Optimum spacing between imaging atmospheric Čerenkov telescopes in the future 50 GeV multi-telescope arrays

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Abstract. Regarding the optimum design of future low energy (50−100 GeV) arrays of imaging air Čerenkov telescopes an important issue is a choice of optimum arrangement (layout) of telescopes within the array. Here we present the basic results of such studies addressed by use of detailed Monte Carlo simulations.

INTRODUCTION

Currently, the TeV Very High Energy (VHE) γ-ray astronomy experiences an unprecedented upgrade of its experimental instrumentation (for review see [1]). Three major forthcoming detectors, CANGAROO III, H.E.S.S., and VERITAS, will exploit a concept of an array of several imaging air Čerenkov telescopes (IACT) operating simultaneously in the so-called *stereoscopic mode* [2]. Recent studies based, in the main, on simulations (e.g., discussion in [3]) assist to infer the optimum basic parameters of a single IACT: *(i)* effective area of optical reflector $\sim 10\,\mathrm{m}^2$; *(ii)* camera field of view [1] – 4.5°; *(iii)* angular size of photo multiplier in the camera focal plane – 0.15°. These parameters have been derived for general assumptions respecting the TeV γ-ray source (point γ-ray source with the Crab-like energy spectrum). Note that the optimum telescope design might have very different parameters, if it is constrained for the most part, by the specific observational goals.

In addition to the design of a single telescope there is a number of important aspects of the array performance. For instance the choice of telescope layout may significantly influence resulting sensitivity of array. Recent observations, made by the HEGRA system of 5 IACTs with relatively small reflectors ($\sim 8.5\,\mathrm{m}^2$), as well as relevant simulations have shown that four Čerenkov light images of air shower allow

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1) Observations of diffuse γ-ray sources will need camera of a larger field of view ($\geq 5°$) in order to map the emission effectively over a broad angular regions.

good reconstruction of shower parameters (i.e., determination of shower arrival direction, primary energy, shower maximum *etc*) and provide a strong rejection of the background cosmic rays (see [4]). Use of more than four IACTs, simultaneously, does not noticeably improve the accuracy of the shower reconstruction. Thus, future multi-telescope arrays could be gathered from the subsystems (cells) of 4 IACTs operating in stereoscopic mode.

The accuracy of shower reconstruction depends on the impact distance of a shower core from the system of telescopes. A 4 IACTs cell with certain separation between the telescopes samples the final distribution of triggered air showers over the impact distance and consequently define the resulting accuracy of shower reconstruction, effective collection area and finally, array sensitivity. Apparently the relevant simulations could be useful to make a choice of the optimum telescope separation. Here we discuss the results of such simulations.

MONTE CARLO SIMULATIONS

The ALTAI computational code was used for generating γ-ray- and proton- induced air showers in the energy range 10 GeV - 50 TeV for two zenith angles of 20° and 60°. In present simulations for each individual shower we saved the response of an extended array of IACTs, arranged in a rectangular lattice of 1000x600 m^2 with 33 m step (589 nodes in total). This method is very effective and robust in performing such extensive simulations. In alternative approach one can save all photons hitting the observation level for each individual shower, and afterwards sample the telescope responses for a certain array layout. However such method is exclusively memory consuming and results in very complicated and rather slow data handling procedure.

Our calculations have been done for 10 m ($S \simeq 82$ m^2) telescopes equipped by the camera in two designs: (1) 271 pixels of 0.25°; (2) 721 pixel of 0.15°. The mean contribution of night sky light for 0.15° pixel, trigger time gate of 10 ns, and photon-to-photoelectrons conversion efficiency of 0.1 was taken as 1 ph.e. In calculations we used the detector response functions (mirror reflectivity, point spread function, quantum efficiency of photo multiplier *etc*) which correspond to currently operating HEGRA IACTs system.

