes an independent detection (5 sigma significance, ≥10 excess events, and more than 5% of the remaining background) in each energy bin. One Crab Unit (C.U.) here is $2.79 \cdot 10^{-7}/(\mathrm{m}^2\ \mathrm{s\ TeV}) \times (E/\mathrm{TeV})^{-2.57}$.

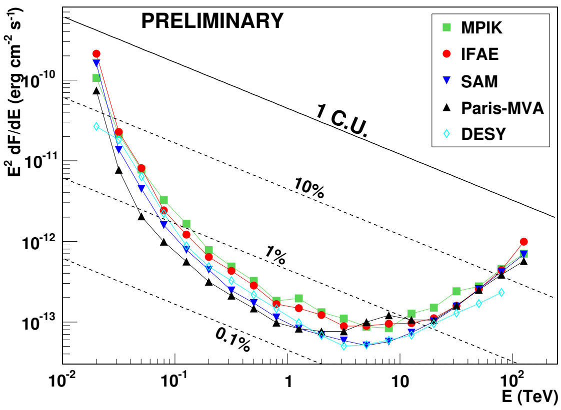

Fig. 4: Differential flux sensitivity of layout candidate 'Array I' given as a function of the estimated energy, for the baseline/MPIK (green squares), IFAE (red circles), SAM (blue downward triangles) and Paris-MVA (black upward triangles) analyses [6] as well as the DESY analysis (cyan diamonds) [7]. The Crab Unit (C.U.) flux (solid black line) is shown for comparison, together with its 10%, 1% and 0.1% flux levels (black dashed lines). The differential sensitivities are optimized for an observation time of 50 h.

can achieve quite substantial improvements in sensitivity as compared to the baseline analysis method, at least in parts of the wide CTA energy range. A comparison of the expected sensitivity for 'Array I' in different analyses is shown in Figure 4.

4 Selected results from prod-1 simulations

The prod-1 round of simulations demonstrated that the initial expectations on the CTA performance were quite realistic, except perhaps at the lowest energies where gamma-hadron selection capabilities are limited by shower fluctuations and possible systematical errors in the subtraction of remaining backgrounds have to be taken into account. As Figure 3 demonstrates, CTA will achieve a high sensitivity down to energies of about 20 GeV, even with the very conventional photo-multipliers assumed in prod-1 simulations, with the few LSTs being responsible for the sensitivity below 100 GeV, where the MSTs start taking over. While SST-s of the 7-m class could have thresholds as low as 200 GeV, their wide separation prevents high-quality data from SSTs alone below a few TeV. The sensitivity can be expected to be dominated by the MSTs between about 200 GeV and 4 TeV, with MSTs dominating to even higher energies when high quality data is required for the best possible angular resolution. Above a few TeV – depending on the implementation – the much larger area covered by the SSTs (at the southern site) results in effective detection areas growing to several square kilometers, for some layout candidates close to 10 km^2.

An important aspect of CTA simulations is related to site-selection criteria, in particular the altitude of the observatory but also the geomagnetic field. A high-altitude site has, in terms of energy threshold, the benefit of being closer to the shower maximum, as discussed in more detail below. A large magnetic field, on the other hand, deflects charged particles, spreading out the resulting Cherenkov light over a larger area and hampering the shower reconstruction and gamma-hadron discrimination. For a study of the combined impact of altitude and geomagnetic field on the energy threshold of CTA see [8], based on simulations of four LSTs. The impact of different site altitude alone on a full CTA installation is illustrated in Figure 5 for the four layout candidates shown in Figure 1 and discussed in more detail below.

5 Work in progress

The prod-2 round of CTA MC production is well on the way, with simulations for the first two of initially planned three candidate sites being close to complete and simulations for the third candidate site ongoing (expected to be complete by mid-2013). The main bulk of these simulations is intended for evaluation of the relative advantages of different site altitudes at different energies, extending the altitude studies from prod-1 shown in Figure 5. The lowest energies are seen to benefit from a high-altitude site – being closer to the shower maximum, and the Cherenkov light less spread out as a consequence, the energy threshold will always be lower at a high altitude. At higher energies – already below 100 GeV – the situation gets more complex since at a very high altitude (above 4000 to 5000 m) more and more particles may reach ground level, complicating the shower reconstruction and gamma-hadron discrimination. Most of these ground-level particles appear close to the shower axis while multi-TeV showers can be observed at larger impact parameters. For these high energies, a high-altitude site is clearly a disadvantage since the lateral distribution of Cherenkov light falls off more rapidly at high altitudes (smaller detection area) and light from the shower maximum is seen at larger angles w.r.t. the shower direction (large instrument field-of-view required, with cost implications). The main task of the prod-2 round will be to find a good

