On design studies for the future 50 GeV arrays of imaging air Čerenkov telescopes

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Abstract

Arrays of imaging air Čerenkov telescopes (IACTs) like VERITAS, HESS have been recently proposed as the instruments of the next generation for ground based very high energy \(\gamma\)-ray astronomy invading into 50-100 GeV energy range. Here we present results of design studies for the future IACT arrays which have been performed by means of Monte Carlo simulations.

We studied different trigger strategies, abilities of cosmic ray rejection for arrays of 4 and 16 telescopes with 10 m reflectors, equipped with cameras comprising 271 and 721 pixels of 0.25° and 0.15°, respectively. The comparative analysis of the performance of such telescope arrays has been done for both camera options, providing almost the same field of view of \(\sim 4.3^\circ\).

An important issue is the choice of the optimum spacing between the telescopes in such an array. In order to maximize the signal-to-noise ratio in observations at the small zenith angles of \(\sim 20^\circ\) as well as at large zenith angles of \(\sim 60^\circ\), different arrangements of IACT array have been examined. Finally, we present a major recommendations regarding the optimum configuration.

Key words: high energy \(\gamma\)-ray astronomy – imaging air Čerenkov technique

1. Introduction

Presently the Very High Energy (VHE) domain, from 300 GeV to 20 TeV, of the cosmic \(\gamma\)-rays is covered by ground based instruments. Imaging air Čerenkov telescopes (IACTs) are able to detect signals from galactic and extragalactic \(\gamma\)-ray emitters within one hour of observations and to measure their energy spectra with a few hours of good data. The variety of the physics results obtained with the currently operating IACTs as well as physics considerations for the forthcoming instruments (Weekes et al., 1997) suggest a prosperous future of VHE \(\gamma\)-ray astronomy indeed.

A major trend in the development of this technique is towards stereoscopic arrays of 10 m IACTs, such as the VERITAS (e.g., Weekes, 1997) and HESS (e.g., Hofmann, 1997) projects, approaching an energy threshold of \(\sim 50-100\)
GeV. An alternative approach might be the construction of a single large (17 m) imaging Čerenkov telescope (MAGIC) in order to achieve the energy threshold as low as 20 GeV (Lorenz, 1997). The stereoscopic imaging of γ-ray-induced air showers has several advantages compared with a stand alone telescope (see Aharonian & Konopelko, 1997) which provide high quality γ-ray observations.

The design of the future IACTs arrays is constrained, first of all, by the physics goals: we are interested in detection of the γ-ray sources at large distances (redshifts: $z \geq 0.1$) with presumably low fluxes. To enlarge the number of targets it is also worth to perform the surveys. Future observations of AGNs would in addition need a good energy resolution over a broad energy range as well as an ability of long time monitoring of a few sources simultaneously. Observations of the extended, diffuse γ-ray sources (e.g., SNRs) would finally need a large field of view in order to accommodate objects of $\sim 0.5 - 1^\circ$ angular size (Völk, 1993). For all that one can define desirable physics parameters of an IACT array: an effective energy threshold of $\sim 50 - 100$ GeV, a sensitivity to γ-ray fluxes as low as $J_\gamma (> 100 \text{ GeV}) \approx 10^{-11} \text{ cm}^{-2} \text{s}^{-1}$, an energy dynamic range up to 50 TeV, an angular resolution of 0.1°, an energy resolution of $\leq 20\%$, and a relatively large field of view ($\geq 4^\circ$). Our previous studies (Aharonian et al., 1997) have shown that these physics parameters could be provided with an array of $\sim 10$ m telescopes, placed at 2.2 km height above sea level. However, the design of the camera (e.g., the angular size of the pixels and the camera field of view) as well as the layout of the telescopes have still to be optimized. For that Monte Carlo simulations have been done. The major results of the simulations are summarized here.

2. 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°. For each shower the response of an extended array of IACTs, arranged in a rectangular lattice of 1000 x 600 m² with 33 m step (589 nodes in total) was saved. The calculations have been done for 10 m ($S \approx 82 \text{ m}^2$) telescopes equipped by a camera in two alternative designs: (1) 271 pixels of 0.25°; (2) 721 pixels of 0.15°. Both designs give almost the same field of view of 4.3°. The mean night sky content per 0.15° pixel per trigger time gate of 10 ns and photon-to-photoelectron conversion efficiency of 0.1 was taken as 1 ph.e.

3. Results and discussion

The sensitivity of IACT technique is determined by the effective detection area of the γ-rays, and the ability of cosmic ray rejection using the orientation and shape parameters of the Čerenkov light images. The resulting signal-to-noise ratio for 1 hr observations is given by $S/N = \eta^{(o)} \eta^{(s)} A_\gamma J_\gamma (A_{cr} J_{cr})^{-1/2} t^{1/2}$.
where $A_\gamma, A_{cr}$ are the detection areas for the $\gamma$-rays and cosmic rays, respectively, with the corresponding fluxes $J_\gamma, J_{cr}$, and $\eta^{(o,s)} = \kappa^{(o,s)}_\gamma / (\kappa^{(o,s)}_{cr})^{1/2}$ are the enhancement factors after application of the orientation and shape analysis cuts ($\gamma$-ray selection criteria). In general, the optimum design of the IACT array should give the maximum S/N ratio. The maximum $\gamma$-ray detection area mainly depends on the system trigger scheme and threshold as well as on the telescope arrangement (basically on the distance, $l$, between neighbour telescopes) whereas $\eta^{(o,s)}$ depend on the camera pixellation and field of view, and on the telescope spacing in the array. Note that all these relations are strong functions of the primary $\gamma$-ray energy. Using the Monte Carlo simulations for the dense grid of the telescopes the optimization of S/N ratio is straightforward. In the following discussion we try to disentangle most important relations in order to make clear the results of a complete array optimization.