OPTIMIZATION CRITERION

Sensitivity of IACT array is determined by a few basic characteristic functions: effective detection areas of γ-rays and cosmic rays (A_γ, A_{CR}), acceptance of γ-rays and cosmic rays after applying the cuts on orientation (d) and shape (s) of the Čerenkov light images ($\kappa_\gamma^{(d,s)}, \kappa_{cr}^{(d,s)}$). The resulting so-called signal-to-noise ratio, calculated for 1 hr observations, is given by

$$\mathrm{S/N} = \eta^{(\mathrm{d})}\eta^{(\mathrm{s})}\mathrm{R}_\gamma \mathrm{J}_\gamma(\mathrm{R}_{\mathrm{cr}}\mathrm{J}_{\mathrm{cr}})^{-1/2}\mathrm{t}^{1/2} \tag{1}$$

where

$$\mathrm{R}_\gamma = \int \mathrm{A}_\gamma(\mathrm{E})\mathrm{F}_\gamma(\mathrm{E})\mathrm{dE}, \ \ \mathrm{R}_{\mathrm{cr}} = \int \mathrm{d}\Omega \int \mathrm{dEF}_{\mathrm{CR}}(\Omega, \mathrm{E})\mathrm{A}_{\mathrm{CR}}(\Omega, \mathrm{E}) \tag{2}$$

are the detection rates for γ-rays and cosmic rays, respectively, assuming certain fluxes – $\mathrm{F}_\gamma, \mathrm{F}_{\mathrm{CR}}$. $\eta^{(d,s)} = \kappa_\gamma^{(d,s)}/(\kappa_{cr}^{(d,s)})^{1/2}$ are the enhancement factors (Q-factors) after application of orientation and shape analysis cuts (γ-ray selection criteria). In general, the optimum design of the IACT array should give the maximum S/N ratio.

