Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 3 (OG part 2), pages 1429–1432

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Design Study of a Low Energy IACT Array for Ground-Based γ-Ray Astronomy

A. KONOPELKO, J.P. FINLEY, G. URBANSKI
Purdue University, Department of Physics, 525 Northwestern Avenue, West Lafayette, IN 47907-2036
akonopel@purdue.edu

Abstract: Recently, ground-based very high-energy (VHE) γ-ray astronomy achieved a remarkable advancement in the development of the observational technique for the registration and study of γ-ray emission above 100 GeV. Construction of telescopes of substantially larger sizes than the currently used 12 m class telescopes can drastically improve the sensitivity of ground-based detectors to γ rays of energy from 10 GeV to 100 GeV. Based on Monte Carlo simulations we have studied the response of an array of three large area imaging atmospheric Cherenkov telescopes (IACT) as a prototype for a future large-scale low energy ground-based experiment. The sensitivity of a three-telescope array as a function of optical reflector size was investigated here in detail.

Introduction

The southern hemisphere HESS array of four 12 m IACTs, located in Namibia, and the northern hemisphere VERITAS array of four similary designed telescopes, located in Arizona, have proven many outstanding advantages of stereoscopic observations of VHE γ rays with the ground-based detectors. The construction and commissioning of the MAGIC experiment, consisting of a single 17 m telescope, equipped with a fast response, high-resolution imaging camera, and located at La Palma in the Canary Islands, has also been completed recently. In the first years of its operation, the MAGIC telescope has demonstrated its performance, comparable to that of HESS and VERITAS, in observations of γ rays with energies above 100 GeV in addition to the unique capability of detecting γ-ray showers ranging in energy well below 100 GeV, though at a relatively low sensitivity level. Currently, the MAGIC collaboration is constructing a second 17 m telescope on the same site in order to enable stereoscopic observations, which can drastically boost the sensitivity of future detections of γ-ray fluxes in the sub-100 GeV energy domain. Motivated by a growing scientific interest of the astrophysical community in γ-ray observations at low energies, the HESS collaboration recently began construction of a single 28 m imaging telescope in the center of their current array. This telescope will be able to detect γ rays with energy as low as 40 GeV, enabling a rather broad overlap in dynamic energy range of this instrument and a future advanced space-born experiment – GLAST.

At present, there are two major competing views on the direction of instrument development for ground-based VHE γ-ray astronomy. A prodigious scientific study, performed recently with the HESS array of IACTs, has strongly motivated various ongoing considerations of substantial expanding the current, rather modest multi-telescope system to much larger arrays, composed of roughly 50 telescopes of 12 m aperture each [1, 2]. Such arrays would increase tremendously the detection area of γ rays, and consequently raise the sensitivity with respect to the γ-ray fluxes above 100 GeV by at least a factor of ten. However, this approach may not necessarily achieve a significant improvement in angular resolution or a substantial reduction in the energy threshold. These are now considered to be the major limiting factors in understanding the morphology and energy spectra of many well-established VHE γ-ray sources. In another approach, an array of a few telescopes of substantially larger aperture, e.g. 20-30 m , can drastically improve the sensitivity of ground-based γ-ray detectors, primarily in the sub-100 GeV energy range [3], while at the same time providing high-quality γ-ray observations at energies above 100 GeV.

Finally, a combination of both approaches could meet most of the scientific requirements determined for the next generation of ground-based instruments [4].

In this paper, based on the Monte Carlo simulations, we investigate the sensitivity of a three-telescope system, considered as a prototype of future low-energy arrays, as a function of telescope aperture.

