Operating performance of the GCT: an end-to-end Schwarzschild-Couder telescope prototype for the Cherenkov Telescope Array

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Abstract

The Cherenkov Telescope Array (CTA) project aims to build the next generation ground-based Very High Energy gamma-ray instrument. The array will feature different sizes of telescopes to cover a wide gamma-ray energy band from 20 GeV to 300 TeV. The highest energies, above 5 TeV, will be covered by a large number of Small Size Telescopes (SSTs) with a field-of-view of around 10 degrees. The Gamma-ray Cherenkov Telescope (GCT), based on a Schwarzschild-Couder dual-mirror optics is one of the proposed SST designs. The GCT is described in this contribution and the first measurements of Cherenkov light made using the telescope and its camera in November 2015 in Meudon are presented.

Keywords: IACT, Cherenkov telescopes, CTA, Schwarzschild-Couder telescope, Cherenkov detector

1. Introduction

Very high-energy (VHE) particles and gamma-rays are a useful tool to study the non-thermal processes in the universe from energetic celestial bodies such as black holes, neutron stars, supernovae, etc. When this radiation enters the upper atmosphere, it interacts with the atmospheric gas and generates a shower of secondary particles. The particles in the shower (e-/e+) travel at speed higher than the speed of light in the atmosphere, therefore resulting in emission of Cherenkov radiation, with its characteristic peak in the blue. The contribution of all showers sums in flash of light lasting 5-20 ns which illuminates an area of few hundreds meters in diameter on the ground.

IACTs (Imaging Atmospheric Cherenkov Telescopes) are one way to measure such Cherenkov flashes. They are ground-based instruments that can measure the energy and direction of the primary cosmic gamma-ray from the shape and intensity of this Cherenkov light flash. The shape of the shower is also used to reject hadron induced cascades, which have a different shower morphology due to the hadronic processes in the cascade. The reconstruction technique is further improved by taking stereoscopic observations of the same shower with multiple teles-

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[1] Supported by the 2012-FP7-ITN, nr 317446, INFIERI EU programme.

copes. Moreover, hadronic showers generated by cosmic rays/hadrons inducing a lot of various secondary particles are more complex than leptonic showers generated by gamma-rays inducing only electron-positron pair cascades. As a result the images of their flashes obtained on the Cherenkov cameras are quite different, which helps to identify the leptonic ones and to identify the signal coming from gamma-rays.

In this context, the global Cherenkov Telescope Array (CTA) plans to be, after the current experiments such as H.E.S.S., MAGIC and VERITAS, the next generation IACT. It will operate over a wide band of energy (from 20 GeV to 300 TeV) and will be ten times more sensitive than the current state of the art experiments [1, 2]. One site in each hemisphere is foreseen. Southern site's array, planned to be located close to the ESO Paranal site in Chile, will be composed of about hundred telescopes divided into three classes of telescopes covering low, medium and high energies. Among them, the SSTs (Small-size telescopes) are dedicated to the highest energy range from 5 TeV to 300 TeV. About 70 of these telescopes are planned. Amongst the SST science requirements, the source localisation shall be in an area smaller than 7 arcseconds and the systematic uncertainty of the photon energy shall be smaller than 15%. The camera pixel charge resolution must be better than 30% (15%) above a signal of about 20(100) photoelectrons (p.e.). The charge resolution depends on the performance of the camera sensors and electronics which must also provide a linear response over a charge range from 0 up to 2000 p.e. Another important requirement for these SSTs is the field of view (FoV), which needs to be larger than 8 degrees. This feature makes these telescopes the first instruments capable of observing over such a large portion of the sky in the gamma-ray band, ensuring they are excellent tools for surveys and extended source observation [3].

Some of these SSTs will be, for the first time in IACT instrumentation, based on a Schwarzschild-Couder (SC) optical design. This last design has never been implemented in astronomy prior to CTA, mainly because of the strong aspherical shape required for the mirrors. However, this design has many advantages for IACTs (large FoV, good angular resolution, reduction of local length and hence of the physical pixel and camera size) allowing more compact, low-cost and lightweight camera and telescope mechanical structure compatible with SST requirements [4].

