

# On the sensitivity of atmospheric Cherenkov telescope arrays for regions with presence of multiple gamma-ray sources

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**Abstract.** The potential of a next-generation ground based gamma-ray telescope array has been investigated. In addition to the ideal Gaussian shaped PSF, more realistic non-Gaussian PSFs with tails have been considered and their impact on the detector performance has been studied. The capability of the instrument to resolve multiple sources has been analyzed and the corresponding detector sensitivity estimated. These scenarios are particularly interesting in the framework of Galactic objects, where the observation of more than one source in the same field of view (FoV) is very likely to happen.

## 1. Introduction

The present generation of ground-based gamma ray telescopes (HESS [1], MAGIC [2] and VERITAS [3]) has in the last years proved the great potential of stereoscopic arrays of imaging atmospheric Cherenkov telescopes (IACT) as effective multifunctional tools for spectral, temporal and morphological studies of gamma-ray sources at energies above a few tens of GeV. Thanks to the excellent scientific results obtained, these currently operating detectors set the appropriate assumptions for a next generation IACT array. In this regard, the upcoming Cherenkov Telescope Array (CTA) observatory represents the most advanced future project in the field of gamma-ray astronomy and astro-particle physics [4]. Thanks to its wide energy range, excellent angular and energy resolution and huge detection area, CTA is expected to reach a factor 10 improved sensitivity in comparison to existing gamma-ray detectors. In this work the CTA observatory has been used as a template for the description of a generic next generation IACT array observing the sky with tens of telescopes and a study of the performances for the detection of weak very high energy (VHE) gamma-ray sources in complex environments at the presence of strong gamma-ray sources has been performed.

## 2. Instrument response

A CTA-like instrument has been defined making use of the publicly available Monte Carlo (MC) calculations performed by the CTA Consortium for a possible layout of the southern array [5]. In particular, the CTA expectations for the effective area, for the background rate and for the



angular resolution have been considered<sup>1</sup> and analytical parameterizations in the energy range from 50 GeV to 100 TeV have been carried out for each of these quantities, shown in table 1. The angular resolution is defined as the 68% containment radius of the gamma-ray point

**Table 1.** Analytical parameterizations for the effective area, the background rate after the rejection cuts and the angular resolution obtained as best-fit to the publicly available MC expectations for a possible layout of the CTA southern array<sup>1</sup>. The energy range of validity is from 50 GeV to 100 TeV.

Analytical representation, with $x = \text{Log}10(E/1\text{TeV})$	
$A_{eff} [\text{m}^2]$	$A_{eff}(x) = \frac{A}{1+B \cdot \exp(-\frac{x}{C})}$ $A = 4.36 \cdot 10^6 \ B = 6.05 \ C = 3.99 \cdot 10^{-1}$
$BgRate [\text{Hz/deg}^2]$	$BgRate(x) = A_1 \cdot \exp\left(-\frac{(x-\mu_1)^2}{2\sigma_1^2}\right) + A_2 \cdot \exp\left(-\frac{(x-\mu_2)^2}{2\sigma_2^2}\right) + C$ $A_1 = 3.87 \cdot 10^{-1} \ \mu_1 = -1.25 \ \sigma_1 = 2.26 \cdot 10^{-1}$ $A_2 = 27.4 \ \mu_2 = -3.90 \ \sigma_2 = 9.98 \cdot 10^{-1} \ C = 3.78 \cdot 10^{-6}$
$\sigma_{PSF} [\text{deg}]$	$\sigma_{PSF}(x) = A \cdot [1 + \exp(-\frac{x}{B})]$ $A = 2.71 \cdot 10^{-2} \ B = 7.90 \cdot 10^{-1}$

spread function (PSF) of the instrument. In first approximation the PSF can be described by a Gaussian. In this ideal scenario, the shape of the PSF is defined by:

$$f_{PSF} = \exp\left(\frac{x^2 + y^2}{2\sigma_{PSF}^2}\right) \quad (1)$$

where  $\sigma_{PSF}$  is the value of the angular resolution. Even though the Gaussian PSF represents the standard assumption, in a more realistic approach a non-Gaussian PSF with tails should be considered. As a matter of fact, as for other telescopes operating in different bands of electromagnetic spectrum, the PSF might have a strongly peaked Gaussian component as well as tails that extend well away from the peak. To account for the presence of such tails and to study their effect on the resolvability of celestial objects, a non-Gaussian shaped PSF has been defined. A possible representation for the non-Gaussian PSF, that is also reported in ref. [6], is given by the following function:

$$f_{PSF}^{tails} = \exp\left(\frac{x^2 + y^2}{2\sigma_{PSF}^2}\right) + R \cdot \exp\left(\frac{x^2 + y^2}{2\sigma_{PSF}^{tails}^2}\right) \quad (2)$$

where  $R$  is the ratio of the normalization factors of the two Gaussians and  $\sigma_{PSF}^{tails}$  is the width of the second Gaussian, below fixed at the value  $\sigma_{PSF}^{tails} = 0.2 \text{ deg}$ . Concerning the ratio  $R$ , here after the  $R = 0.3$  scenario is considered. A large value of  $\sigma_{PSF}^{tails}$  with respect to  $\sigma_{PSF}$  (that at high energies reaches values as good as  $\sim 0.03 \text{ deg}$ ) corresponds to a significant modification of the PSF shape introduced by the tails. The presence of the tails in the PSF can compromise a proper resolution of the sources due to their additional fake emission which increases the noise and distorts the source image.

