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

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ABSTRACT

We present studies for optimizing the next generation of ground-based imaging atmospheric Cherenkov telescopes (IACTs). Results focus on mid-sized telescopes (MSTs) for CTA, detecting very high energy gamma rays in the energy range from a few hundred GeV to a few tens of TeV. We describe a novel, flexible detector Monte Carlo package, FAST (FAst Simulation for imaging air cherenkov Telescopes), that we use to simulate different array and telescope designs. The simulation is somewhat simplified to allow for efficient exploration over a large telescope design parameter space. We investigate a wide range of telescope performance parameters including optical resolution, camera pixel size, and light collection area. In order to ensure a comparison of the arrays at their maximum sensitivity, we analyze the simulations with the most sensitive techniques used in the field, such as maximum likelihood template reconstruction and boosted decision trees for background rejection. Choosing telescope design parameters representative of the proposed Davies–Cotton (DC) and Schwarzchild–Couder (SC) MST designs, we compare the performance of the arrays by examining the gamma-ray angular resolution and differential point-source sensitivity. We further investigate the array performance under a wide range of conditions, determining the impact of the number of telescopes, telescope separation, night sky background, and geomagnetic field. We find a 30–40% improvement in the gamma-ray angular resolution at all energies when comparing arrays with an equal number of SC and DC telescopes, significantly enhancing point-source sensitivity in the MST energy range. We attribute the increase in point-source sensitivity to the improved optical point-spread function and smaller pixel size of the SC telescope design.

1. Introduction

The ground-based imaging atmospheric Cherenkov telescope (IACT) technique has led to significant progress in the field of very high energy (VHE; $E > 100$ GeV) gamma-ray astronomy over the last 25 years. To date, 145 sources have been detected at VHE with ~60 sources discovered only in the last five years.[1] IACTs allow us to study a wide range of scientific topics, many uniquely accessible by VHE astronomy. Current and future generations of IACTs aim to probe the origins and acceleration processes of cosmic rays [1–3] and explore the nature of black holes and their relativistic jets. Other key objectives include the search for dark matter, axion-like particles [4,5], and Lorentz invariance violation [6]. This will require extensive observations on a number of source classes such as pulsars and pulsar wind nebulae [7], galactic binaries [8], supernova remnants [9], active galactic nuclei [10,11], and gamma-ray bursts [12,13]. The extragalactic sources can be used as “backlights” to study the attenuation on the extragalactic background light, useful for constraining star formation history and other cosmological parameters such as the Hubble constant [14].

VHE gamma rays entering the Earth’s atmosphere undergo e^+e^- pair production, initiating electromagnetic cascades. The relativistic charged particles in the shower emit Cherenkov ultraviolet and optical radiation, which is detectable at ground level. The majority of the emitted Cherenkov light is narrowly beamed along the trajectory of the gamma-ray primary in a cone with an opening angle of ~1.0°. Due to the beaming effect, the majority of the Cherenkov light falls within a Cherenkov light pool with a diameter of 200–300 m and a nearly constant light density. By imaging the Cherenkov light emitted by the shower particles, IACTs are able to reconstruct the direction and energy of the original gamma ray and to distinguish gamma rays from the much more prevalent cosmic-ray background. High

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[1] http://tevcat.uchicago.edu/ .

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resolution imaging of the Cherenkov shower offers significant benefits for IACTs by enabling a more accurate measurement of the shower axis which has an intrinsic transverse angular size of only a few arcminutes. However the finite shower width and stochastic fluctuations in the shower development fundamentally limit the performance of IACTs.

The designs of IACTs are governed by a few key factors. At low energy, the number of Cherenkov photons compared to the night sky background necessitates a large $\mathcal{O}(10\text{–}20\ \mathrm{m})$ mirror diameter and high quantum efficiency camera. The camera must also be able to capture the signal very quickly since the duration of a Cherenkov pulse can be as short as a few nanoseconds. The optical point-spread function (PSF) and camera pixel size should ideally be suitably smaller than the angular dimension of the gamma-ray shower. However the high cost-per-pixel of camera designs used in current generation IACTs has generally dictated pixel sizes that are significantly larger ($0.1°\text{–}0.2°$) than the angular size of shower structure. Multiple viewing angles of the same shower offered by an array of telescopes drastically improves the reconstruction performance and background rejection. Finally, at high energy, the sensitivity of IACTs is limited by gamma-ray signal statistics, requiring an array with a large effective gamma-ray collection area.

All current generation IACTs are based on single-dish optical systems. These have small spherical mirror facets attached to either a spherical dish (i.e. Davies–Cotton (DC) [15,16]) or a parabolic dish. The parabolic dish reduces the time spread of the Cherenkov signal but introduces a larger off-axis optical PSF. An intermediate design with a spherical dish but a larger radius of curvature (intermediate-DC) can be used to achieve an improved time spread while maintaining off-axis performance [17,18]. These single-dish designs are appealing because they are relatively inexpensive, mirror alignment is straightforward, and the optical PSF at large field angles is better than that of monolithic spherical or parabolic reflectors [19].