Simulations

The atmospheric showers produced by γ rays and protons were simulated using the numerical code described in [5]. The primary energy of simulated showers was randomized within the energy range from 10 GeV to 10 TeV. Events were weighted according to a power-law primary energy spectrum. The maximum impact distance of the shower axis to the centre of the telescope array was 10^3 m. The detailed procedure of simulating the camera response accounts for all efficiencies involved in the process of Cherenkov light propagation and acquisition. The overall efficiency of the photon-to-photoelectron (ph.-e.) conversion was $\sim$0.1. The standard 'picture' and 'boundary' technique was applied for image cleaning. The simulated images were parameterized using the standard measures of their angular extent and orientation in the telescope focal plane. Further details on the simulation procedure can be found in [3].

Using the same sample of simulated γ-ray and cosmic-ray showers, the response of the array of three identical telescopes of various aperture sizes, i.e. 17, 20, 24, and 30 m, was calculated. The telescope coordinates were set up according to the center-symmetric triangular layout. The spacial separation between the telescopes and the center of the array was 50 m. The imaging cameras consisted of 1951 photo-multiplier tubes of $0.07°$ each. This results in a $3°$ diameter field of view.

Detection Areas and Rates

The standard triggering scheme of imaging cameras requires a signal in two or three adjacent pixels (PMTs) to exceed, simultaneously, a certain threshold measured in the number of photoelectrons. The choice of trigger threshold is usually constrained by a minimal allowed accidental trigger rate, which is induced by continuous illumination of the camera pixels by the night sky background light. This accidental trigger rate has to be substantially suppressed with respect to the actual rate of recorded air shower events. The individual pixel load due to reflected background light is proportional to the aperture of the telescope reflector. Evidently, a larger telescope requires a higher trigger threshold in order to suppress accidental trigger rate. Exploiting a two-fold coincidence trigger for telescopes with aperture sizes in the range from 17 to 28 m, the corresponding trigger threshold is expected to be about 9-15 photoelectrons, respectively. The simulated events were accepted for further consideration if the images in at least two telescopes out of three passed the trigger criterion.

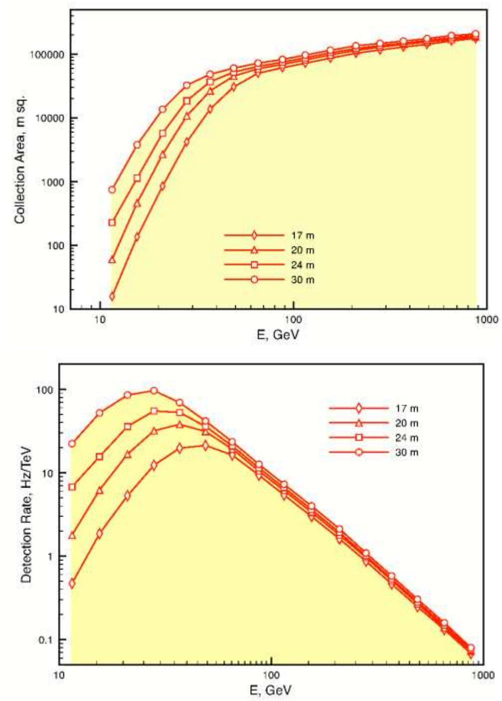

Figure 1: Detection areas and rates of γ-ray showers for the array of three imaging telescopes of various aperture sizes.

Triggered γ-ray showers show a substantial increase in the detection area over the energy range from 10 to 100 GeV for telescopes of larger aperture (see Fig. 1). Large telescopes are able to detect γ-ray showers of low energy at significantly larger impact distances. At the same time, in the energy range well above 100 GeV, telescopes of

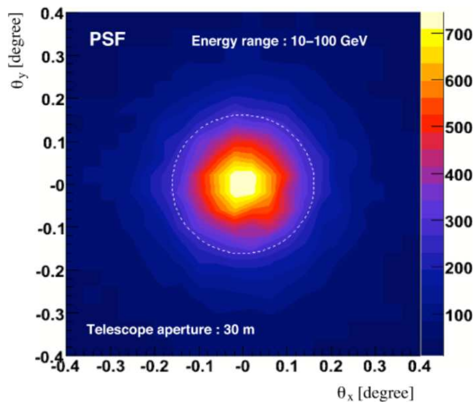

Figure 2: The simulated point spread function (PSF) for a point-like γ-ray source observed with the array of three 30 m telescopes. The radius of the dashed white circle corresponds to the σ-parameter of a two-dimensional Gaussian fit.

very different apertures yield almost identical detection areas. For these high energy γ-ray showers a rather narrow imaging camera of 3° diameter is a major limiting factor. The images of the high-energy γ-ray showers, which are often registered at very large impact distances with respect to the telescopes, are focused onto the focal plane outside of the actual camera edge.