<sup>1</sup> The CTA performance file can be accessed at:  
<https://portal.cta-observatory.org/Pages/CTA-Performance.aspx>

### 3. Multiple sources study

Simulations of excess maps of two nearby sources have been performed for different separation distances between the two objects. The background events have been uniformly distributed in the map according to the background estimation reported in table 1, whereas the two gamma-ray sources have been simulated assuming a Gaussian spatial distribution, characterized by an angular size  $\sigma_{src1}$  and  $\sigma_{src2}$  for the first and the second source, respectively. Concerning the energy spectrum of the sources, a Crab-like power-law spectrum in the form:

$$dN/dE = n \cdot N_0 \times (E/1\text{TeV})^{-\Gamma} \quad (3)$$

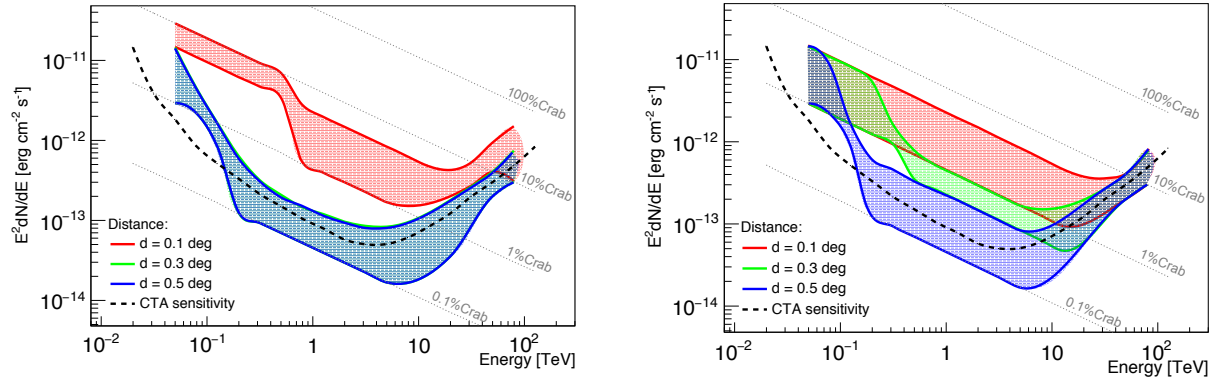
has been considered, with  $\Gamma = 2.62$  as measured in ref. [7]. The flux strength is given in units of Crab flux at 1 TeV:  $N_0 = 2.83 \cdot 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ . The first source, here after call *test source*, corresponds to the target of the observation. On the other hand, the second nearby object represents an additional source of the background: the gamma photons emitted by this *background source* fall in the region of interest (ROI) and limit the capability to resolve the test source. The closer is the background source, the higher is its contribution to the total background, traditionally attributed only to cosmic rays (CR). This increase in background would result in a significant reduction of the sensitivity for observations in the specific regions rich in gamma-ray sources. This scenario is of particular interest in the contest of gamma-ray emitters located in the crowded regions of the Galactic plane, where the chance of clustering of two or more gamma-ray sources within 1 degree is high.

#### 3.1. The sensitivity

The sensitivity of the telescope is defined as the minimum flux of gamma rays for a statistically significant detection. The publicly available CTA sensitivity is obtained from detailed MC simulations and the baseline analysis is applied to the simulated data for deriving the curve [5], which foresees to improve the sensitivity of the current ground-based detectors by an order of magnitude. This factor concerns the observations of a single point-like object, isolated from any other source. Nevertheless, the increase of the number of detected gamma-ray sources corresponds to a reduction of the average distance between objects, leading to the multiple sources scenario previously described. This implies that the sensitivity curves obtained under the assumption of only CR background may significantly overestimate the capability of the instrument to resolve weak sources.

