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# The Gamma-ray Cherenkov Telescope, an end-to end Schwarzschild-Couder telescope prototype proposed for the Cherenkov Telescope Array

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## ABSTRACT

The GCT (Gamma-ray Cherenkov Telescope) is a dual-mirror prototype of Small-Sized-Telescopes proposed for the Cherenkov Telescope Array (CTA) and made by an Australian-Dutch-French-German-Indian-Japanese-UK-US consortium. The integration of this end-to-end telescope was achieved in 2015. On-site tests and measurements of the first Cherenkov images on the night sky began on November 2015. This contribution describes the telescope and plans for the pre-production and a large scale production within CTA.

**Keywords:** IACT, CTA, Cherenkov telescope, GCT, Schwarzschild-Couder telescope, SIPM detector, MAPM detector

# 1. INTRODUCTION

High-energy cosmic rays and gamma-rays are interesting messengers to explore energetic celestial bodies such as black holes or neutron stars, and cataclysmic cosmic events such as supernovae. Cosmic rays have been discovered in 1912 by Victor Hess. They trigger, when entering the Earth's atmosphere, a cascade of particles called an air shower, which emits a characteristically brief (only a few billionth of a second) flash of blue light, known as Cherenkov light, illuminating an area of a few hundred meters in diameter on the ground. They can be observed from the ground by several ways: either directly by detecting the charged particles, or indirectly by observing the Cherenkov light. Imaging Atmospheric Cherenkov Telescopes (IACTs) are based on this last technique. They are ground-based telescopes, which use large reflectors to focus Cherenkov light onto detectors. The shower can be stereoscopically reconstructed from images captured by several cameras [1] and the properties of the incident particles (proton or gamma-ray, arrival direction, energy...) can be determined by this way as shown in Figure 1.

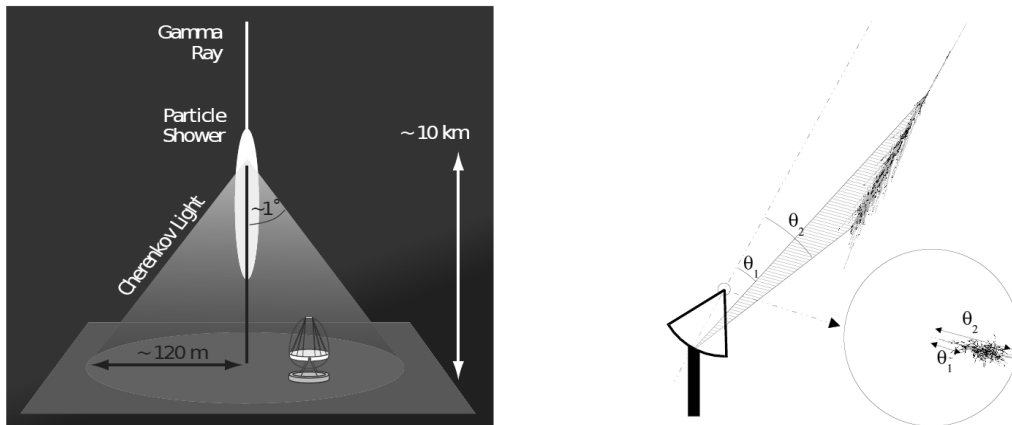


Figure 1. IACT technique. Left: Formation of a shower and collection by several dishes on the ground. Right: the shower angular image is projected into the camera focal plane [1].

There are currently three main operating IACT systems [2], H.E.S.S, MAGIC and VERITAS. The Cherenkov Telescope Array (CTA), managed by an international consortium gathering 1,200 members working in more than thirty countries, aims to build the next generation ground-based Very High-Energy imaging Cherenkov instrument [3], [4]. It will be devoted to the observation of gamma rays over a band of energy, from about 20 GeV to above 100 TeV and will be ten times more sensitive than current IACTs as shown in Figure 2.

