29th International Cosmic Ray Conference Pune (2005) **5**, 391–394

Monte Carlo studies of possible upgrades of current arrays of imaging Cherenkov telescopes

Gernot Maier and Johannes Knapp
University of Leeds, LS2 9JT Leeds, United Kingdom
Presenter: Gernot Maier (gm@ast.leeds.ac.uk), uki-maier-G-abs1-og27-poster

At present several second generation imaging Cherenkov telescope systems are in operation (CANGOROO [1], HESS [2]) or currently under construction (MAGIC [3], VERITAS [4]). All are based on the idea of a telescope array with 2-4 telescopes operating together. The main advantages of these systems compared to stand-alone telescopes are superior rejection of background events from primary muons or cosmic rays showers, angular resolution of $\sim 0.1^\circ$ or better, energy resolution $<20\%$, and significant sensitivity in the energy range below 100 GeV. We discuss in this paper four different scenarios for future upgrades of these experiments: the addition of telescopes, and the replacements of the cameras by systems with either higher pixel densities, larger fields of view, or new high quantum efficiency photodetectors. The analysis is based on Monte Carlo simulations, the VERITAS design is used as a representative example for the different IACT systems. Direction reconstruction accuracies, off-axis acceptance, energy thresholds, and γ-ray detection rates are compared.

1. Introduction

The rapid development of gamma-ray astronomy in the energy range between 150 GeV and 1 TeV is well documented by the contributions to this subject area in these proceedings. The number of detected galactic and extragalactic sources in the field has been almost doubled over the last two years and flux sensitivities below 1% of the flux of the Crab Nebula have been achieved. In 2006, four systems of imaging Cherenkov telescopes located in both hemispheres will be operational and further increase the catalog of high energy gamma ray sources. The history of the Whipple telescope shows that these systems will likely undergo several upgrades over the next ten years.

The goal of all upgrades is to achieve higher flux sensitivity for time resolved studies of variable objects (like AGNs, GRBs,..), to extend the energy range into the 10-100 GeV range, and to improve the angular reconstruction accuracy. The interest in lower energies is motivated by the large number of detected gamma-ray sources in the sub-GeV region by the EGRET experiment, the steep energy spectra of most sources, and the extended γ-ray horizon. Higher angular accuracy is motivated by the study of extended sources and the high physics potential of spatially resolved imaging of gamma-ray sources. The large extension of sources like RXJ 1713.7-3946 ($\sim$ 15 arcmin [2]) is motivation for considering cameras with large field of views. These cameras help are well suited for an efficient sky survey and the detection of serendipitous sources. Additionally, an improvement of the detection of high energies events is expected.

The different configurations of the telescope arrays examined are summarized in Table 1. The basic shape of the array is a hexagon with a side length of 80 m and one telescope at the center. In the case of four telescopes, only every second corner of the hexagon is occupied. Each telescope consist of a Davies-Cotton reflector of 12 m diameter. The focal length is 12 m. The cameras are equipped with circular shaped photomultipliers with characteristics similar to the Photonis XP2970 models. Light cones are simulated, which yield a geometrical collection efficiency for Cherenkov photons hitting the focal plane of 90%. The local trigger system consists of a simple multiplicity trigger of three PMTs with signals above threshold in a time window of 5 ns. The trigger thresholds are chosen to be at a constant signal-to-noise level. (see Table 1). The array trigger requires at least two telescope with a local trigger in a time window of 10 ns.

The current development in high quantum efficiency PMTs (HEPMTs) show, that at least a factor of two in

Table 1.

Name	number of telescopes	field of view	no of PMTs per camera	PMT radius [mm]	trigger threshold [pe]	high efficiency PMTs
V4	4	3.5°	499	15	6.5	no
V4(HEPMT)	4	3.5°	499	15	9.0	yes
V4(FINE)	4	3.5°	1498	8.8	3.5	no
V4(LFOV)	4	5.5°	1273	15	6.5	no
V7	7	3.5°	499	15	6.5	no

improvement compared to the current available PMTs is feasible [5]. For this analysis, the quantum efficiency of the Photonis XP2970 is simply multiplied by two. Almost equivalent to the use of HEPMTs, and therefore not taken into account here, is the extension of the mirror size, which increases the Cherenkov photon collection area.

