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Performance of a prototype system of Cherenkov telescopes at high altitude

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The current generation of Cherenkov telescopes have mirror collection areas of 57–240 m^2 and operate at roughly 2 000 m above sea level. In this contribution, a **H**igh **A**ltitude **T**elescope **S**ystem (HATS) with comparably small (28 m^2 mirror area) Cherenkov telescopes at a high altitude site (4 300 m a.s.l.) is studied via detailed Monte Carlo simulations. The performance in terms of energy threshold (150 GeV) and sensitivity is improved as a consequence of the high altitude site with respect to a smaller altitude site. A system of telescopes of this size is inexpensive and competitive with current telescopes for point like sources. Furthermore, it could serve as a prototype for future large Cherenkov telescopes at high altitude sites.

1. Introduction

The current generation of major imaging Cherenkov telescopes has established γ-ray observations as an active and succesful part of high energy astrophysics. The developments of the field are currently aiming at further reducing the energy threshold to reach ultimately the lowest achievable energy threshold with the air Cherenkov technique of approximately 5 GeV as suggested in [1]. Currently, different approaches on how to reduce the energy threshold determined by the sensitivity to detect air Cherenkov light are being discussed: (i) Increase of the mirror dish size (ii) improve the quantum efficiency of the photon detectors (iii) increase the observational altitude. The approach (i) is currently followed by the H.E.S.S. collaboration suggesting to add a large 600 m^2 telescope to the existing 4 H.E.S.S. telescopes. The MAGIC collaboration has been investigating the use of enhanced quantum efficiency detectors including GaAsP hybrid photon detectors which reach quantum efficiencies of up to 50 % at roughly 500 nm (see e.g. [2]). A better rejection of the night sky background by use of fast digitization is already approaching the limit given by the intrinsic width of the Cherenkov light pulse.

Finally, we consider approach (iii) in this contribution in the context of a prototype array of Cherenkov telescopes (HATS). The comparably small prototype telescopes suggested with a mirror surface of 28 m^2 each are substantially smaller and therefore less expensive than the current generation of instruments which have a mirror surface in the range of 57–240 m^2. Certainly, operating a Cherenkov telescope at a high altitude site is challenging as the site would be remote, the weather conditions include a number of hazards, and the construction and operation of a telescope given the low air pressure are additional complications. The problems of the remoteness and the difficult working environment for an on-site shift crew could be overcome by designing the telescopes for automated or even robotic operation.

2. Simulations and results

Simulations

The simulations used are based upon CORSIKA v6.022c [4]. The altitude was chosen to be 4 300 m a.s.l. An array of 5 telescopes with 28 m^2 mirror surface area on a square with 85 m side length plus a central telescope has been simulated. The mirror dish is assumed to have an aperture of 6.5 m diameter with 100 individual 60 cm diameter glass mirrors following the Davies-Cotton spherical design. The focal length is set to 7.5 m which corresponds to a f/D=1.25 necessary for a good image quality. A parabolic mirror is not required given the small time dispersion of less than 1 ns in the Davies-Cotton setup. The camera consists of 271 photo multiplier tubes arranged in a hexagonal pattern with Winston cones to enhance the light collection and reduce stray light contamination. The individual pixel diameter corresponds to a full opening angle of $0.16°$ and the field of view of the camera is 3° wide. The trigger required for individual telescope is a coincidence of 2 neighboring pixels exceeding a signal of 6 photoelectrons. The simulation includes the effect of night sky background. The multi-telescope trigger requires two telescopes to trigger to register an event. The detector simulation [5] includes complete ray-tracing, detailled simulation of photo-multiplier response, triggering, and digitization. The same simulation has been in use and verified with the HEGRA and H.E.S.S. Cherenkov telescopes. In particular, the camera and electronics setup used here is almost identical with the one succesfully used to model the HEGRA Cherenkov telescopes.

