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Monte Carlo simulations of alternative sky observation modes with the Cherenkov Telescope Array

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ABSTRACT

We investigate possible sky survey modes with the Middle Sized Telescopes (MST, aimed at covering the energy range from ~100 GeV to 10 TeV) subsystem of the Cherenkov Telescope Array (CTA). We use the standard CTA tools, `CORSIKA` and `sim_telarray`, to simulate the development of gamma-ray showers, proton background and the telescope response. We perform simulations for the H.E.S.S.-site in Namibia, which is one of the candidate sites for the CTA experiment. We study two previously considered modes, parallel and divergent, and we propose a new, convergent mode with telescopes tilted toward the array center. For each mode we provide performance parameters crucial for choosing the most efficient survey strategy. For the non-parallel modes we study the dependence on the telescope offset angle. We show that use of both the divergent and convergent modes results in potential advantages in comparison with use of the parallel mode. The fastest source detection can be achieved in the divergent mode with larger offset angles (~6° from the field of view center for the outermost telescopes), for which the time needed to perform a scan at a given sensitivity level is shorter by a factor of ~2.3 than for the parallel mode. We note, however, the direction and energy reconstruction accuracy for the divergent mode is even by a factor of ~2 worse than for other modes. Furthermore, we find that at high energies and for observation directions close to the center of the array field of view, the best performance parameters are achieved with the convergent mode, which favors this mode for deep observations of sources with hard energy spectra.

1. Introduction

Imaging Air Cherenkov Telescopes (IACT) detect gamma rays using the Cherenkov images of their electromagnetic showers developing in the atmosphere. The IACT technique has rapidly progressed over the last 20 years (see, e.g., a review in [1]) and, with the current generation of IACT instruments [2–4], it is now the most accurate and sensitive detection technique in the very high energy gamma-ray astronomy. The Cherenkov Telescope Array (CTA), the next generation of IACT detectors currently in final stages of design, is expected to improve the sensitivity of present observatories by an order of magnitude, covering the energy range from a few tens of GeV to hundreds of TeV [5]. The experiment will consist of two arrays, one in the northern and one in the southern hemisphere, each including a large number of telescopes (~ 30 for northern and ~ 100 southern hemisphere), with a large field of view (FOV) of 5°–10° (depending on the telescope type). This will allow for several schemes of observation:

- deep observations – all telescopes pointed onto one object (intensive data taking);
- normal observations and monitoring – a few telescopes oriented towards each of several potentially interesting sources;
- sky scans – all telescopes scan a large area of sky in the long-term observations to detect new or transient sources.

In this work we thoroughly investigate the last one, i.e. sky scans.

On the experimental ground, scans were first performed by the HEGRA system of IACTs in search for a TeV gamma-ray signal from one quarter of the Galactic plane [6,7]. At the same time, the Whipple telescope collected data from nightly calibration scans which covered a sky region 12.5°-wide in declination [8]. Neither of these observations detected TeV emission. Nevertheless upper limits were derived for a large number of sources and the sky-scan techniques and data analysis methods were developed. Later, during the 1400 h-long survey of the Galactic plane conducted by the

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H.E.S.S. telescope system [9–11], over a dozen new sources were detected [12].

For CTA, an improved Galactic plane survey should be a major objective and it will also be capable of performing an all-sky survey in unprecedentedly short time at high sensitivity; the scientific rationale and feasibility of both survey types are thoroughly discussed in [13]. As also discussed in [13], such surveys can be performed in various modes of observation, in particular, large number of high-performance IACTs allows for using non-parallel modes with an enlarged FOV. The proper adaptation of such a mode for a specific telescope array can be a non-trivial task. The optimization of the pointing strategy, taking into account numerous characteristics of an array, e.g. distance between telescopes, FOV, energy threshold etc, can significantly reduce the observation time needed to achieve a given sensitivity.

In this work we consider the array of Middle Sized Telescopes (MST) working in various, parallel and non-parallel, modes. By performing high-statistics Monte Carlo (MC) simulations of the sky-survey observations, we derive for each mode the basic performance parameters at both trigger and analysis levels, which then allow us to compare efficiencies of the modes. Our study is a part of an intensive work within the CTA Monte Carlo Work Package aimed at optimizing the CTA observation scheme. Whereas we consider in detail different modes with the MST array, independent investigations are currently performed for the divergent mode of Large Sized Telescopes (LST) sub-array and the full CTA array working in divergent modes.

2. Sky survey modes

Fig. 1 illustrates possible modes for a large telescope array used for sky surveys. The parallel and divergent configurations were considered before in [13]; below we introduce also a novel, convergent mode (note the difference between our terminology and that of [13], were the parallel mode is referred to as convergent).