2. Simulations

The Monte Carlo simulations consist of shower simulations with CORSIKA 6.20 [6] followed by detailed modeling of the telescope arrays [7]. The atmospheric profile is modeled using a U.S. Standard atmosphere. The observation height for the telescope system is 1800 m a.s.l.. Showers of primary gamma-rays are simulated according to a Crab-like spectrum in the energy range from 10 GeV to 10 TeV with a zenith angle of 30°. The energy spectrum of the Crab Nebula is taken from [8] as $J = 3.2 \times 10^{-7}(E/1\mathrm{TeV})^{-2.49}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$. The shower cores are distributed randomly on a circular area with a radius of 500 m around the center of the array. The telescope simulation consists of two parts, the propagation of Cherenkov photons through the optical system and the response of the cameras and electronics. The signal in a PMT is created by summing up single photo-electron pulses with appropriate time and amplitude jitters applied. Night sky background, electronic noise and all efficiencies, including mirror reflectivities, geometrical, quantum, and collection efficiencies, and losses due to signal transmission have been modeled. The simulation chain has been extensively tested to reproduce the characteristics of the VERITAS-1 telescope [9].

3. Event reconstruction

The event reconstruction chain consist of image cleaning, second moment image analysis [10] for the signals in each camera and the reconstruction of shower direction and impact parameter on the ground, using all available images. Images are cleaned by cutting on pixels with low signal-to-noise ratio at values of five and three times the pedestal variations for image and border pixels, respectively. In the second moment analysis the axes and widths of the 2dim Gaussian are determined, that fits the image best. Images of the size of at least five pixels are chosen for the array reconstruction. The intersection of the elongated longer axes of the different images defines the reconstructed shower direction [11]. Only events with at least three images are used.

4. Energy thresholds and trigger rates

Fig. 1 shows the differential γ-detection rate for a Crab-like source. The figure on the left shows the differential energy spectrum for events with at least three telescopes with a local trigger. It shows that four telescopes equipped with high efficiency photomultipliers are, at the trigger level, equivalent to a system with seven telescopes. The energy threshold is conventionally defined as the position of the peak at the energy spectrum of the source convoluted with the effective area with the detector. It is 140 GeV for the system called V4 and

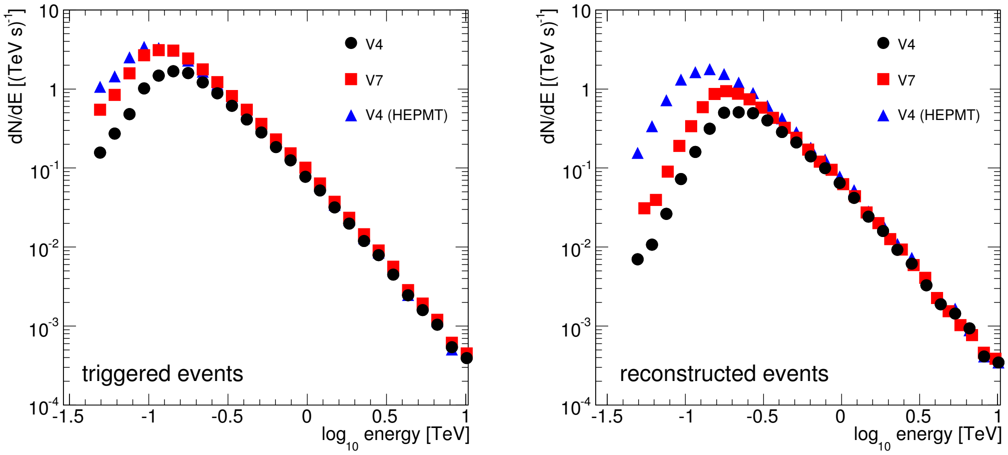

Figure 1. Differential trigger rate for a Crab-like source for events with at least three triggered telescopes (left) and after cuts on successful reconstruction (right) (see Table 1 for description of the labels).

125 GeV for V4 HEPMT and V7. The respective integral rates of γ-rays from the Crab Nebula are 31, 49 and 50 γ's/min.

Fig. 1 right shows the differential energy spectrum for events available for the reconstruction, i.e. with at least three images of more than four pixels each. Four telescopes with HEPMTs have a significantly lower energy threshold (125 GeV) and higher γ-ray rate (31 γ's/min) than all other cases (200 GeV, 20 γ's/min for seven telescopes, 225 GeV and 15 γ's/mim for four telescopes). The high quantum efficiency cameras have in general much better defined images with more pixels, which results in the better performance after reconstruction. The seven telescope array is as sensitive as four telescopes with HEPMTs at low energies, but most images are too small to be useful in the reconstruction.