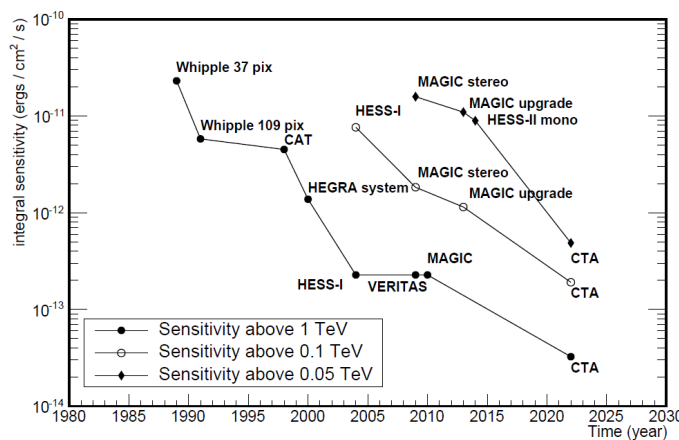


Figure 2. Evolution of integral sensitivities of the IACTs over time above 100 Gev (open circles) and 1 TeV (filled circles). The expected sensitivities of CTA are also shown. From De Naurois et al. [1].

Two sites, one in each hemisphere, are foreseen. Southern site's array, planned to be located at the ESO (Cerro Armazones) site in Chile, will be composed of about hundred telescopes divided into three classes of telescopes with different mirror areas to cover the low, intermediate and high-energy domains. Among them, the Small-Sized Telescopes (SSTs) are devoted to the latter range, as they are more sensitive from 5 TeV to above 100 TeV. At these energies, the limiting factor is not the number of Cherenkov photons produced in the extended air shower, but rather the number of showers observed. Therefore, the SSTs, though possessing a modest mirror diameter of about 4 m, will be spread over an area greater than 4 km<sup>2</sup>, to maximize the effective area of the array. Precise characteristics of the SST sub-array (size of the telescopes, number and spacing) have been defined by Monte-Carlo simulations and leads to seventy 4-meter SSTs spaced by about 250 meters. Besides the SST science requirements described in Hinton et al. <sup>[5]</sup> and Dumas et al. <sup>[6]</sup>, the systematic uncertainty of a photon candidate energy shall be smaller than 15% and the camera pixel charge resolution must be better than 30% (15%) above a signal of about 20 (100) photoelectrons (p.e.). The point spread function (PSF) size, determined by the area where 80% of the energy is spread, shall be smaller than a pixel size e.g. 6 mm. The charge resolution depends on the performance of the camera's photodetectors and electronics, which must also provide a linear response over a charge range from 0 up to 2000 p.e.

Table 1. Scientific requirements of CTA for SST telescope design. (a) The throughput includes the vignetting. (b) Cost for mass production of 70 SSTs. (c) This precision includes the systematic and the statistic errors. (d) The angular resolution depends on the energy; we give here the most constraining. (e) About 1,500 observational hours per year are foreseen for CTA.

Optical parameters		Observational parameters	
Designation	Value	Designation	Value
Field-of-view (FoV)	> 8°	Pointing precision	<7 arcsec (after post-calibration)
Optical PSF quality	< 0.25°	Tracking precision	< 5 arcmin <sup>(c)</sup>
Mirror area	> 4.5 m <sup>2</sup>	Source localisation	< 5 arcsec
Pixel size	6×6 mm <sup>2</sup>	Slew speed	> 90°/min
Throughput	> 60% <sup>(a)</sup>	Angular resolution	0.02° <sup>(d)</sup>
Telescope parameters		Maintenance parameters for CTA array	
Cost running	< 312 person.hours/yr	Reliability of operation	97 % of observational hours <sup>(e)</sup>
Unit cost (mass prod.)	< 250,000 € <sup>(b)</sup>	Power consumption	< 10 kW
Total lifetime	30 years	Night lost for maintenance	< 3 observational nights/yr

Some of these SSTs will be, for the first time in IACT instrumentation, based on a Schwarzschild-Couder (SC) optical design. Indeed, IACTs commonly use variations of a one-mirror Davies Cotton optical design and since the studies of Karl Schwarzschild and André Couder in the beginning of last century, SC Dual-Mirror optical design has never been implemented in ground-astronomy before CTA. This is mainly because of the strong aspherical shape required for the mirrors which is difficult to achieve. However, such design offers many advantages and could be an asset in the specific case of the SSTs: large field-of-view (FoV), good angular resolution over this entire FoV, reduction of focal length and hence of the physical pixel and camera size allowing a more compact and lightweight camera <sup>[7]</sup>.