The GCT (Gamma-ray Cherenkov Telescope) is one of the two SST prototypes based on a SC optical design proposed for the CTA [3]. It has been designed and built by a Australian-Dutch-French-German-Japanese-UK consortium. This paper presents a general summary of the GCT and preliminary results obtained with the telescope in November 2015 just before its inauguration in Meudon.

2. Description of the GCT

This section briefly describes the main characteristics of the GCT design, shown in figure 1, and its performance. Details can be found in [5, 6].

Figure 1: The GCT prototype entirely mounted and equipped with its Cherenkov camera on the Meudon's campus of the Observatoire de Paris in November 2015 ©'The GCT subconsortium'.

Mirrors. The GCT is equipped with two aspherical concave mirrors M1 and M2. Because of the few constraints on the optical parameters, non-conventional lightweight metallic mirrors are used for the GCT prototype, allowing to relax the constraints on the manufacturing process [7].

Mechanical structure. The telescope mechanical structure has been optimized to provide a lightweight (8.1 tons), simple, rigid and compact structure. It offers an ingenious camera removal mechanism which allows, in addition to a tip-tilt mount to adjust the position of the camera and, thanks to a rotation of the camera supporting arm, an easy access to the camera for its maintenance and its installation. As a result, the final mechanical structure fulfils specifications in terms of stiffness, as detailed in [6] and shown in figure 2.

The telescope is easy to assemble since only four FTEs for two days were required to assemble it in Meudon from pre-assembled and set subsystems, in particular, the installation of the camera, shown in figure 3, lasted only 15 minutes with three people.

Camera. The target photosensor for the GCT camera is Silicon Photomultiplier (SiPM), nonetheless the first prototype, shown in figure 4 while mounted on the telescope, is based on Multi Anode PhotoMultiplier (MAPM). Although in this paper we focus on the latter, electronics and mechanics of the final GCT camera will only change slightly, mostly the front-end electronics (FEE) to account for different photosensors and a general review of the design to incorporate the lesson learnt from prototyping phase.

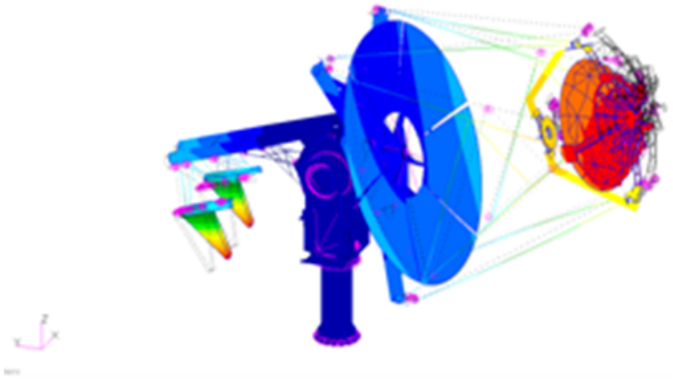

Figure 2: First eigenmode at 3.5 Hz of the telescope computed by MD.Nastran. The non-deformed structure appears in blue dotted lines ©'The GCT subconsortium'.

Figure 3: Installation of the GCT camera on the telescope with the Camera Removal Mechanism. The arm is here at an intermediate position between the ground level and the focal surface in front of the secondary mirror visible on the right of the picture ©'The GCT subconsortium'.