Assuming a power-law energy spectrum of γ rays as $dF_\gamma \propto E^{-2.6}dE$, which is close to the energy spectrum of the Crab Nebula (standard candle), one can compute corresponding differential detection rates (see Fig. 1). It is apparent that the telescopes of larger apertures secure significantly lower energy threshold, defined as the peak energy of the differential detection rate. Increase in the telescope aperture from 17 to 30 m leads to a reduction of the energy threshold from 80 GeV down to 30 GeV. It is worth noting that the array of three 30 m telescopes provides rather high detection rate of 10 GeV γ rays (see Fig. 1).

Angular Resolution

For each individual γ-ray shower the images in all triggered telescopes can be used for stereoscopic reconstruction of the shower direction. In the present analysis, only 'high-quality' images of amplitude grater than 50 ph.-e. with their center of gravity located at the angular distance less than 1.2° from the camera center are accepted for the directional reconstruction. The shower arrival direction, i.e. the mean weighted intersection point of major axes in the camera focal plane of all available high-quality images, has been computed for each simulated event. Distribution of arrival directions for simulated γ-ray showers (see Fig. 2) can be fitted to a two-dimension Gaussian function. The σ-parameter of the Gaussian fit stands for the angular resolution of the directional reconstruction. Results obtained for telescopes of various aperture sizes are summarized in Fig. 3. Interestingly, an array of three telescopes with larger apertures may noticeably improve the angular resolution at low energies (below 100 GeV). The low energy γ-ray showers observed with the telescopes of relatively small aperture generated images of a very small size, barely overruning the threshold of 50 ph.-e., and it does not allow an accurate measurement of the image orientation. In addition, most of these images are located very close to the center of the camera's field of view and reveal poorly recognizable elliptical shapes. The telescopes of larger apertures drastically increase the photoelectron content of the recorded images and therefore enable registration of low energy γ-ray showers at much larger impact distances . Both factors help to improve the angular resolution.

Background Rejection

In fact, the Cherenkov image is a two-dimensional projection of the development of the air shower in space. More sensitive telescopes can see more Chrenkov light from the same air shower. A larger telescope could see Cherenkov emission from many more branches of atmospheric cascades and correspondingly provides a better picture of the shower development. A toy model air shower has a spacial shape of a spheroid of given width and length.The canonical parameters of image shape, *Width* (w) and *Length* (l), approximately reproduce the actual spacial extent of the shower. Thus the volume of the spheroid containing all charged particles emitting Cherenkov light in the shower can be estimated as $V_c \propto w \times w \times l$ (deg^3). The total amount of light accumulated in the shower image, *Size* (s), directly relies on the telescope sensitivity and primarily its aperture. Such a toy model suggests that the mean spacial density of Cherenkov light emitted within the shower vol-

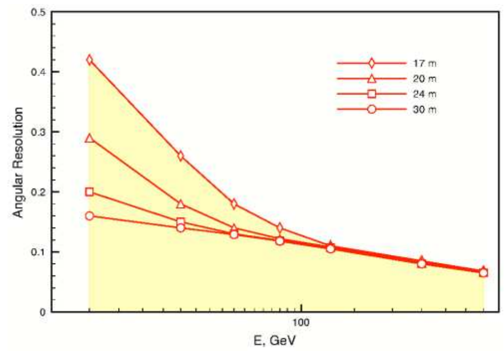

Figure 3: Angular resolution (σ-parameter) of the array of three telescopes of various aperture sizes.

ume, $\rho = s/V_c$ (ph.-e./$\deg^3$) is independent of the telescope aperture. In Fig. 4 the parameter ρ^{-1} is plotted for γ-ray showers of energy from 50 to 100 GeV registered by the telescopes of various aperture sizes. Indeed, the distribution of the ρ^{-1}-parameter for different telescope apertures show similar shapes. Note that such scaling does not work for the cosmic-ray showers, which have irregular spacial profile, and therefore it can be used as an additional selection criterion.