The Gamma-ray Cherenkov Telescope (GCT) team is an international sub-consortium of CTA, currently building a dual-mirror prototype for the SSTs. It emerged in 2014 from the SST-GATE telescope team in France and the international CHEC camera team. The telescope proposed is based on a SC optical design and aims to demonstrate that it is technically possible to achieve the theoretically predicted SC performances within the SST requirements described in Hinton et al. <sup>[5]</sup> and to design a prototype structure of SST for the CTA array. Design studies of the mechanical structure started in 2011. In 2015, the critical design review was held in the summer, followed by the end of telescope integration and its inauguration in November 2015 in Meudon, close to Paris. First Cherenkov light and preliminary results were obtained with the telescope in the same period.

This paper presents a general overview the GCT and its current status. Section 2 briefly describes the mechanical design, the optical structure and the camera as well as the command and control of the telescope. Section 3 presents preliminary results obtained with the telescope. Finally, in the last section, plans for the pre-production and the CTA production in the next years are discussed.

## 2. DESCRIPTION OF THE GCT

The GCT is composed of four mechanical subsystems, optical elements (mirrors, actuators and a camera at the focal plane) and auxiliary systems, as shown on the top level Product Breakdown Structure (PBS) of Figure 3. Figure 4 shows the GCT prototype fully equipped with its Cherenkov MultiAnode Photo-Multipliers (MAPMs) camera on the Meudon campus of the Observatoire de Paris, close to Paris, just before its inauguration in November 2015.

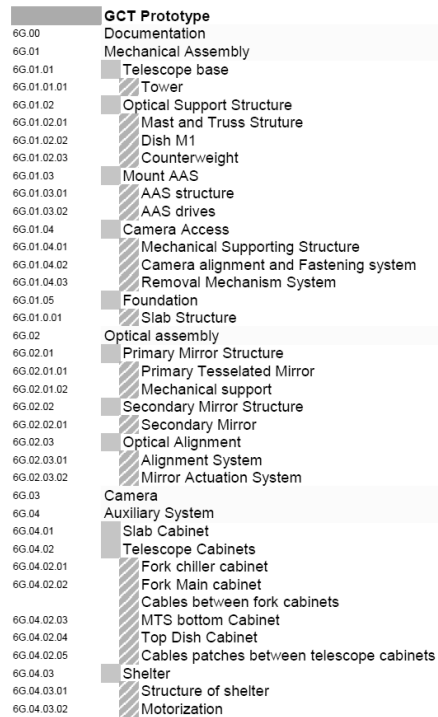


Figure 3. GCT top level PBS.



Figure 4. The GCT in November 2015 © 'The GCT Consortium'.

In order to guide the design of the telescope, an automatic performance budget has been built at the earliest phase of the project. The main difference from a classical error budget is that it gives directly the impact on the performance of a change in the design. Building a performance budget has several advantages because it requires understanding the links

between the different sub-systems and how they contribute to the global performance. It also helps to make technical choices by trying different error allocations during the design phase [8]. For CTA, the telescopes shall achieve good pointing performance and good light-collection efficiency.

A RAMS (Reliability, Availability, Maintainability, and Safety) process was initiated and monitored at the beginning of the project. A functional analysis was done before the implementation of the failure mode, effects and criticality analysis (FMECA) method using the European Cooperation for Space Standardization (ECSS) standard ECSS-Q-ST-30-02C 6 March 2009 as a guideline. Management and safety risks were recorded and monitored using a risk register and the ECSS standard ECSS-Q-ST-40-02C 15 November 2008 as a guideline. Regular reporting to CTA regarding the RAMS activity was also required.

This section describes the design and integration of GCT components. Current tests are described in Dournaux, Gironnet et al. [9] and Dournaux, Amans et al. [10].

## 2.1 Optical assembly

The GCT is equipped with two aspherical mirrors: the primary mirror (M1) with a diameter of 4 m and the secondary mirror (M2) with a diameter of 2 m. Optical parameters of the telescope are reminded in Table 2.

Table 2. Specifications of the SST-GATE telescope.

