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MC Simulation and Layout Studies for a future Cherenkov Telescope Array

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Abstract: Detailed Monte Carlo simulations of possible configurations for a future large-scale installation of Imaging Atmospheric Cherenkov Telescopes, the CTA (Cherenkov Telescope Array), have been carried out. This includes a full treatment of shower fluctuations, night sky background, registration of the signal and reconstruction of the registered showers. Although not representing a detailed design study, the simulations demonstrate that a sensitivity at the level of 1 mCrab can be achieved with existing technology and analysis methods. Spectra of somewhat stronger sources may be measured over more than three orders of magnitude in energy. Combining a large number of IACTs allows to achieve unprecedented levels of hadron rejection and angular resolution. Among the options studied are systems with a modest number of very large telescopes and/or larger numbers of smaller telescopes, of different spacings, pixel sizes, etc. Systems consisting of two or three different telescope sizes may achieve an energy coverage from a few 10 GeV to 100 TeV and more.

Introduction

After detection and study of little more than a handful of VHE γ-ray sources by the first and second generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) and IACT systems, the current generation has tremendously extended the list of known Galactic and extra-galactic sources. The most important ingredients to this success have been the improved sensitivity, in particular with stereoscopic systems, and also the increase in the energy range coverage. VHE γ-ray observations have more and more impact in mainstream astrophysics and astro-particle physics. But current instruments are still far from fully exploiting the IACT technique. A major step forward is planned with the *Cherenkov Telescope Array* (CTA) as a large-scale installation, aiming at another big improvement in sensitivity and increasing the energy coverage once again.

The actual performance of an array of IACTs depends on a large number of technical and design parameters. These include the general layout of the installation, including telescope optics, field-of-view and pixel size, signal shapes, and trigger logic. Many of these parameters are intimately related, either technically or by constraints on the total cost. As the impact of most parameters on the overall performance is not straightforward to evaluate in a quantitative way, a full simulation of the detector response to gammas and background events is generally needed. Since the gamma-hadron discrimination of CTA is going to surpass even that of the best current instruments by a large margin, huge numbers of background showers have to be simulated. Analytical methods or semi-analytical simulation tools cannot help in this novel regime where only rare combinations of random fluctuations in the development of hadron-induced showers lead to events that would be mistaken as gamma-showers.

Simulations and analysis

Current MC simulation studies, preceding a detailed CTA design study, started from a number of predefined configurations - based on experience with prior and current instruments. Different simulation and analysis codes were adapted and applied to these configurations, including the Heidelberg H.E.S.S. simulation code `sim_hessarray` as well as the MAGIC-II simulation and analysis codes. At the shower simulation level, both of these use CORSIKA [1] but are completely independent in the subsequent simulation of the telescope response and in the analysis of the resulting data. About 10 billion (10^{10}) proton-induced events plus electron background were simulated in addition to more than a billion γ-ray events, distributed over four different base configurations.

The image analysis basically followed standard second-moments stereo analysis practises, as outlined in [2]. For low-energy events additional gamma-hadron discriminating parameters were found to be very useful, including the height of shower maximum $h_{\max}$, the variance of energy estimates from individual telescopes, and so on. Different gamma-hadron discrimination methods were tried and used, including standard box cuts on image intensities, mean reduced scaled width and length of the images (shape cuts), reconstructed direction (angle cut), $h_{\max}$, and so on, but also Random Forest methods (see [3] for details), based on the same or largely equivalent gamma-hadron discrimination parameters. Results from both analysis methods are consistent but preliminary and subject to further improvements – in particular in the low-energy domain.

As far as sensitivity is concerned, the traditional representation is the integral flux limit $F_{\min}(> E)$ for a 5 σ significance detection with at least 10 signal events above an energy E. But for many purposes, a differential flux limit with the same constraints for each energy bin is more useful (typically with four or five bins per decade in energy). We used the Li&Ma approximation [4] for the resulting significance. Systematics in the background determination are taken into account by effectively combining 1% of the remaining background after cuts with the square of statistical errors in the signal region.