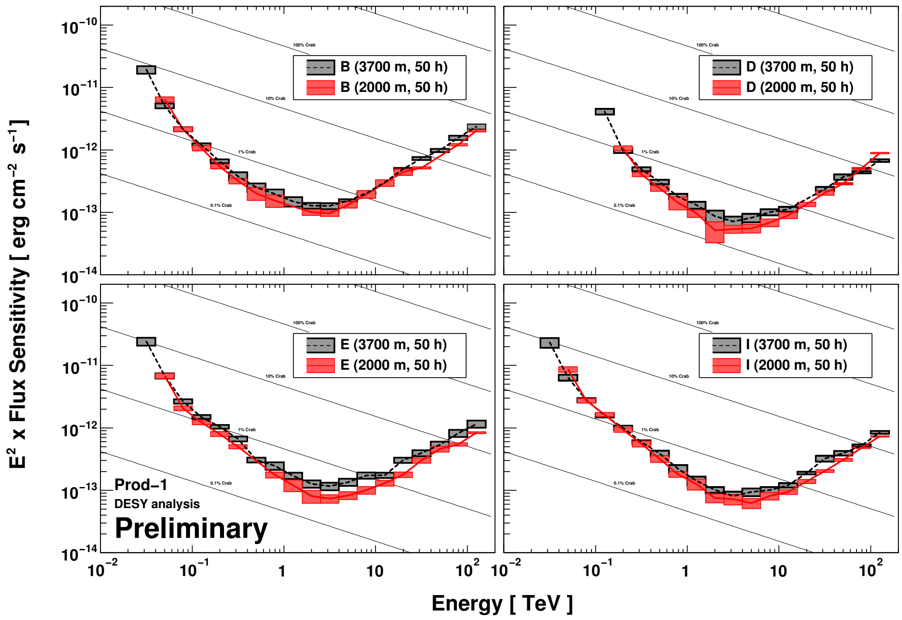

Fig. 5: Differential sensitivity of the four layout candidates from Figure 1 at 2000 m altitude (red, solid line) and 3700 m (black, dashed line), based on the DESY analysis (20° zenith angle, 50 h observation time). Apart from the different altitude, the simulations are for the same hypothetical site configuration.

compromise between the lowest possible energy threshold and the largest possible high-energy detection area, at any given cost of a CTA installation.

Another aspect related to the CTA site selection process is the evaluation of the performance penalty for a site with elevated nightsky brightness. For this purpose, some of the simulations are being reprocessed for a NSB brightness elevated by up to a factor of three.

In addition, some of the simulations include alternate instrument set-ups, matching latest designs, in order to evaluate the relative merits to be expected from these designs. These include three different options of 4-m class SSTs [9, 10, 11] (in addition to a 7-m class SST type) as well as the 9-m class mid-size telescopes with Schwarzschild-Couder dual-mirror optics (SC-MSTs) [3]. An extension of the southern CTA site by 36 SC-MSTs is being considered and would result in a substantial sensitivity improvement in the key energy range between 300 GeV and 3 TeV [12].

A longer-term task is the continuing improvement of reconstruction, calibration and analysis methods for the CTA observatory. In terms of reconstruction includes the best possible measurement of the original direction and energy of incoming gamma rays and the discrimination between gamma rays and the background by other particles, in an installation with several different types of telescopes. In comparison to current instruments, with different telescopes at different sites, the calibration of CTA telescope systems benefits from the cross-calibration capability between the different telescope types at the same site. In addition, current practices for the calibration of the instruments can be (and will be) improved through better monitoring of atmospheric conditions and instrument response, also checking how well simulations correspond to measured conditions, and how remaining deviations can be accounted for in the analysis.

6 Conclusions

With the previous (prod-1) and the current (prod-2) simulation rounds, the CTA design and layout optimization can be expected to yield quantitative results on the merits of different site altitudes, over the complete energy regime to be covered by the Cherenkov Telescope Array. The prod-2 round will also provide a comparison of different options for the smaller size telescopes, in terms of expected performance of the full instrument. Finally, the recording of traces for all pixels in the prod-2 telescopes should help to settle the question how large the benefit of a more advanced signal measurement (implying larger data rates and more computing efforts) will be on the overall CTA instrument performance.

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