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Monte Carlo comparison of medium-size telescope designs for the Cherenkov Telescope Array

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Abstract: The Cherenkov Telescope Array (CTA) is a future very high energy gamma-ray observatory. CTA will be comprised of small-, medium- and large-size telescopes covering an energy range from tens of GeV to hundreds of TeV and will surpass existing telescopes in sensitivity by an order of magnitude. The aim of our study is to find the optimal design for the medium-size telescopes (MSTs), which will determine the sensitivity in the key energy range between a few hundred GeV to about ten TeV. To study the effect of the telescope design parameters on the array performance, we simulated arrays of 61 MSTs with 120 m spacing and a variety of telescope configurations. We investigated the influence of the primary telescope characteristics including optical resolution, pixel size, and light collection area on the total array performance with a particular emphasis on telescope configurations with imaging performance similar to the proposed Davies-Cotton (DC) and Schwarzschild-Couder (SC) MST designs. We compare the performance of these telescope designs, especially the achieved gamma-ray angular resolution and differential point-source sensitivity. Finally we investigate the performance of different array sizes to demonstrate impacts of financial constraints on the number of telescopes.

Keywords: CTA, gamma-rays, monte carlo, simulations

1 Introduction

The Cherenkov Telescope Array (CTA) is the future next generation Imaging Atmospheric Cherenkov Telescope (IACT) observatory. CTA aims to surpass the current IACT systems like HESS, MAGIC and VERITAS by an order of magnitude in sensitivity and enlarge the observable energy range from a few tens of GeV to far beyond one hundred TeV [1]. To achieve this broad energy range and high sensitivity, CTA will be comprised of three different telescope sizes. These are denoted according to their mirror diameter into large-size telescopes, medium-size telescopes (MSTs), and small-size telescopes.

In this paper we investigate the effect of the optical point-spread function and the camera pixel size on the achievable point-source sensitivity. We investigate MSTs since they are most sensitive in the energy range where the best angular resolution is achieved and small pixels sizes are most feasible.

The main motivation for this study is to determine if the current, well-tested single-mirror design (Davies-Cotton, DC) or a new two-mirror design (Schwarzschild-Couder, SC) would be the best choice for the medium-size CTA telescopes. The SC telescopes can achieve much smaller optical point-spread function (PSF), minimal aberrations over a wider field of view, and a smaller plate scale, allowing for a more compact camera. However, SC telescopes require many more readout channels and more complicated mirror designs that increase their price compared to a DC telescope with similar mirror area. We simulate idealized telescope parameters for both designs and compare their gamma-ray PSF and point-source sensitivity. We also investigate the sensitivity of arrays with different numbers of telescopes with a specific focus on the performance of arrays with and without a US contribution of 36 telescopes.

2 Simulations

Gamma-ray and proton air showers were simulated with the CORSIKA Monte Carlo (MC) package [2] and the QGSJet-II hadronic interaction model [4]. Simulations were performed for an array at an elevation of 2000 m and geomagnetic field configuration similar to the proposed southern hemisphere sites. Showers were simulated at 20° zenith angle over the energy range from 10 GeV to 30 TeV. All simulations use the same array layout comprising 61 telescopes forming a square with 120 m inter-telescope spacing. Each array is composed of identical telescopes. To study the performance of a reduced array without a US contribution we additionally simulated a 21 telescope array by using a subset of telescopes from the 61 telescope layout (see Figure 1).

2.1 Telescope Designs

We simulated a range of optical PSFs and pixel sizes that bracket the imaging performance of the DC- and SC-like telescope designs. The proposed designs for the DC- and SC-MST have a 68% optical PSF containment radius (R_{68}) of 0.04°-0.1° over the FoV and 0.02°-0.04° over the FoV, respectively. The simulated pixel sizes (R_{pix}) are between 0.06° and 0.16°. We use the configurations with R_{68}/R_{pix} of 0.08°/0.16° and 0.02°/0.06° as representative of configurations with DC- and SC-like imaging performance, respectively. For both configurations we assume a field of view of 8°.

Besides imaging resolution, the other important characteristic of the telescope optical system is the total effective light collection area,

$$A_{\text{opt}}(\lambda_0,\lambda_1) = A_M \int_{\lambda_0}^{\lambda_1} P(\lambda)\varepsilon(\lambda)d\lambda, \qquad (1)$$

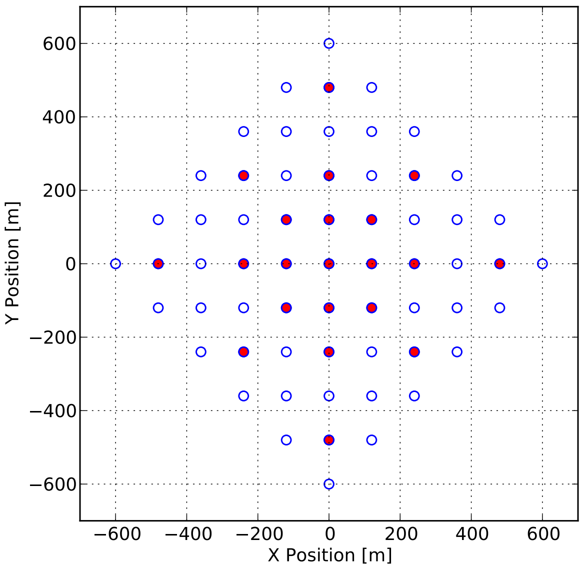

Figure 1: Comparison of the telescope positions of the two simulated array geometries with 61 telescopes (open blue circles) and 21 telescopes (filled red circles).