Simulated system configurations

The present study focused mainly on the low to medium energy range on the scale of current IACT instruments, i.e. a few 10 GeV to a few TeV. Nei-

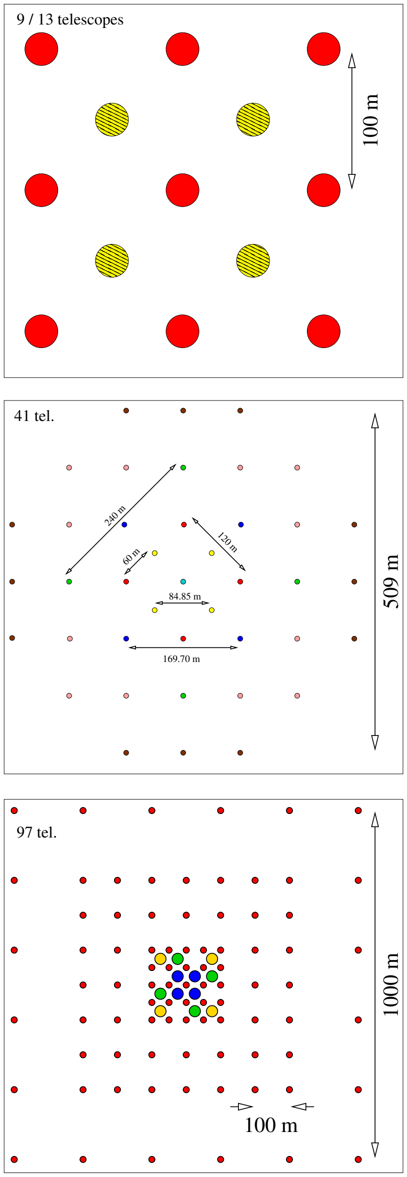

Figure 1: Simulated configurations. Top: 9- and 13-telescope configurations, with telescopes of about 420 m^2 mirror area each. Middle: A system of 41 telescopes of about 100 m^2 each, covering a wide range of telescope separations. Bottom: A very large array (covering 1 km^2) with 97 telescopes, including three sets of four telescopes with 600 m^2 mirror area each plus another 85 telescopes of the 100 m^2 class, with relatively wide f.o.v. and high quantum efficiencies.

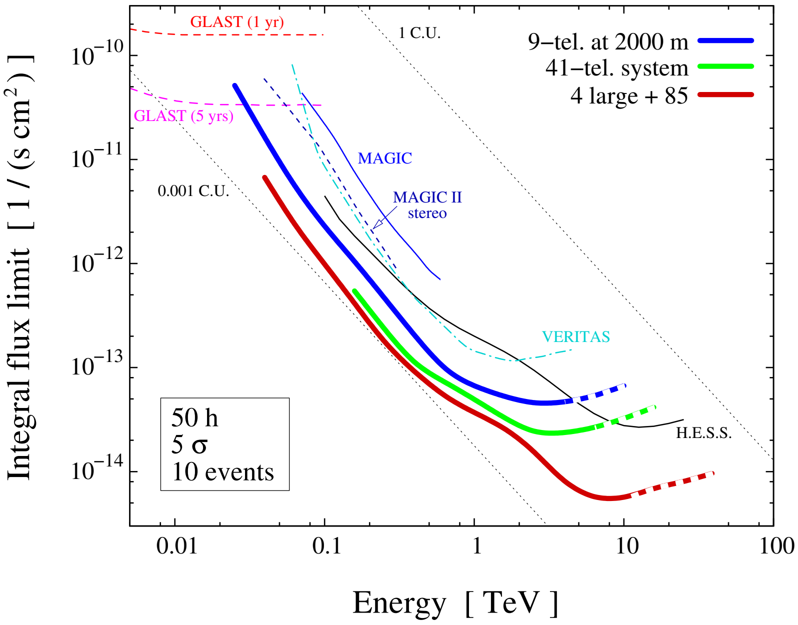

Figure 2: Comparison of conventional integral flux $F(>E)$ sensitivity of three test configurations at 20° zenith angle with current and near-future IACTs [2, 5, 6] as well as the GLAST all-sky survey [7]. The '1 Crab Unit' (C.U.) and milli-Crab dotted lines correspond to the HEGRA power-law fit to the flux of the Crab Nebula [8]. Note that array configurations and in particular data analysis have not been optimized yet (and cuts not optimized for high energies, see dashed part of lines).

ther the system configurations nor the analysis was optimized for high energies (above 10 TeV).

Configurations studied so far include systems made of one size of telescopes only (either very large – 23 m – or moderate size – 12 m), as well as systems with two different telescope sizes (28 m and 12 m). Layouts include systems with constant spacing of telescopes as well as graded spacings – densely packed in the centre and more widely separated at the perimeter. While most of the simulations were done for 2000 m or 1800 m altitude, some were also carried out for higher altitudes up to 5000 m. Figure 1 shows the three basic configurations tested at low altitudes. The final CTA layout emerging from a full design phase will not necessarily resemble any of them.

While the 12 m telescopes resemble current H.E.S.S. telescopes, both in terms of the Davies-Cotton optics and the camera pixels, the larger telescopes are based on parabolic dishes with spherical mirror tiles and finer pixels (0.10° for the 23 m and 0.07° for the 28 m telescopes). A field of view of 5° was assumed, except for the 12 m telescopes in the 97-telescope configuration with 7° f.o.v. PMTs with standard bi-alkali quantum efficiency and afterpulse rates were assumed except for the 97-telescope configuration with a 50% higher Q.E. and correspondingly higher night-sky background.