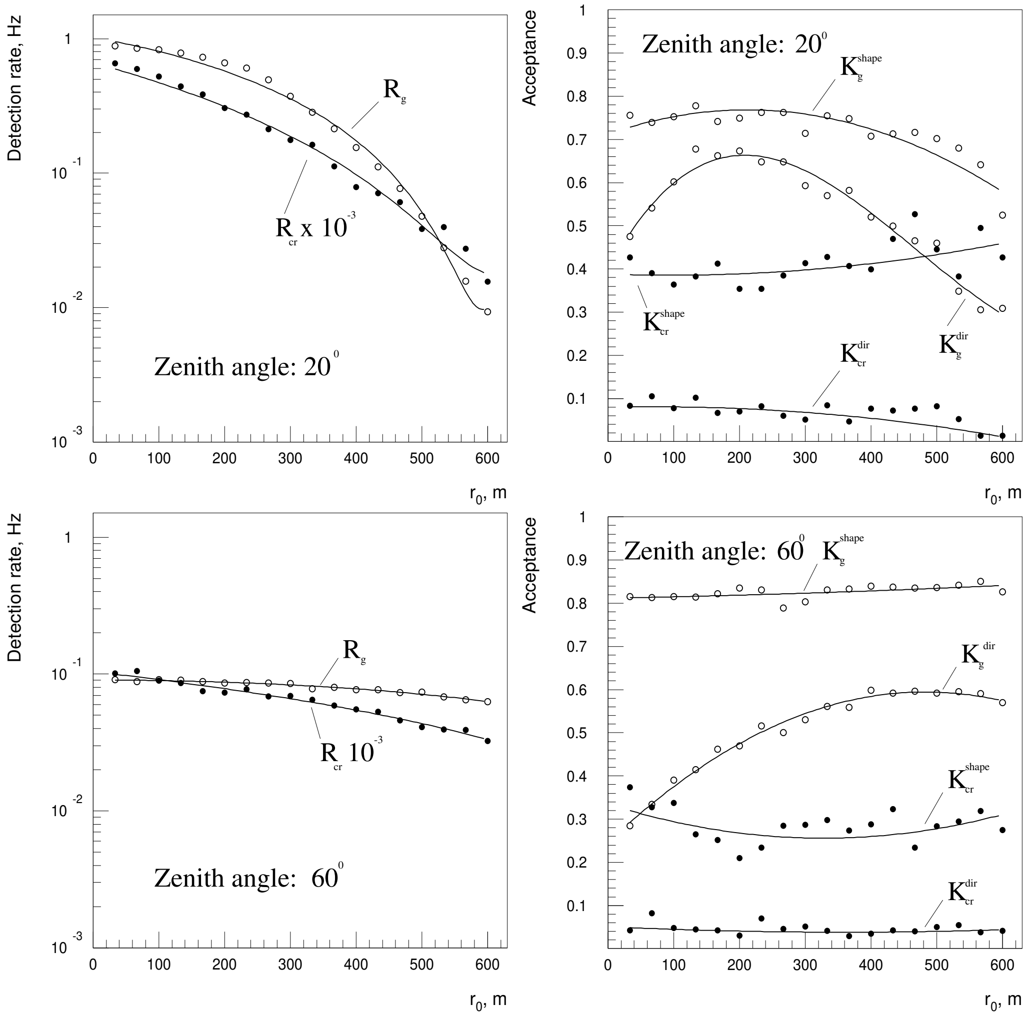

FIGURE 1. Detection rates and acceptances after application of orientation and shape cuts, $\mathrm{K}^{\mathrm{dir}}_{\gamma,\mathrm{cr}}$, $\mathrm{K}^{\mathrm{shape}}_{\gamma,\mathrm{cr}}$, for γ-ray and cosmic ray air showers simulated for a 4 IACTs cell with separation between the telescopes – $\mathrm{r_o}$. Data corresponds to the simulations at zenith angles of 20° and 60°.

The functions $\mathrm{R}_\gamma, \mathrm{R}_{\mathrm{cr}}, \eta^{(\mathrm{o,s})}$ depend on *(i)* single telescope trigger (local trigger), as well as on the system trigger (global trigger), *(ii)* analysis methods used for the

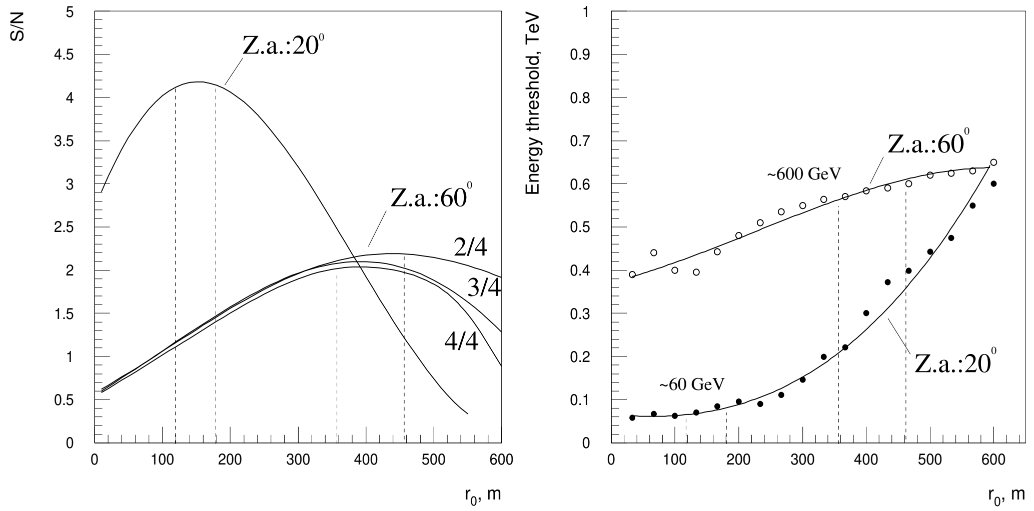

FIGURE 2. Signal-to-noise ratio (left panel) and corresponding energy threshold (right panel) as a function of the separation between the telescopes, r_o.

data reduction; *(iii)* separation between the telescopes. Here we used the trigger logics for array which allows to get the minimum possible trigger threshold in order to reduce as low as possible the energy threshold of array ($\simeq 50$ GeV). Note that the results on optimum telescope separation might be very different in case of much larger energy threshold of the array ($\gg 100$ GeV), the larger distances may be preferable in such a case. For the shower reconstruction and rejection of cosmic rays we used here the standard tools developed for the HEGRA IACTs system [4].