which is the product of the mirror area (A_M) with the weighted average of the optical efficiency ($\varepsilon(\lambda)$) with a Cherenkov-like spectral distribution ($P(\lambda)$). We compute the effective light collection area over the wavelength interval of 250 nm to 700 nm and a Cherenkov spectral distribution calculated for an emission height of 10 km. We simulated two telescope configurations chosen to be representative of DC- and SC-MST designs of equal cost. Both telescopes have an aperture of 10 m and $A_{\rm opt}$ of 6.3 m^2 (SC-MST) and 14.9 m^2 (DC-MST).

2.2 Trigger and DAQ

A simplified detector model is used to simulate the time-integrated signal in each pixel. The pixel signal is the sum of the detected Cherenkov photo electrons (phes) and a noise component modeled as the sum of a Poisson-distributed NSB term and a Gaussian-distributed electronics noise term with an RMS of 0.1 phe per channel. The mean NSB amplitude in each pixel is $\Delta\Omega(A_{\rm opt}/11.8\ {\rm m}^2) \times (100\ {\rm phe\ deg}^{-2})$ where $\Delta\Omega$ is the pixel solid angle. The NSB amplitude was chosen to be representative of the sky brightness of an extragalactic observation field and an integration gate of 10 ns. Each telescope camera containing more than 60 phe is assumed to trigger, and at least two telescopes must trigger to produce an array trigger. All array triggered events are further processed.

2.3 Analysis

Reconstruction of the telescope image data into event-level parameters proceeds in three stages. First, an image cleaning is performed to select pixels with statistically significant signal amplitude. The shower trajectory is then reconstructed using a geometric analysis of the moments of the light distribution in each camera. Finally, a likelihood-based reconstruction is performed using templates for the light distribution in each telescope derived from MC simulations. In addition to the event trajectory and energy, a number of parameters useful for gamma-hadron discrimination are calculated such as the goodness-of-fit of the telescope images with respect to the image templates. Background suppression is performed with the TMVA boosted decision tree (BDT) method [3]. The decision trees (DTs) are trained with independent samples of simulated gamma-ray and proton events. Energy-dependent cuts on the BDT output variable and θ^2, the squared angular separation between the reconstructed and source directions, are optimized under the assumption of a point-like source distribution with an intensity equal to 1% of the Crab Nebula flux.

2.4 Telescope array layouts

The price for an individual telescope and the total budget of CTA are not yet finalized, so we investigated possible array configurations with reduced number of telescopes. The array layouts comprise of 21, 25, 41 and 61 Telescopes. These studies demonstrate that the number of telescopes has a significant impact on the total sensitivity regardless of the telescope type. The number of telescopes are chosen to match the MST number in the CTA configuration I and E [5] and the extension of I and E by up to 36 US telescopes. In the case of the configuration I we replaced the 4 Large-size telescopes with medium-size telescopes. The final CTA layout will have a much better sensitivity at low Energies ($E < 100$ GeV) and above 3 TeV due to the large- and small-size telescopes.

3 Results & Conclusions

The gamma-ray PSF improves when reducing the pixel size as long as the optical PSF is smaller than the pixel size. The SC-like telescope array shows a 40% improved gamma-ray PSF compared to the DC-like telescopes at all energies (see Fig. 2). Figure 3 shows that the SC-like array has a 30–40% better differential point-source sensitivity relative to the DC-like array at energies above 100 GeV which is mainly due to the improved gamma-ray PSF. Below 100 GeV the smaller light collection area of the SC-like telescope configuration is a disadvantage resulting in a higher reconstruction energy threshold and an equal or slightly worse differential sensitivity.

While the SC-like array is more sensitive compared to the DC-like array, no SC telescope has been built to date. The results presented here provide encouragement to build an SC prototype telescope to test if the performance can be achieved under realistic conditions. However, our studies show that the extension of the array by the US contribution will improve the sensitivity of CTA in its key energy range (0.3 to 3 TeV) by a factor of 2–3 depending on the type of telescopes choosen. That would reflect in an decrease of observation time by a factor 4–9 and would allow the study of many more objects or a much faster survey of the gamma-ray sky.