Integral and spectral sensitivity

Figure 2 shows the integral sensitivity of the three low-altitude test configurations for 50 hours of observation time in comparison with a number of current and near-future ground and space-based detectors. An improvement of up to an order of magnitude with respect to the best current instruments is seen, despite analysis techniques being still under development.

Even more dramatic can be the improvements in the capability to obtain high-quality spectra within a short time-frame, as illustrated in figure 3 for a

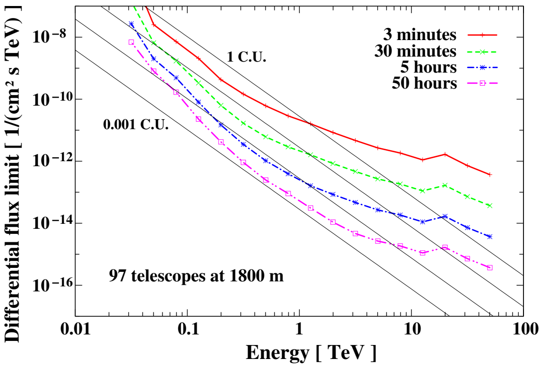

Figure 3: Differential sensitivity (5σ significance, at least 10 events in each energy bin) of a system consisting of 12 telescopes of 600 m^2 mirror area plus 85 telescopes of 100 m^2 (figure 1 bottom) for different observation times.

system of 97 telescopes. Within 5 hours of observation time of a 0.1 C.U. source, high quality spectra could be obtained from 30 GeV to 10 TeV. Or within just 30 minutes from 50 GeV to 1 TeV, only counting spectral bins detected at 5σ significance or better. If the instrument would be dedicated to an all-sky survey, such a survey could be accomplished within two years at a level of one to two percent of the Crab flux.

Important factors for the improvement in sensitivity include the area covered, the γ-hadron separation and the angular resolution. For fixed total cost, each of them depends in different ways on the telescope size and separations. For the largest energy range accessible to a single IACT system, a dense central core of large telescopes plus a wider array of smaller telescopes seems the obvious solution. As it turns out, the wider array also improves γ-hadron separation at the lowest energies by vetoing against hadron showers where a γ-like sub-shower would be picked up by the large central telescopes. For such reasons, it turns out to be important to simulate the response of the full telescope systems and not each component individually.

At high altitudes, the threshold energy is typically reduced by a factor of two but remaining backgrounds after cuts are larger than at lower altitudes. At the lowest energies their sensitivity would typically be dominated by background systematics after a few hours of observation time. High altitude sites seem better suited for observations of short-term variability than for long observations of steady sources – in particular after an all-sky survey by GLAST.

Conclusions and outlook

Preliminary studies of a future Cherenkov Telescope Array have been carried out, indicating that the desired 1 milliCrab sensitivity can be achieved, at least in the 100 GeV to 1 TeV range. For covering a wide energy range at a reasonable overall cost, at least two different telescope types/sizes will be required. A third type of smaller telescopes with fewer readout channels may be required to extend the energy range to 100 TeV and beyond. Proper optimization of the telescope parameters and the CTA layout will be done in the forthcoming design phase. At the same time, analysis methods will be better adapted to complex IACT systems. Based on the results of our initial study with non-optimized layouts and rather simple analysis methods, prospects look indeed bright that CTA can achieve its design goals – including a milli-Crab sensitivity – within the anticipated budget.

References

[1] D. Heck et al. CORSIKA: A Monte Carlo code to simulate extensive air showers. Technical Report FZKA 6019, Forschungszentrum Karlsruhe, 1998.

[2] F.A. Aharonian et al. (HESS Collaboration). *Astron. Astroph.*, 457:899–915, 2006.

[3] R.K. Bock, A. Chilingarian, M. Gaug, et al. *Nucl. Instr. Meth. A*, 516:511–528, 2004.

[4] T.-P. Li and Y.-Q. Ma. *Astrophys. J.*, 272:317, 1983.

[5] C. Baixeras et al. MAGIC phase II. In *Proceedings of the 29th ICRC, Pune*, volume 5, page 227, 2005.

[6] T.C. Weekes et al. VERITAS proposal. Technical report, 2000.

[7] Toby Burnett. Technical Report LAT DOC AM-04369, University of Washington, 2004.

[8] F.A. Aharonian et al. (HEGRA Collaboration). *Astroph.J.*, 539:317–324, 2000.