Designation	Value	Designation	Value
Focal length	2,283 mm	Primary mirror diameter	4 m
F-number	0.578	Secondary mirror diameter	2 m
Plate scale	0.025°/mm	Mirror M1 – Mirror M2	3,561.1 mm
Effective mirror area	10 m <sup>2</sup> (6.8 m <sup>2</sup> for prototype)	Mirror M2 – camera	510.7 mm

The mirror M1 is tessellated and made of six petals. Only two petals are currently set on the prototype, as shown in Figure 4. The other four are dummies with similar surface area and mass than the real petals in order to simulate inertial and wind loads properly. For the prototype, lightweight metallic mirrors are used. This choice, as well as pro and cons of this technique, are largely discussed in Dournaux et al. [9].

## 2.2 Mechanical assembly

The telescope mechanical structure was designed to provide a lightweight (8.1 tons), simple and compact -5.4 m × 8 m in zenithal configuration- structure compatible with the demanding CTA specifications in terms of stiffness, cost and lifetime; to decrease manufacturing costs by using commercial-off-the-shelf modules and similar systems in the telescope; and to ease the assembly and the maintenance phases. It consists of four main subsystems: (i) the Tower, (ii) the Alt-Azimuth System, allowing the telescope to move in azimuth in the range ±270° and in elevation from 0 to 90°, (iii) the Optical Supporting Structure, allowing to maintain the optical components at a distance within the allowable range defined by the requirements [5] and (iv) the Camera Access, providing the mechanical support and position settings of the camera.

A first feature of this design is the use of the same worm gear assembly for elevation and azimuth axes allowing a cost reduction and an easier maintenance and spare management. A second one is the possibility to rotate the dish M1 in order to facilitate the installation and the maintenance of the mirrors. This movement is enabled thanks to the use of separate systems for the dish M1, which supports the M1 panels, and for the mast support. The last main specificity consists of the camera removal mechanism which provides, in addition of a mount allowing to adjust the position, along and perpendicular to the optical axis, as well as the tilts of the camera, an easy mounting / unmounting operation to access to the camera for its maintenance.



Figure 5: The GCT camera removal mechanism. The camera is in an intermediate position between a lower position (at less than 1 meter from the ground) and its observing position in front of the secondary mirror at the right. A pulley behind the secondary mirror allows the camera to go up or down. © 'The GCT Consortium'.

This results in a mechanical structure which fulfils specifications in terms of stiffness, cost or lifetime and which is easy to assemble since only four people for two days were required to assemble the whole mechanical structure from pre-assembled and set subsystems. In particular, the installation of the camera lasted only 15 minutes with three people<sup>[10], [11]</sup>.

### 2.3 Camera

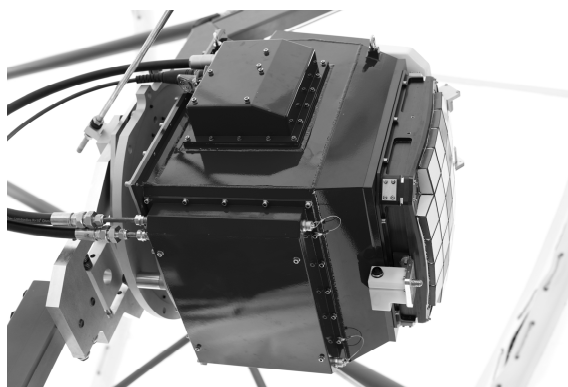


Figure 6: The GCT MAPM camera on the telescope in November 2015. © 'The GCT Consortium'.

According to the optical design, the focal plane of the camera is placed between the M1 and the M2 (Cf. Table 2) and is curved in a convex shape with a radius of 1 m. Two camera prototypes, with similar physical size and weight ( $\sim 50$  kg) and a diameter of roughly 45 cm, instrumented with 2048 6-mm pixels, are tested on the prototype structure. With a pixel-FoV of  $\sim 0.2^\circ$ , the total FoV seen by the camera is about  $9^\circ$ . The only difference is the nature of the photosensors used since the first camera prototype uses MultiAnode Photo-Multipliers (MAPMs) tiles whereas the second one uses Silicon Photo-Multipliers (SiPMs) tiles. GCT optical system enables indeed to use, for a 4-meter primary diameter and 0.2 degree pixel size,  $6 \times 6$  mm<sup>2</sup> pixels which are readily available at modest cost in the form of SiPMs or MAPMs. Details in the architecture, design and performance of these cameras can be found in references<sup>[12], [13], [14], [15]</sup>. The GCT MAPM camera prototype has been successfully integrated and tested on the telescope by the end of 2015 as seen in section 3. The development of the SiPM camera prototype is currently in progress<sup>[15]</sup>. Another observational campaign on sky is scheduled in Meudon in September 2016.