4 Acknowledgments

We gratefully acknowledge support from the agencies and organizations listed in this page: `http://www.cta-observatory.org/?q=node/22`

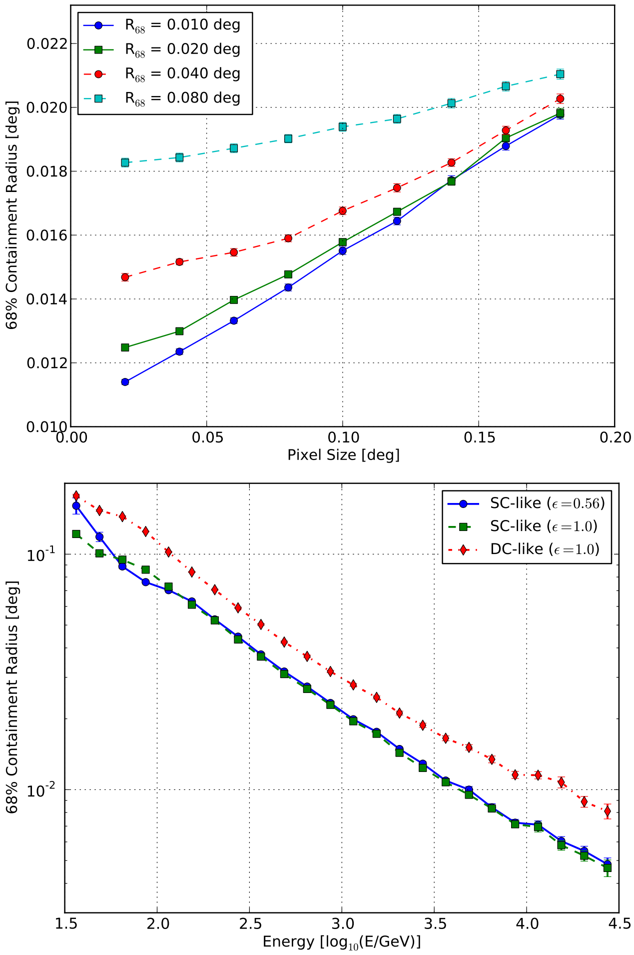

Figure 2: **Top:** 68% containment radius of the gamma-ray PSF at 1 TeV versus pixel size shown for a 61 telescope MST array composed of telescopes with increasing 68% optical PSF containment radii: 0.01° (blue circles and solid line), 0.02° (green squares with solid line), 0.04° (red circles and dashed line), 0.08° (cyan squares and dashed line). **Bottom:** 68% containment radius of the gamma-ray PSF versus gamma-ray energy for an array composed of telescopes with SC-like imaging performance with effective light collection area scaled by 0.56 (blue circles and solid line) and 1.0 (green squares and dashed line) and a DC-like imaging performance (red diamonds and dot-dashed line).

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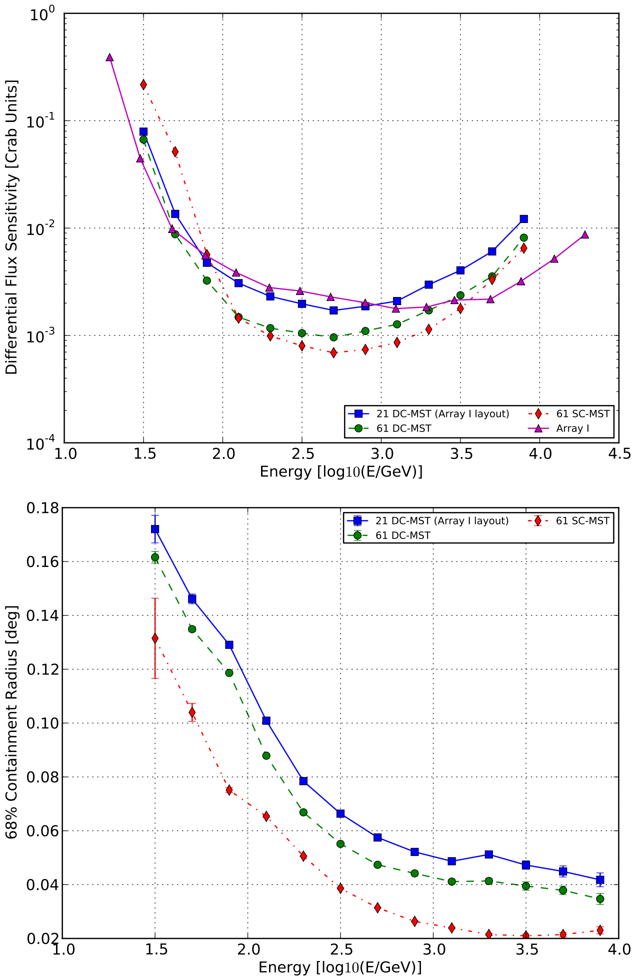

Figure 3: **Top:** Differential point-source sensitivity for an array of 21 DC-MSTs (blue squares and solid line), 61 DC-MSTs (green circles and dashed line), 61 SC-MSTs (red diamonds and dot dashed line), and one of the proposed CTA designs (array I) with 18 DC-like MSTs [5] (magenta triangles and solid line). The array I comprises large-size and small-size telescopes not included in our simulation. **Bottom:** 68% containment radius of the gamma-ray PSF versus gamma-ray energy for the three array configurations shown in the left figure.