

CTA – the Cherenkov Telescope Array

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High energy gamma-ray astronomy is a newly emerging and very successful branch of astrophysics. Exciting results have been obtained by the current generation Cherenkov telescope systems. The design study of the very large Cherenkov Telescope Array system (CTA) with a sensitivity about an order of magnitude better than current instruments and a wider energy coverage from a few tens of GeV to over 100 TeV is ongoing, with a baseline solution based on proven technology, the main challenges being on the cost and reliability fronts. This new facility — CTA — will be operated as an observatory for the science community, based on two sites: Southern, with a wide energy range covering especially the Galactic sources; and Northern, with a focus on low energies for Extragalactic objects. This observatory will reveal an order of magnitude more sources than in the current VHE catalogues, allowing for example population studies of classes such as Pulsar Wind Nebulae (PWNe) and Active Galactic Nuclei (AGN). Due to its higher sensitivity and better angular resolution it will be able to detect new classes of objects and phenomena that have not been visible until now. The scientific potential and status of the design study of CTA are reported.

1 Introduction

The domain of Very High Energy (VHE) Gamma-Ray astronomy has reached maturity with the advent of the latest generation of gamma-ray telescope systems, which have developed the Atmospheric Cherenkov Technique (ACT) to sensitivities which are an order of magnitude over the previous generation. In Europe, H.E.S.S. and MAGIC are the leaders in this domain, having advanced the techniques of stereoscopy for the former and large mirror area for the latter, with both using fast, fine-imaging cameras. With the second phase of these experiments soon in operation, HESS-II will explore the gain from very large image mirror area, while MAGIC-II will introduce stereoscopy. So, there is a clear convergence in operation for the latest generation of ACT telescopes. The idea of launching a large project in Cherenkov astronomy, gathering all the current European expertise in the domain, rapidly took form thanks to the success of this current generation of experiments.

2 Goals of CTA

The goal of CTA is to create the future ground-based gamma-ray observatory, with a jump of a factor of 10 in sensitivity over the currently-operating experiments (down to a milliCrab level), providing a deeper vision of the gamma-ray sky, and allowing much finer temporal resolution for variable sources (e.g. AGNs). In parallel, the energy range to be explored should extend from a few 10's of GeV to above 100 TeV, allowing new source classes to be discovered, and the emission mechanisms in the known source classes to be better investigated (e.g., comparison of leptonic vs. hadronic models in SNRs, binaries), and a wide parameter space for possible Dark Matter annihilation sources to be explored. Additionally, an improvement in angular resolution will not only provide increased background rejection for the point-like sources (AGNs, binaries), but will allow also fine mapping of the extended Galactic sources (PWNe and SNRs) and possibly the nearest extragalactic sources (M87, Cen A). Given that the gamma-ray sky is already known to contain a rich catalogue of sources, full-sky coverage is most desirable, with Northern and Southern installations of the observatory, adapted to the sky coverage, i.e. better low-energy coverage for the Northern installation where the extragalactic sky would be the preferred target, and with a wider energy range for the Southern one for which the region around the Galactic centre will be fully accessible. These goals could be achieved by means of two extended, mixed arrays of Cherenkov telescopes (detailed below) with the additional advantage that such large, extended arrays would have an inherent flexibility of operation, allowing both deep field investigations and surveys, in parallel with monitoring of the brightest variable sources and reactivity to alerts from other instruments.

3 Conceptual Design of CTA

On the basis of the experience with and convergence of the current generation of ACT Telescopes, it is clear that the technology to achieve the goals of the CTA is available, with the current generation being considered as “Prototypes”. The goals can be achieved with extended, mixed arrays of Cherenkov telescopes, with a gradation in telescope performance:

- Detection at the highest energies, from 10–100 TeV, encounter the major difficulty of the sparseness of the signal even from strong sources. This leads to the requirement of an extended array comprising a couple of tens of telescopes over $\sim 10 \text{ km}^2$, of small size ($\sim 5\text{--}7\text{m}$ diameter) but with very wide Field-of-View (FoV, $7\text{--}10^\circ$) in order for air-showers to be seen in stereo by widely-separated detectors, and relatively coarse pixelization ($\sim 0.25^\circ$ or larger). Such an array is mainly required on the Southern site, where Galactic sources — unaffected by absorption of the extragalactic background light — are the preferred target.
- In the core energy range from 100–10 TeV, where the current generation of ACT telescopes operates most efficiently, an extended array is also required for increased collection area, providing a higher proportion of “golden events” where the shower impact parameter is contained within the array (giving better angular resolution and increased sensitivity), and which will also provide flexibility of use of sub-arrays. An array of a few tens of telescopes covering $\sim 1 \text{ km}^2$, of mid-size (10–13m diameter), with wide FoV ($5\text{--}8^\circ$, for mapping of extended objects) and moderate pixelization ($\sim 0.2^\circ$ or smaller) is under consideration.
- At the lowest energies, a central section of a few large telescopes (0–25m diameter), with improved photo-detector performance and a FoV of $4\text{--}6^\circ$ with finer pixelization ($\sim 0.1^\circ$), will provide access to the lowest energies, and therefore to the most distant AGNs and to Galactic sources with spectral cut-offs (e.g. pulsars), as well as linking up to the spectral information provided by satellite detectors (FermiGST, AGILE) at lower energies. As detailed above, the Northern site will concentrate more on this low-energy regime.

The parameters concerning the mix of telescopes, layout, mirror area, camera pixelization, and the electronics' trigger and sampling rapidity are part of the Design Study which is underway within

the collaboration, and are optimized in a multi-dimensional parameter space with consideration given to performance for the physics goals, and to cost and reliability/durability.

4 The CTA Design Study

The Design Study on CTA is proceeding, based on a large consortium of institutes, including most European groups in this and related fields, and interested parties from the US and Japan.

The cost and reliability/durability challenges are primordial in these studies, the latter being of particular importance for such a large project of long duration, since the installations will operate as an observatory with a life-time of the order of 30 years. The cost envelope within which the optimization is being performed supposes that 100k€ will be needed for the Southern site, and 50k€ for the Northern (capital costs). To achieve this goal will already require advances in the cost model for some components, and implies that a gain of a factor of 10 in sensitivity can be achieved with a factor of 10 cost ratio over the current generation.

It should be noted that the project aims to have of the order of 100 telescopes operating in remote locations (on two sites), with of the order of 100,000 electronics channels, and 10,000 m² of mirror area. So, as an indication, an savings/increase of 10k€ per telescope, or 10€ per channel, or 100€/m² per mirror is equivalent to a saving/increase in overall cost of 1 M€.

The Design Study has been divided into a number of Work Packages (WPs) in the management structure, including Physics, Monte Carlo & Data Analysis, Site evaluation & infrastructure, Mirror (optics, control), Telescope (structure, drives, control systems), Focal Plane Instrumentation (photo-detectors, light-guides, mechanics), Electronics (read-out and trigger), Atmosphere Studies and Calibration, Observatory Operation & Access, Data (handling, processing, management, access), and Quality Assurance & risk assessment. The aims of some of these WPs are briefly described below (space does not permit all to be described).

The physics goals are taken into account in the optimization based on certain “benchmark” sources (being defined by the Physics WP given the key physics topics for CTA). The Monte Carlo WP provides the instrument response for a number of base configurations, initially defined using “Toy Model” methods based on full simulations, but a number of these base configurations will be fully simulated using the codes extended from the previous generations (air-shower and instrument simulations). The cost of each element of the base configurations (e.g., mirror area, photo-detectors, electronics, telescope mounts) allows the overall cost to be found, and together with the instrument response should allow the “physics bang-for-the-buck” to be estimated, and the base configurations to be winnowed and adjusted — in a complex feedback loop between the Physics, Monte Carlo, and technical WPs which it is hoped will converge rather rapidly.

The Site WP concerns the evaluation of sites based on a number of defined meteorological, technical, and infrastructural criteria based on existing data (meteo stations, satellite measurements), to achieve a candidate shortlist for which more precise measurements, infrastructure and political evaluations can be made for comparison in the definitive choice.