**Gamma-ray detection rate.** The background light per pixel per trigger time gate ($\sim 10$ ns) sets the minimum trigger threshold at the level of 8 and 13 ph.e. for the local trigger schemes: 3/721 (signal in each of any three neighbour pixels from 721 exceed the trigger threshold) and 2/271 for two camera designs, respectively. The global system trigger demands at least two telescopes to be triggered locally within the time gate of 50 ns. It limits the random noise trigger rate at 0.1 Hz with a corresponding single-telescope trigger rate of $\sim 400$ Hz (W. Hofmann, private communications). For these conditions both camera designs give $\sim 50$ GeV energy threshold, determined as the energy corresponding to the maximum of the differential $\gamma$-ray detection rate, assuming the $\gamma$-ray energy spectrum $dN_\gamma/dE \propto E^{-2.5}$. The integral $\gamma$-ray rate, $R_\gamma$, at zenith, is expected to be about 1 Hz from the Crab Nebula for a 4 IACTs array and remains almost constant for a telescope spacing of less that $\sim 120$ m. Note that after the conventional software analysis cuts the number of survived low energy $\gamma$-rays of $\sim 50$ GeV is noticeably reduced ($\geq 30\%$) and the peak in the differential detection rate may shift to the higher energies ($\sim 100$ GeV) depending on the assumed $\gamma$-ray spectrum.

**Angular resolution.** The stereoscopic observations allow to measure the shower direction by superposition of a several images in one common focal plane. The accuracy of this reconstruction – the angular resolution – can be defined as one standard deviation of the difference between the true and reconstructed direction of the $\gamma$-ray showers. Our Monte Carlo simulations show that the angular resolution for the array of telescopes in two camera designs, noted above, is roughly the same for small zenith angles ($\sim 20^\circ$). The angular resolution strongly depend on the average content of the background light in the camera pixels. A fine pixellation ($0.15^\circ$) helps to improve drastically the angular resolution at large zenith angles ($60^\circ$). The angular resolution of the telescope array substantially improves by increasing the baseline distance, $l$, up to $\sim 120$ m for $20^\circ$ zenith angle and up to $\sim 360$ m at $60^\circ$ zenith angle. For the energy threshold of 50 GeV, the optimum layout gives $\eta^{(o)} \simeq 3$ with
70 % of the γ-rays within 0.3° for the small zenith angles.

**Cosmic ray rejection.** For the second moment analysis the Monte Carlo simulations do not show noticeable difference in the ability of cosmic ray rejection for the two camera options. Using the mean scaled Width parameter one can get $\eta^{(s)} \sim 3$ for an energy threshold of 50 GeV. Note that $\eta^{(s)}$ does not depend on the telescope spacing whereas it substantially increases at energies far above the energy threshold (≥ 100 GeV). Multi-telescope coincidences (3,4) give better cosmic ray rejection. The low energy γ-ray triggers ∼ 50 GeV provide a dominant rate of 2 and 3 pixel events for the camera designs of a coarse pixellation (0.◦25). In this case the ratio of a minimum pixel signal to the trigger threshold is close to one and these events are unlikely to be extracted from the cosmic rays. Note that for good imaging the minimum pixel signal (slightly above the image tail cut) has to be substantially lower than the telescope trigger threshold providing the accurate measure of the image shape by sufficient number of pixels.

**Field of view.** The images of low energy γ-rays ($E_\gamma \leq 100$ GeV) are concentrated very close to the camera center (∼ 0.5°). The Čerenkov light images from air showers observed at large zenith angles also shrink to the camera center because of a large distance from the shower maximum to the telescope. In observations at small zenith angles (∼ 20°) the high energy showers ($E \geq 10$ TeV) are partially truncated by the camera edge. The effective detection of such events needs an extended camera field of view up to at least ∼ 4.5°. A large field of view is important for the observations of diffuse sources as well as for performing large area surveys.

**Optimum baseline distance.** We have tested different possible arrangements of 16 IACTs. For instance one can set the array layout as a sparse grid, or, as a 4 independent cells (which are scattered on the observation plane at the distances ≥ 250 m) with 4 telescopes within each cell. Our simulations show that both layouts give almost the same integral γ-ray detection rates and final signal-to-noise ratio, whereas the grid structure is preferable for the registration of the low energy γ-rays ($E \sim 50 – 100$ GeV). The resulting S/N ratio strongly depends on the spacing (grid baseline distance) between the telescopes. The optimum baseline distance for observations at small zenith angles (20°) is about 120 m. A further increase of the baseline distance leads to the corresponding increase in the energy threshold of the system. Large zenith angle observations need a large distance between the telescopes (up to 360 m). For that the peripheral telescopes of a grid can be effectively used.

**Summary**

The physics motivations and current design studies allow us to set the possible arrangement of a low energy (≥ 50 GeV) IACT array as a quadrangular grid
of 16 telescopes with \(\sim120\) m baseline distance. Each of telescopes has a 10 m reflector and is equipped with a fine resolution camera: 817 pixels of 0.16\(^\circ\), which covers \(\sim4.5\)\(^\circ\) field of view (optionally a number of telescopes could have a camera of a large field of view \(\geq5\)\(^\circ\) with the pixels of 0.25\(^\circ\)). The array permits different operational modes, which include the observations with a complete array (search at the level of a maximum sensitivity), the large zenith angle observations, search for diffuse, extended \(\gamma\)-ray sources as well as performing large area surveys. Such an array allows monitoring of several \(\gamma\)-ray sources with the subgroups of 4 telescopes in order to maintain simultaneously a number of research programs.

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