RESULTS

For the Crab-like energy spectrum of the γ-rays and standard cosmic ray spectra we calculated the functions $R_\gamma, R_{cr}, \eta^{(d,s)}$ for the 4 IACTs cell of a different spacing (see Figure 1). One can see in Figure 1 that γ-ray detection rate, R_γ, drops down with increase of r_o-parameter because of reducing the effective collection area of γ-rays. At the same time for relatively large separation ($r_o \simeq 120 - 160$ m) the reconstruction accuracy increases and the same angular cut ($\theta^2 < 0.1°$) provides much higher acceptance of γ-rays, κ^d (see Figure 1). The efficiency of the shape cut (we analyzed the data by *mean scaled Width*) does not strongly depend on r_o. Note that the fall of the γ-ray detection rate for larger separations (> 100 m at $20°$ zenith angle) will be much faster for telescopes equipped with the camera of relatively narrow field of view ($\ll 4°$) because the images will be truncated by the camera edge.

Resulting signal-to-noise ratio is shown in Figure 2. For $20°$ zenith angle the calculated signal-to-noise ratio reaches maximum in the range of $r_o = 120 - 180$ m whereas at $60°$ zenith angle the "plateau" of S/N curve starts at about 320 m. One can see from Figure 2 that the S/N maximum is relatively broad (150 ± 30 m for $20°$) and any choice of array spacing within this range could provide almost the same S/N ratio. However, the energy threshold of array rises up with increase of r_o (see Figure 2). In order to keep the energy threshold at $\simeq$50 GeV for small zenith angles ($20°$), and correspondingly, at $\simeq$ 500 GeV for the large zenith angles ($60°$) the spacing between telescopes in array has to be about 120 m and 360 m, respectively. Note that independent studies based on the data taken with the HEGRA system of 5 IACTs allow to make similar conclusion respecting the optimum separation between the telescopes in array [5].

Finally, the layout of an array of 16 IACTs can be chosen in form of rectangular grid with the separation between the telescopes of 120 m. In this case the separation between the peripheral telescopes in array will be of about 360 m. Such distance is optimum for the large zenith angle observations. The array can be used *(i)* as a single detector observing an object with all 16 telescopes; *(ii)* as four subsystems (cells) of 4 IACTs operating independently; and even *(iii)* as 16 stand alone telescopes. Evidently the operation mode will be chosen according to particular observational program (e.g., precise spectroscopic measurements, routine monitoring of a number of objects, *etc*).

These is an alternative layout of array in form of four cells with 4 IACTs at relatively large distance ($\gg 250$ m) in order to have four independent subsystems. Note that almost all low energy γ-ray events (≤ 100 GeV) are concentrated within the cell of 4 IACTs and the detection area is determined by the geometrical area of a cell. The array of 16 telescopes arranged in form of rectangular grid corresponds to 9 cells whereas other design has only 4 such cells and apparently provides lower rate of ≤ 100 GeV γ-rays but at the same time gives a rather high rate of ≥ 100 GeV γ-ray showers.

CONCLUSIONS

Base on Monte Carlo simulations we found that the arrangement of 10 m class imaging air Čerenkov telescopes in rectangular grid with the spacing between the telescopes of 120 m is close to the optimum one. Such array may effectively fulfill most of the physics goals relevant for the future γ-ray observations in the energy range above 50 GeV.

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