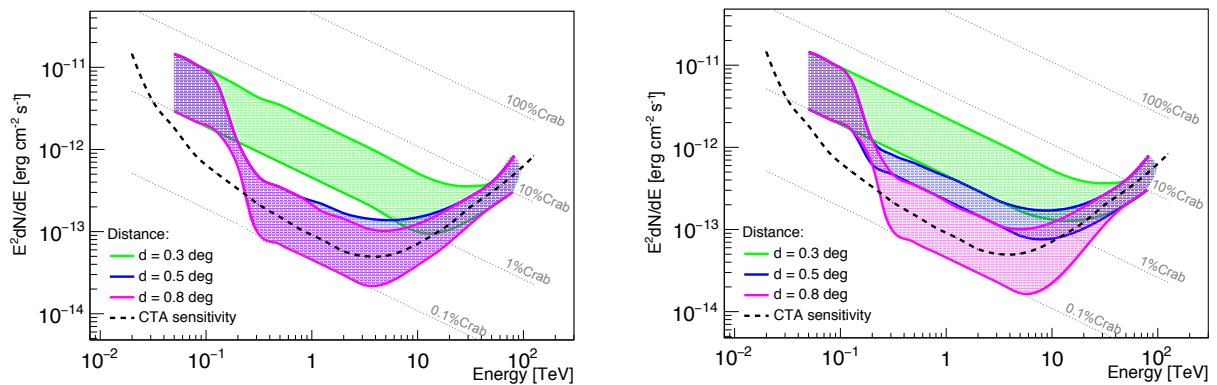
We estimated the flux sensitivity for 50 hours of observation of a point-like test source placed close to a companion having a flux strength of 0.1 Crab. Exploiting the criteria used by the CTA Consortium to compute the differential sensitivity, in each energy bin (five intervals per decade of reconstructed energy, i.e. intervals of the decimal exponent of 0.2) we verified the presence of at least 10 excess events, i.e.  $S \geq 10$  being  $S$  the number of signal events in the ROI of the test source), and a significance of at least five standard deviations calculated according to the formulation of *Li & Ma* [8] ( $N_\sigma \geq 5$ ). In addition, in order to account for the background systematics, a signal excess at five times the assumed 1% background systematic uncertainty is required [9], i.e.  $S/B \geq 0.05$  with  $B$  the total number of background events in the ROI given by both the CRs and the photons emitted by the background source.

On the left of Fig. 1, the differential sensitivity for a point-like source located in the proximity of a second point-like source, is shown for three distances between these two sources: 0.1 deg, 0.3 deg and 0.5 deg. The uncertainty in the estimation of the minimum detectable flux, due to the discrete flux levels used in the simulation, is quantified by the dashed areas which define estimated sensitivity ranges. For each distance, the upper curve corresponds to the minimum flux obtained from the finite sample of simulated fluxes, and the lower curve is given by the closest weaker flux we dealt with in our simulation. In the same plot we show the sensitivity curve for a point-like source expected for the layout of CTA South considered in this work [5].



**Figure 1.** Differential flux sensitivities for a point-like source corresponding to 50 h observation time. The range of sensitivities are shown by dashed regions (see text). The calculation are performed under the assumption of existence of a neighbor point-like (on the left) and extended (on the right) background gamma-ray source of strength 0.1 Crab, placed at three different distances to the test source. In calculations we assume a pure Gaussian distribution for PSF. The black dashed line is for the publicly available CTA sensitivity related to the observation of an isolated point-like object performed with one of the possible layouts for its the southern array<sup>1</sup>.

Fig. 1 shows that the sensitivity at the presence of a source of 0.1 Crab can be significantly (up to an order of magnitude) worse than it follows from the CTA curve<sup>1</sup>. The effect cannot be ignored in environments densely populated by gamma-ray sources and this mostly concerns the Galactic plane. Since most of the Galactic sources are extended, on the right of Fig. 1 we show also the sensitivities in the regions around an extended gamma-ray source with an angular size of 0.2 deg. The sensitivities shown in Figs. 1 are obtained under the assumption of a pure Gaussian PSF (Eq. 1). However, in reality PSF has a broader non-Gaussian distribution with tails. This apparently should extend the region of reduced sensitivity around strong gamma-ray sources. The effect of the non-Gaussian PSF on the sensitivity is illustrated in Fig. 2, for a point-like (on the left) and for an extended (on the right) background gamma-ray source. For the assumed shape of the non-Gaussian PSF with tails (calculated for  $R = 0.3$ ) the zone of the reduced sensitivity extends up to  $\sim 1$  deg.



**Figure 2.** Same as Fig. 1, but for the case of non-Gaussian PSF with tails described by Eq. 2 with  $R = 0.3$ .

#### 4. Summary

We used the publicly available performance of a possible layout for the CTA southern observatory to characterize the basic features of a next-generation IACT array. The potential of such array has been studied in the contest of crowded environments populated by multiple sources, especially interesting in the framework of the Galactic plane where the clustering of objects within 1 degree is expected. We showed that the presence of a gamma-ray source nearby a test source creates an additional and unavoidable background which might dominate over the CR noise, traditionally considered as the only source of background. Correspondingly the detector sensitivity can not be improved infinitely in regions dense with VHE gamma-ray sources. In correspondence to these scenarios, we observed a worsening in the minimum detectable flux (up to an order of magnitude), further impoverished by the presence of tails in a realistic non-Gaussian PSF. Such tails compromise the detection capability of the instrument and make the observation of weak sources even more challenging. Depending on the shape of PSF and the distance to the test source, the minimum detectable flux is increased by a factor of a few or even by an order of magnitude. This implies an increase of the required minimum observation time by one to two orders of magnitude. Generally, this statement concerns all energy intervals. However, one should note that the situation could be more optimistic at multi-TeV energies, especially above 10 TeV, where the energy resolution becomes better, and, at the same time, the number of sources (PeVatrons) is expected to be dramatically decreased.

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