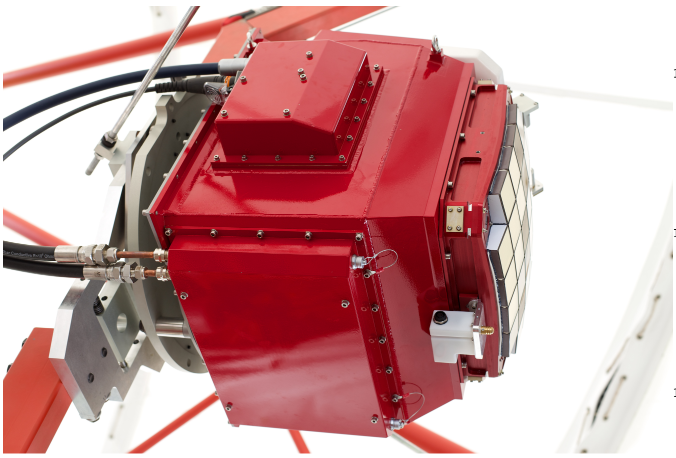

Figure 4: The GCT-MAPM camera on the telescope in November 2015 ©'The GCT subconsortium'.

To record the very fast signal as described in section 1, the camera is able to acquire the full waveform (about 100 ns) in each of the 2048 6 mm-pixels (arranged in 32 tiles of 64 pixels) on its 45 cm diameter focal plane at a rate of up to 600 events per second. Digitation at 1 GSample/second, 12 bit precision is provided by a custom front-end electronics module [8]. The data lines cross a backplane and are gathered on 2 DAQ Boards acting as a switch to serialise the data from sixteen modules each and providing absolute timestamp and synchronization with a White Rabbit interface. The backplane also generates and redistributes to the FEE the camera readout signal based on a 2 nearest-neighbour algorithm of the first level trigger lines from the FEE. The 400 W of heat inside the camera is redistributed by metal baffles and four fans and extracted by a chilled plate where cold water is circulated by an external chiller unit. Two motors operate a watertight lid at the focal plane that provides shielding from weather elements and protects the photosensors when the telescope is in its parking position during the day. Four calibrated LED flashers, each at a corner of the focal plane plate, can be controlled during operation to calibrate the photosensors and the electronic chain through the reflection on the secondary mirror of the telescope.

3. First Cherenkov light and preliminary results

During the integration campaign of the camera on the telescope structure in preparation for the inauguration, the weather condition was adverse to detect showers on the night sky.

Nonetheless we tried to test the system in the evening of November 26th and acquire on-sky data when the sky cleared. Attention was made to point the telescope as far out as possible from the city lights and the moon, which was almost full. From analysis of the baseline we estimated a Night Sky Background rate of about 500 MHz, which is about 20-30 times the expected value at the CTA goal site in the desert of Chile. The extremely noisy condition forced us to reduce the gain of the MAPM by a drop in the High Voltage of about 200 V from the nominal operating value.

In a favourable window time of few minutes we acquired 12 events. In figure 5 we report, as an example, one of the events together with the waveform recorded in two of the pixels in the event record. Only pedestal subtraction is applied to the data. We estimate the brightest pixel peak to be about 275 p.e. with a rough calibration based on the extrapolation of the gain measured at single p.e. illumination level performed in the lab at nominal HV. The duration of the event is only few nanoseconds and the peak of the light intensity is moving across the camera with the signature characteristic of an air shower signal. We therefore exclude any possible background that could mimic the signal.

Given the small number of events recorded, we did not perform any detailed image analysis to reject hadron events. We can assume the vast majority of them are likely to be generated from hadronic interaction.

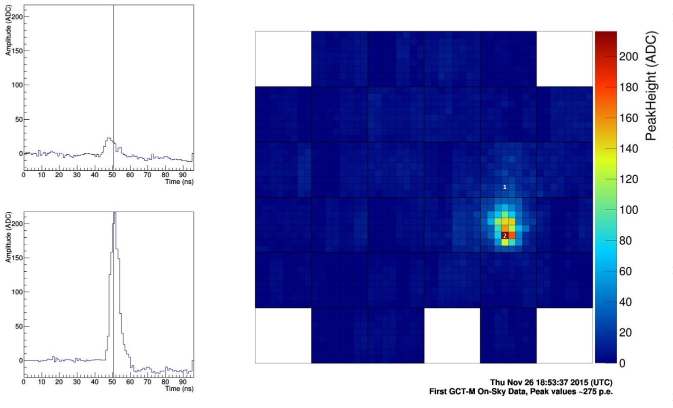

Figure 5: Example event recorded. Left: Waveform in two different pixels, marked with 1 (top) and 2 (bottom) on the right panel. A vertical line is drawn at the same time in the two waveforms to guide the eye. Right: Non calibrated, pedestal substracted waveform peak height (ADC count) ©'The GCT subconsortium'.