### 2.4 Auxiliary systems

Amongst the auxiliary system of the telescope, the Telescope Control System (TCS) aims to enable the telescope to move and to be controlled with the required precisions and speeds. Hardware and software are made from Beckhoff commercial-off-the-shelf devices. Three on-board cabinets connected with power supply and network (Internet and fieldbus) as well as a chiller, cooling the camera, are implemented on the telescope. Pointing movements are now

successfully remote-controlled. Details on the architecture of the TCS and on the tests made can be found in Dournaux et al. <sup>[10]</sup> and Fasola et al. <sup>[16]</sup>.

Another auxiliary system, specific to the GCT, is the shelter. Because of specific weather conditions in Meudon, we decided to place the prototype inside a standard fabric shelter. Its presence on the CTA site has not yet been confirmed by the CTA consortium but is under discussion as it may reduce the maintenance cost by several millions of euros. In the case of a consortium agreement for the establishment of a shelter for SSTs, its size will be adjusted to match with the other SSTs sizes. For the GCT, the current shelter in Meudon occupies an area of 10 meters by 6 meters. The optimum surface would be 11 or 12 meters by 7 or 8 meters.

A pointing monitor is also foreseen in order to get the real pointed direction in the sky and to compare it with the position obtained on the focal plane of the telescope. The information collected by the pointing monitor will be used to calibrate the movements of the telescope in order to tend towards the best achievable trajectory for the telescope. It will be mounted on the M2.

### 3. PRELIMINARY RESULTS

The telescope was tested on-site in November 2015 under poor conditions for the detection of air showers (almost full-moon, lights of Paris, etc.): the estimated night sky background rate was about 500 MHz (photoelectrons/sec/pixel), about 50 times higher than that expected in Chile.

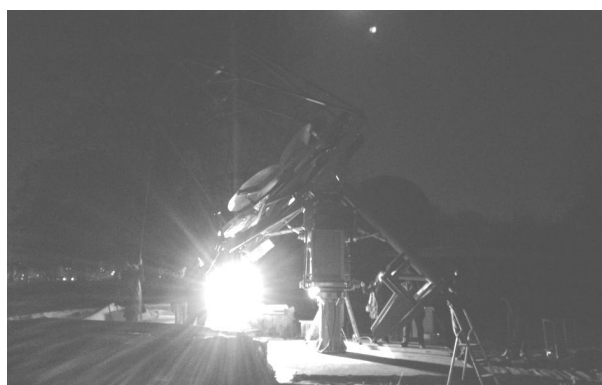


Figure 7: The GCT at night before the observation of events.

In spite of these conditions, 12 events were acquired in a few minutes. Their duration was a few nanoseconds and the peak light intensity moved across the camera with the signature characteristic of an air shower signal <sup>[17]</sup>. An example event is shown in Figure 8.

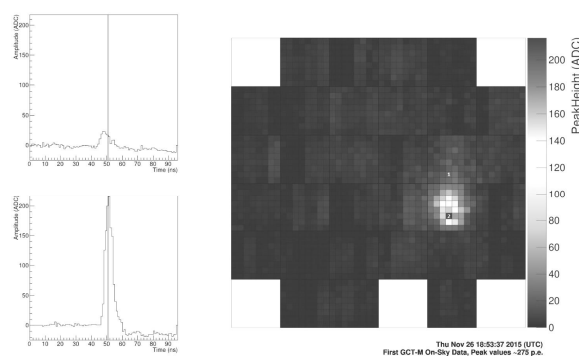


Figure 8: Example event. Left: Waveform in two different pixels, marked with 1 (top) and 2 (bottom) on the right panel. A vertical line is drawn at the same time in the two waveforms to guide the eye. Right: Uncalibrated, pedestal subtracted waveform peak (ADC counts). © 'The GCT Consortium' <sup>[17]</sup>.