The possibility of improving the PSF (especially off axis) and reducing the plate scale of IACTs has driven the study of Schwarzschild–Couder (SC) aplanatic telescopes with two aspheric mirror surfaces.[2]. The improved PSF across the field of view (FoV) allows for more accurate surveying and mapping of extended sources. The reduced plate scale is highly compatible with new camera technologies such as silicon photomultipliers or multi-anode photomultiplier tubes. These technologies allow for a cost-effective, finely-pixelated image over a large FoV. Studies have been performed providing solutions for mirror surfaces optimized to correct spherical and coma aberrations. These solutions are also isochronous, allowing for a short trigger coincidence window [20]. The first SC prototype is still being developed [21] and has several challenges to overcome. In particular, the tolerances of the mechanical structure in the camera and mirror alignment system are relatively stringent, which translates to a higher cost. To provide comparisons at a fixed cost, our SC simulations use a smaller mirror area than that of the baseline DC design.

The Cherenkov Telescope Array (CTA) is an example of a next-generation IACT observatory. CTA aims to surpass the current IACT systems such as H.E.S.S. [22], MAGIC [23] and VERITAS [24] by an order of magnitude in sensitivity and enlarge the observable energy range from a few tens of GeV to beyond one hundred TeV [25]. To achieve this broad energy range and high sensitivity, CTA will incorporate telescopes of three different sizes spread out over an area of $\sim 3\ \mathrm{km}^2$. Telescopes are denoted by their mirror diameter as large-size telescopes (LSTs, $\sim$24 m), medium-size telescopes (MSTs, $\sim$12 m), and small-size telescopes (SSTs, $\sim$4 m in the current design). The baseline designs for the LST and MST both feature a single reflector based on the DC optical design. Telescope designs based on dual-reflector SC optics are also being developed for both medium- and small-sized telescopes. The medium-size SC telescope (SCT) would fill a similar role to the MST and predominantly contribute to the sensitivity of CTA in the energy range between 100 GeV and 1 TeV. In this paper we explore a range of telescope models but focus primarily on the comparison of designs with characteristics similar to the MST and SCT. In the subsequent discussion we use MST to refer to all telescope designs with a primary mirror diameter of 9–12 m. DC-MST and SC-MST are used to specifically refer to telescopes with the imaging characteristics similar to the MST and SCT designs, respectively.

The baseline design of CTA includes $\sim$4 LSTs, $\sim$30 MSTs, and $\sim$50 SSTs. The sensitivity could be improved by a factor of 2–3 in the core energy range by expanding the MST array with an additional 24–36 SCTs. With these additional telescopes, the combined MST and SCT array enters a new regime where the internal effective area is comparable to the effective area of events landing outside the array. These so-called contained events have much improved angular and energy resolution as well as background rejection. Extensive work is underway to optimize the design of CTA for the wide range of science goals [18]. The scope of previous studies has been primarily on a straightforward expansion of existing telescope designs to larger arrays.

In this paper, we describe a novel, flexible Monte Carlo simulation and analysis chain. We use them to evaluate the performance of CTA-like arrays over a large range of telescope configurations and design parameters. Section 2 describes this simulation and the simplified detector model. In Section 3, we explain the analysis chain, including a maximum likelihood shower reconstruction using simulated templates. This reconstruction was used for comparisons between the maximum sensitivity for each array configuration. In Section 4, we show comparisons between possible CTA designs, focusing primarily on the number of telescopes and the DC versus SC designs. We conclude in Section 5.

2. Simulation

We have studied the performance of a variety of array geometries and telescope configurations for a hypothetical CTA site at an altitude of 2000 m. Details of the site model and array geometry are described in Sections 2.1 and 2.2. Simulations of the telescope response were performed using a simplified detector model described in Section 2.3.

2.1. Air-shower simulations

Simulations of the gamma-ray and cosmic-ray air shower cascades were performed with the CORSIKA v6.99 Monte Carlo (MC) package [26] and the QGSJet II-03 hadronic interaction model [27]. We used a site model with an elevation of 2000 m, a tropical atmospheric profile, and an equatorial geomagnetic field configuration with $(B_x, B_z) = (27.5\ \mu\mathrm{T}, -15.0\ \mu\mathrm{T})$. This site model is identical to the one used in [18] and has similar characteristics to the southern hemisphere sites proposed for CTA.

Gamma-ray showers were simulated as coming from a point on the sky at 20° zenith angle and 0° azimuth angle, as measured from the local magnetic north over the energy range from 10 GeV to 30 TeV. Protons and electrons were simulated with an isotropic distribution that extends to 8° and 5° respectively from the direction of the gamma-ray primary. We use the spectral parameterizations for proton and electron fluxes from [28]. To account for the contribution of heavier cosmic-ray nuclei we increase the proton flux by a factor 1.2.

2.2. Array geometry

Proposed designs for CTA employ three telescope types (SST, MST, and LST) with variable inter-telescope spacing from 120 m to more than 200 m [18]. The number of telescopes of each type and their

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[2] Though segmented, the mirror surfaces are often referred to as a singular mirror for brevity.