4. Conclusion

The GCT is a compact, light and low-cost telescope with easy maintenance which is designed to fulfil CTA performance goals. First observation of Cherenkov light for a CTA prototype was achieved, even in extremely challenging conditions: very high NSB rate, telescope at sea level, one-third of the primary mirror area in place and no optimisation of the mirror alignment. The lesson learned from the campaign are driving minor changes in the hardware/software architecture, and the development of a more sophisticated analysis chain is proceeding in common with the CTA software infrastructure, in preparation for another data taking campaign in 2016. At the same time, the construction and testing of the second prototype of the camera based on SiPMs as well as tests on the mechanical structure of the telescope are undergoing.

In the official current configuration of building seventy SSTs in the CTA southern array, the collaboration plans to build about thirty-five GCTs. A first pre-production phase should provide three telescopes from 2017 in order to test telescopes in desert conditions and to validate the design for mass production. The construction phase of the full array is planned from 2018 to 2021.

References

[1] M. Actis, G. Agnetta, F. Aharonian, A. Akhperjanian, J. Aleksić, E. Aliu, D. Allan, I. Allekotte, F. Antico, L. Antonelli, et al., Design concepts for the Cherenkov Telescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy, Experimental Astronomy 32 (3) (2011) 193–316.

[2] B. Acharya, M. Actis, T. Aghajani, G. Agnetta, J. Aguilar, F. Aharonian, M. Ajello, A. Akhperjanian, M. Alcubierre, J. Aleksić, et al., Introducing the cta concept, Astroparticle Physics 43 (2013) 3–18.

[3] T. Montaruli, T. Greenshaw, H. Sol, G. Pareschi, The small size telescope projects for the Cherenkov Telescope Array, arXiv preprint arXiv:1508.06472.

[4] V. Vassiliev, S. Fegan, P. Brousseau, Wide field aplanatic two-mirror telescopes for ground-based γ-ray astronomy, Astroparticle Physics 28 (1) (2007) 10–27.

[5] A. De Franco, R. White, D. Allan, T. Armstrong, T. Ashton, A. Balzer, D. Berge, R. Bose, A. Brown, J. Buckley, et al., The first GCT camera for the Cherenkov Telescope Array, arXiv preprint arXiv:1509.01480.

[6] J.-L. Dournaux, J.-M. Huet, D. Dumas, J.-P. Amans, G. Fasola, P. Laporte, J.-J. Bousquet, H. Sol, Performance of the mechanical structure of the SST-2M GCT proposed for the Cherenkov Telescope Array, arXiv preprint arXiv:1508.06415.

[7] D. Dumas, J.-M. Huet, J.-L. Dournaux, P. Laporte, C. Rulten, J. Schmoll, H. Sol, F. Sayède, P. Micolon, J.-F. Glicenstein, et al., SST dual-mirror telescope for Cherenkov Telescope Array: an innovative mirror manufacturing process, in: SPIE Astronomical Telescopes+ Instrumentation, International Society for Optics and Photonics, 2014, pp. 91512U–91512U.

[8] L. Tibaldo, J. Vandenbroucke, A. Albert, S. Funk, T. Kawashima, M. Kraus, A. Okumura, L. Sapozhnikov, H. Tajima, G. Varner, et al., TARGET: toward a solution for the readout electronics of the Cherenkov Telescope Array, arXiv preprint arXiv:1508.06296.

Acknowledgments

The authors gratefully acknowledge support from the agencies and organizations listed under Funding Agencies at this website: `http://www.cta-observatory.org/`.