The Telescope WP goals, as described in the conceptual design above, requires the definition and evaluation of three sizes of telescope, using standard optics (parabolic or Davies-Cotton dishes, with no secondary mirror) as a base-line. The dish type will be adapted to the telescope size, while in general the focal distance relative to the diameter will be kept as large as affordable (1.4–2), for better isochronicity and lower aberrations. For the larger telescopes, active mirror control may be used if the inherent telescope stiffness would not allow a Point Spread Function (PSF) less than 1 mrad. Commercial components will be used as much as possible, for reliability and cost concerns. Note that the 30-year lifetime aimed for requires a failure rate an order of magnitude below the current generation.

In the Mirror WP, the goal is to achieve a 1–2.5 m² hexagonal mirror panel, with a reflectance above 80% in the wavelength range which is useful for the ACT (300–600 nm), weighing less than 30 kgs, with a PSF below 0.6 mrad. Proven solutions exist for this, based either on aluminized monolithic glass or on machined aluminium plate on a aluminium honeycomb, but these suffer

from fast aging and high weight, or from high cost, respectively. New solutions based on carbon-epoxy composites or aluminized glass sheets on a polymer foam substrate are being investigated, with the long-term performance over many weather cycles and response to frosting problems being key issues under evaluation.

Concerning the cameras, the Focal Plane Instrumentation (FPI) and Electronics WPs are major cost drivers. A clear decision has been reached to have a fully-integrated camera, in which the signals from the photo-detectors are processed all the way to digitization and the resulting data are sent over optical fibres to the central data acquisition systems. This approach simplifies the communication and cabling, and allows full advantage to be taken of the rapidity of the Cherenkov signals by telescope-triggering within the cameras. It will also allow a modularity at the camera level to be achieved (in which a “spare” camera can be installed in case of breakdown, pending repair in a central workshop). However, it does engender a heavier camera, requiring careful consideration of the problems of temperature stabilization and weather protection.

The FPI WP is leading studies with industrial partners on the photo-detectors, where the base-line solution of Photo-Multiplier Tubes (PMTs) is being extended with the examination and comparison of new products (super/ultra-bialkali photo-cathodes, hemispherical windows, ...) on the basis of photo-detection efficiency in the relevant wave-length range, accessibility of the single-photo-electron signal for calibration purposes, and low after-pulsing rate for the reduction of random coincidence triggers. The FPI WP also is investigating the camera mechanics and optics, with Winston-cone light guides and protective windows for the cameras, with optimally light-weight, robust, and easy-access camera mechanics.

Within the Electronics WP, major efforts are underway to integrate as many elements of the electronics chain as possible within a single custom Integrated Circuit. These elements include the pre-amplification, pixel-level trigger comparators, analogue signal storage, analogue-to-digital conversion (ADCs), digital signal buffering in FIFOs, and data transfer (LVDS, Ethernet...). Such integration will allow unit costs to be brought down (lower component cost, simpler integration on circuit boards), and will increase the reliability and robustness of the electronics. Partial solutions of this type exist already in current instruments (the “Swift Analogue Memory”, SAM, used in HESS-II and the “Domino Ring Sampler” DRS-2 used in MAGIC-II), but increased integration is sought with the NeCTAr project and the “Dragon” card based around the DRS-4 chip, on which developments are proceeding. The Electronics WP is also concerned with the camera and array triggering for which several solutions exist in current instruments.

Note also that parallel developments proceed on more speculative research efforts (e.g. advanced photo-detectors such as silicon PMs), for which the planned design should not preclude their integration if such technologies mature early, or their integration in later upgrade cycles.

5 Conclusions

The CTA project for the future major of Atmospheric Cherenkov Observatory is proceeding in the Design Study phase, organized in a number of Work Packages whose work is advancing. Prototypes of components are being constructed, which will allow the design decisions to be made and construction to begin in 2012/13, with aim of completion of the full arrays in 2018. CTA will then be the major observatory in VHE gamma-ray astronomy, combining guaranteed astrophysics and physics returns with significant discovery potential.

References

1. Please see the many contributions to these proceedings concerning the current physics from the ACT detectors, and also the contributions for HESS-II and MAGIC-II in near-future upgrades, and that on AGIS for the similar future concept from the mainly North American consortium.