These results were preliminary and no attempt was made to identify whether the events were due to gamma-rays or hadronic interactions<sup>[17]</sup>. PSF measurements, currently in progress<sup>[9]</sup>, should allow to refine these results.

#### 4. PLANS FOR CTA LARGE-SCALE PRODUCTION

Final layout and staging of CTA northern and southern arrays are currently under discussion. A total of about seventy SSTs are planned for the CTA southern site. It is foreseen that this large sub-array will include three SSTs prototypes: SST-1M, ASTRI and GCT. A description of the two other concepts can be found in Montaruli et al.<sup>[18]</sup>.

The GCT consortium aims to build 35 SST Dual Mirrors systems as in-kind contribution to the CTA Observatory (CTAO). In a first pre-production phase, three complete GCTs are going to be assembled on the Chilean CTA site. The three cameras will be fully assembled and tested at the three camera assembly sites in Europe, while the telescope components will be manufactured in industry in Europe and shipped to the CTA site for their final assembly and testing. This first step aims to test the telescopes in the desert conditions and to validate the production procedure before starting the large-scale production. The first call of tender should be made by the end of 2016. The telescope commissioning for science operations, with the cameras mounted, will conclude this pre-production phase in 2018 and will start the final production phase of 32 additional systems, from 2018 to 2021. The same approach will be followed during the production phase. Telescope components will be manufactured in industry in Europe while the cameras will also be assembled in Europe. The telescope assembly and in turn the camera mounting onto the telescopes will take place on site. This schedule is summarized in Figure 9. Potential design or manufactory changes for these steps are detailed in Dournaux, Gironnet et al.<sup>[9]</sup> and Dournaux, Amans et al.<sup>[10]</sup>.

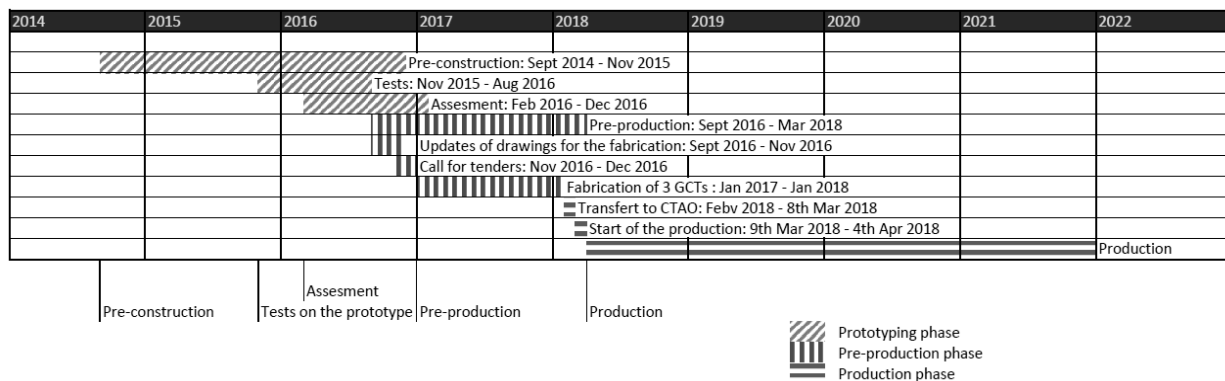


Figure 9. GCT prototype and construction plan.

#### 5. CONCLUSION

GCT is an end-to-end telescope based on a Schwarzschild-Couder (SST) optical design and proposed for the SST sub-array of the future CTA. Design studies led to a lightweight telescope (8 tons) with easy assembly and maintenance. In the current prototype phase, one telescope mechanical structure and two cameras, based on MAPM and SIPM, are built and tested. At the end of November 2015, Cherenkov events were recorded on the night sky with the GCT prototype on the Meudon site of the Observatoire de Paris. That was the first and still the only Cherenkov light achieved by a prototype of CTA, and the first Cherenkov images obtained from a dual-mirror telescope. The test and assessment phases are now going on. The GCT consortium aims to build 35 telescopes on the southern site of CTA as in-kind contribution to the CTAO. Three GCTs should first be built in 2017 during a pre-production phase, then the 32 others systems will be built during the production phase expected to start in 2018.

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