The off-axis sensitivity for γ-rays with 150 and 500 GeV primary energy is shown in Fig.2 left. Only events which triggered at least three telescopes are included here. Not surprisingly the system equipped with the wide field of view cameras accepts showers out to the largest offset from the pointing direction ($\sim 2°$). Seven telescopes have an acceptance generally about 50% higher than systems with high efficiency cameras or V4. All cameras with 3.5° field of view show a strong decrease in acceptance with larger offsets.

5. Reconstruction Accuracy

The angular resolution is here defined as the 68% value of the distribution of the differences in space angle between actual and reconstructed source position. As can be seen in Fig.2 right, the angular resolution is energy dependent and is at the level of 0.1° or better. Seven telescopes give the best angular resolution for all energies, systems with high efficiency PMTs give a significant improvement at small energies. This is for the latter one due to the large images, which results in a better determination of the orientation of the image axes. The performance of the optical system and fluctuations of the lateral extension of the light-emitting region in the shower limit the precision of the angular reconstruction, better results can only be achieved by averaging over several measurements of the same event. This is the reason why the system with smaller PMTs is mainly better at smaller energies than four telescope systems (it has more images with at least five pixels), and the seven telescope system gives a significant improvement over the whole energy range.

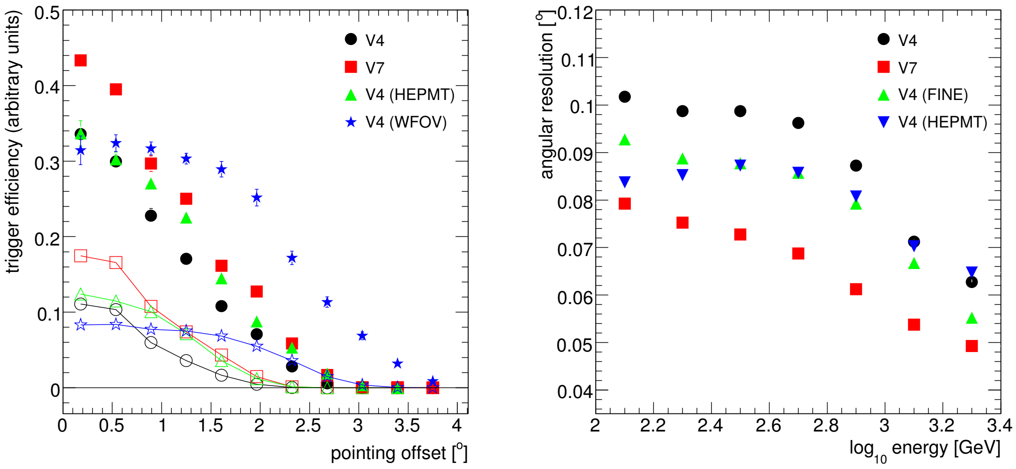

Figure 2. 3-telescope trigger efficiency for off-axis sources (left, open symbols: 150 GeV γ-ray showers, filled symbols: 500 GeV showers). Angular resolution vs. primary energy (right) (see Table 1 for description of the labels).

6. Conclusion

This study of possible extension to arrays of imaging Cherenkov telescopes shows that a replacement of the current photomultipliers by high quantum efficiency PMTs give the best overall improvement. In particular the low-energy performance: the number of images per event and reconstruction accuracy is better or equivalent to seven telescopes. Increasing the number of telescopes has on the other hand additional advantages of flexibility and the option of observing multiple sources simultaneously. As well, it has to be mentioned, that high quantum efficiency PMTs are still in the R&D phase and presently not available on large scales.

Acknowledgments

GM acknowledges the support as a Feodor Lynen Fellow of the Alexander von Humboldt foundation.

References

[1] C. Itoh et al., Astronomy & Astrophysics, 402, 443 (2003)
[2] F. Aharonian et al., Nature, 432, 75 (2004)
[3] C. Baixeras et al., Nucl. Physics B (Proc. Suppl.) 114, 247 (2003)
[4] T. Weekes et al., Astroparticle Physics, 17, 221 (2002)
[5] D. Paneque et al., NIM A, 504, 109 (2003), E. Lorenz et al., NIM A, 504, 280 (2003)
[6] D. Heck et al., Report FZKA 6019, Forschungszentrum Karlsruhe (1998)
[7] C.Duke & S.LeBohec, http://www.physics.utah.edu/gammaray/GrISU/
[8] M. A. Hillas, The Astrophysical Journal, 503, 744 (1998)
[9] G. Maier et al., *Monte Carlo Studies of the first VERITAS telescope*, 29th ICRC, Pune (2005)
[10] M. A. Hillas, Proc. 19th Int. Cosmic Ray Conf., 3, 445 (1985)
[11] W. Hofmann, Astroparticle Physics 12, 135 (1999)