Very high fluctuations in shower development of the low-energy γ-ray showers is a major limiting factor for effective rejection of dominating background cosmic-ray showers. Despite the evident advantages in imaging with telescopes of larger apertures, the rejection power still remains very poor in the energy range below 100 GeV, irrespective of telescope aperture. Using an analysis based on standard parameters of image shape (*w*, *l*) the rejection factor of cosmic-ray background can be scaled with the shower energy within a 10-100 GeV energy range as $q \propto 7 \cdot (E/20\,GeV)^{2/3}$, providing a constant acceptance of γ-ray showers at the level of about 60%. Thus, at low energies the rejection power only marginally improves with the rise of the telescope aperture.

Sensitivity

Stereoscopic arrays of IACTs of large apertures enable very high detection rates of γ-ray showers of energy from 10 to 100 GeV. It is apparent that the integral detection rate of γ rays is a strong function of the telescope aperture, $R_\gamma \propto 2 \cdot (\mathrm{D}/17\,\mathrm{m})^{3/2}(\mathrm{Hz})$ (Crab-like source). The detection area of 20 GeV γ-ray showers for the ar-

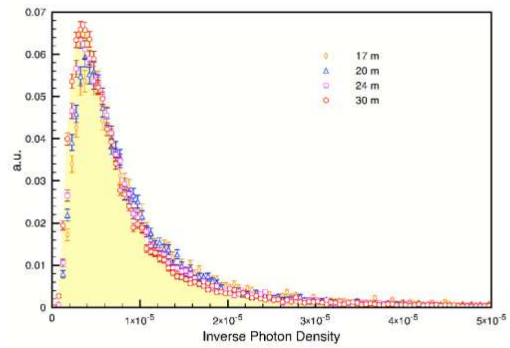

Figure 4: Distribution of parameter ρ^{-1} for simulated γ-ray showers of energy from 50 to 100 GeV seen by telescopes of different apertures.

ray of three 30 m telescopes is by a factor of ten larger than that of the array of 17 m telescopes. The estimated sensitivity of the array of three 20 m-class telescopes is $\mathrm{F}_\gamma^{\min}(> 20\,\mathrm{GeV}) \propto 6 \cdot 10^{-11}(\mathrm{D}/17\,\mathrm{m})^{-2.5}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Summary

In the past, the development of instrumentation for the ground-based VHE γ-rays astronomy was mainly driven by the reduction of energy threshold. The low energy threshold evidently gives a significant increase in a number of γ-ray events for the same observing time, given the rather steep energy spectra of many well-established TeV γ-ray sources. Expansion into sub-100 GeV energy domain brings this technique to unavoidable performance limitations. However, future arrays of telescopes of large apertures can still be efficient enough for effective detection of a few tens of GeVs γ rays, and they can be very competitive when measured against other ground-based or space-born detectors operating in a similar energy domain.

References

[1] W. Hofmann. *γ-Ray Workshop, Palaiseau, 2005, astro-ph/0603076v2*.

[2] I. de la Calle Perez and S.D. Biller. *Astropart. Phys.*, 26:69, 2006.

[3] A. Konopelko. *Astropart. Phys.*, 24:191, 2005.

[4] CTA: Cherenkov Telescope Array. *www.mpi-hd.mpg.de/hfm/CTA/CTA.html*.

[5] A. Konopelko et al. *NIM*, A450:419, 2000.