The performance of a telescope system operating in the sky survey mode depends on the FOV of the system and the time of observation needed to achieve a given significance level, i.e. its sensitivity.

In the simplest approach, sky surveys may be performed with telescopes pointed parallely into the same direction of the sky (Fig. 1a), however, in such a case the FOV of the telescope system is highly limited by the FOVs of individual telescopes. The FOV of a telescope array can be significantly enlarged by slightly deviating the pointing direction of each telescope. In the divergent mode, telescopes are inclined into the outward direction, see Fig. 1b, by an angle increasing with the telescope distance from the array center. As explained below, a performance improvement for such a configuration can be expected primarily at high energies of primary photons.

For the divergent configuration, images of gamma rays impinging close the array center are shifted toward the camera edge, which leads to a leakage[1] or complete loss of an event. While the larger loss of events is mostly pronounced for the lower-energy gamma rays, the leakage effect concerns mainly events with higher energies. As a result even if an event is registered it is poorly reconstructed. On the other hand, orientation of telescopes in the divergent mode is suitable for efficient detection of events with large impact parameter and/or arriving from directions further from the FOV center (in both cases mainly with high energies).

Qualitatively, one can expect that those negative effects can be reduced for the opposite orientation, i.e. with outer telescopes inclined toward the array center, see Fig. 1c. A quantitative comparison of the performance of the three modes and a related issue, i.e. an optimal value of the offset angle (giving the amount of the difference of the pointing directions, as defined below), appears crucial for planning the most efficient survey strategy.

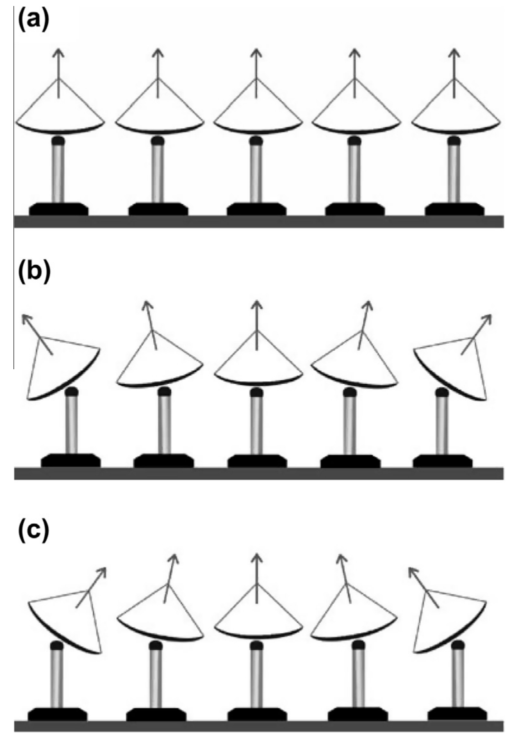

Fig. 1. Three modes of configuration of the telescope system used in the sky-survey scans: (a) normal (parallel) mode; (b) divergent mode; (c) convergent mode.

3. MC simulations

For all three modes, we simulate the response of the telescope array to the Extensive Air Showers (EAS) induced by gamma rays and proton background. To simulate the development of EAS we use CORSIKA 6.99 code [14,15], used as a standard in CTA. We simulated 2.1×10^7 gamma rays and 3.8×10^8 proton events[2] – both with energies between 30 GeV and 10 TeV generated from differential spectra with the spectral index $\Gamma = -2.0$. However, in our analysis, we use event weights corresponding to spectra with $\Gamma = -2.57$ for gamma rays and $\Gamma = -2.73$ for protons. Gamma rays are simulated from a point-like test source with the direction defined by the Zenith angle Za = 20° and the Azimuth Az = 180° measured with respect to the magnetic North. The background proton showers are simulated isotropically with directions within a 10° half-angle cone (larger than the FOV of all considered modes) centered on the direction of the gamma-ray source. We set the maximum impact parameter for gamma rays to 1000 m and for protons to 1500 m. The detector array is assumed to be located at the Namibian (H.E.S.S.) site at the altitude of 1800 m a.s.l.

The response of the telescope array is simulated with the CTA sim_telarray code [15,16]. We use the MST subarray of the CTA array *E* from the so-called *production-1*; the subarray includes 23 telescopes with positions shown in Fig. 2. The direction of the central telescope No. 5 is always approximately in the center of the FOV of the array (a slight displacement may occur due to the presence of telescopes No. 12 and 15, which break the symmetry); then, this direction is used to define various configurations and

[1] The effect of cutting off an image at the camera edge.

[2] including the number of re-used showers.