For the study of the performance of HATS several different sets of simulated air showers have been produced including γ-ray, proton, and Helium initiated showers with vertical incidence direction. The core location is randomly chosen to fall in circular area with a diameter of 800 m. The γ-ray spectrum simulated follows the spectral shape of the Crab nebula [3] whereas for the charged cosmic rays the directly measured cosmic ray spectral energy distribution of the proton and Helium species have been used. Heavier elements have not been included in this set of simulations but previous simulations have shown that including heavier species increases the overall trigger rate by less than 10 % [6]. The charged cosmic rays have been simulated to be isotropic within a cone along the optical axis of the telescope with half opening angle of $5°$ which is sufficiently broad to include triggers of far off-axis events. The gamma-rays have been simulated to be inclined to the optical axis by 0.5° to simulate the realistic case of a wobble type observation in which a background estimate is derived using a displaced background region in the camera's field of view.

Results

The background rate of charged cosmic rays at the trigger level is for protons 15.5 ± 1.6 Hz, for Helium 5.5 ± 0.5 Hz and for heavier species estimated to be less than 2 Hz. For γ-ray events from a Crab like source, the integral rate of event triggers is 0.24 Hz.

The collection area and differential trigger rates are shown in Fig. 1 (a,b). For means of comparison, the figures also include the respective curves for a smaller version of the proposed telescope with only 8.5 m^2 at 2 200 m a.s.l. and at 4 300 m a.s.l. to disentangle the improvement of energy threshold as a consequence of the altitude and as a result of changing the mirror size. In Fig. 1a, the effect of the reduced size of the Cherenkov light pool is clearly visible: While getting closer to the shower maximum, the size of the light pool decreases while the photon density increases. Additionally, the impact of absorption is reduced as the atmospheric column density traversed by the light is reduced with respect to a lower altitude site. The fraction of light suffering Rayleigh scattering is reduced. The effect of Mie scattering depends strongly on the site and may not be improved by chosing a high altitude site. In the simulations performed here, a desert-like atmosphere with the corresponding aerosole profile has been assumed.

The threshold defined as the peak in the differential count rate is reduced by a factor of two (from about 600 GeV to 300 GeV) when moving the telescopes closer to the shower maximum. Finally, increasing the mirror surface by more than a factor of three reduces the threshold to below 200 GeV. Note, the trigger settings have remained the same for all set-ups.

The simulated showers triggering at least two telescopes are subject to a simple reconstruction algorithm: The image analysis includes a two stage tail cut to remove night sky background contaminated pixels and the first three moments of the cleaned images are calculated. Finally, the major axes of the images of multi-telescope events are combined to calculate geometrically the direction and impact parameter of the air shower. The resulting sensitivity is calculated for a 50 hour observation using cuts on the shower direction and image

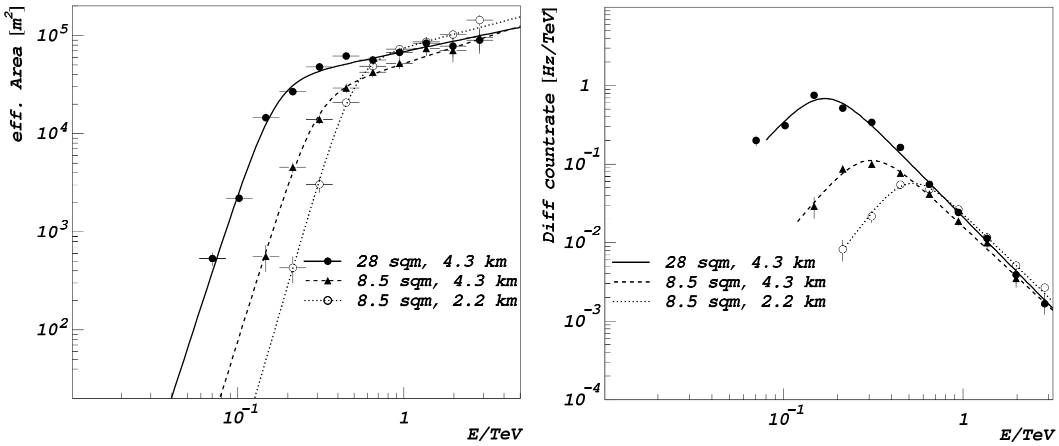

Figure 1. a) Collection area for triggered events. b) Differential count-rates for a Crab like source: The three set-ups considered are a small dish (8.5 m^2) at 2.2 km a.s.l. and 4.3 km a.s.l. and a larger dish (28 m^2) at 4.3 km. This allows to disentangle the effect of the altitude and of increasing the mirror area on the energy threshold. The collection area of the telescopes decreases for events well above threshold as the geometrical size of the light pool decreases with increasing altitude. Note, the change of the threshold (defined as the peak in the differential count rate) as the telescopes are located closer to the shower maximum (from 2.2 to 4.3 km a.s.l.): The energy threshold decreases by a factor of 2 from about 600 GeV to 300 GeV while when additionally increasing the mirror size decreases the threshold to below 200 GeV. The trigger threshold setting of the telescopes is identical for all three set-ups.

parameters which are chosen to retain 50 % of the γ-ray signal. These cuts are not optimized but chosen in such a way that in realistic observations, spectroscopy over a wide range of energies will be possible. Cuts with a substantially smaller efficiency for γ-ray detection give a slightly improved sensitivity albeit with strongly reduced event statistics at high energies.

The resulting sensitivity curve for 50 hours and 5 σ detections with at least 10 excess events is shown in Fig. 2, adapted from [7]. The sensitivity curve is shown together with the respective curves for other currently operational (MAGIC I, HESS) and future installations (MAGIC II, VERITAS, GLAST). As can be seen, the expected sensitivity of HATS is similar to the one obtained with MAGIC I above 150 GeV and close to the one of H.E.S.S. below 1 TeV. At higher energies, the sensitivity is limited by the small field of view and the reduced size of the Cherenkov light pool at high altitudes. But clearly, sources with a few per cent of the Crab flux are detected within 50 hours of observation time. As an example, the expected observation time to detect Cas A with 5 σ is estimated to be 20 hours with some uncertainty depending on the mostly unconstrained energy spectrum [8]. The marginally extended first unidentified source of TeV γ-rays (TeVJ2032+4130 [9]) is expected to be detected with HATS within 7 hours of observing time [8].

3. Conclusions

The challenging task of reducing the energy threshold of future ground based γ-ray observations may be solved by installing Cherenkov telescopes at high altitude sites [1]. However, the technical difficulties associated with the installation and operation of large aperture ($A_{\rm mirr} > 100$ m^2) Cherenkov telescopes at high mountain altitude are not yet fully solved. A prototype system as suggested here (HATS) could serve in multiple ways

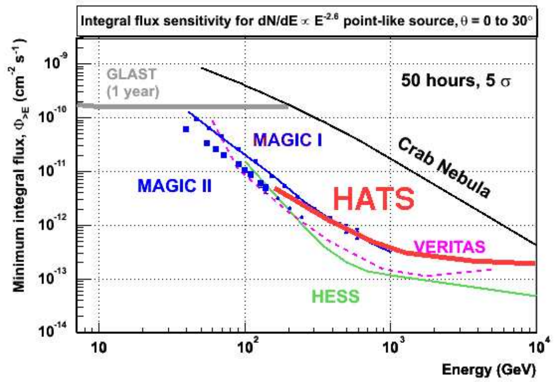

Figure 2. The sensitivity for an integral flux above energy E for 50 hours of observation time, requiring at least 10 excess events. The figure is adapted from [7].

to (i) verify the predicted performance and the reduced energy threshold (ii) establish the key technologies including robotic operation, and (iii) serve as a competitive instrument for astrophysical observations in the very high energy gamma-ray band. In the context currently operational the new telescope systems, HATS would naturally extend the coverage of variable sources in the time domain and could be a new member of currently forming international networks [10].

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