

SST-GATE: An Innovative Telescope for the Very High Energy Astronomy

Philippe Laporte, Jean-Laurent Dournaux, H el ene Sol, Simon Blake, Catherine Boisson,
Paula Chadwik, Delphine Dumas, Gilles Fasola, Fatima de Frondat, Tim Greenshaw,
Olivier Hervet, James Hinton, David Horville, Jean-Michel Huet, Isabelle J egouzo, J urgen
Schmoll, Richard White, Andreas Zech

GEPI – Observatoire de Paris, CNRS, Univ. Paris Diderot
5, Place Jules Janssen, 92190 Meudon, France

LUTH – Observatoire de Paris, CNRS, Univ. Paris Diderot
11, Av. Marcellin Berthelot, 92190 Meudon, France

Durham University
CfAI (Centre for Advanced Instrumentation), NetPark Research Institute
Joseph Swan Road, Netpark, Sedgefield, TS21 3FB, United Kingdom

University of Liverpool
Liverpool L69 7ZE, United Kingdom

ABSTRACT

The Cherenkov Telescope Array (CTA) is an international collaboration that aims to create the world's largest (ever) Very High Energy gamma-ray telescope array, consisting of more than 100 telescopes covering an area of several square kilometers to observe the electromagnetic showers generated by incoming cosmic gamma-rays with very high energies (from a few tens of GeV up to over 100 TeV). Observing such sources requires – amongst many other things - a large FoV (Field of View). In the framework of CTA, SST-GATE (Small Size Telescope – GAMMA-ray Telescope Elements) aims to investigate and to build one of the two first CTA prototypes based on the Schwarzschild-Couder (SC) optical design that delivers a FoV close to 10 degrees in diameter. To achieve the required performance per unit cost, many improvements in mirror manufacturing and in other technologies are required. We present in this paper the current status of our project. After a brief introduction of the very high energy context, we present the opto-mechanical design, discuss the technological trade-offs and explain the electronics philosophy that will ensure the telescopes cost is minimised without limiting its capabilities. We then describe the software needed to operate the telescope and conclude by presenting the expected telescope performance and some management considerations.

Keywords: very high energy, Cherenkov, gamma-ray astronomy, CTA, Small Size Telescope, Telescope prototyping, Schwarzschild-Couder, Dual-mirror, GATE.

1. INTRODUCTION

The current generation of ground-based Imaging Air Cherenkov Telescopes (IACTs) has opened a new window in the area of very high energy (VHE) astronomy and has demonstrated the large diversity of sources in this energy range. Current instruments cover energies from about 100 GeV up to a few 10 TeV, providing thus access to the most energetic, non-thermal emission regions in the sky. The spectacular astrophysics results from the current IACTs [1,2] has led the international community to engage the CTA project to investigate the cosmos more deeply in the VHE domain with an instrument that provides about an order of magnitude increase in sensitivity, significant improvements in the spectral coverage, the angular, spectral and temporal resolution, as well as an improved flexibility in the observational modes.

With its enhanced performance, CTA is expected to lead to major discoveries in the fields of astronomy, astrophysics, cosmology, particle physics and fundamental physics. The CTA consortium expects to detect of the order of a thousand sources of different types (e.g. supernovae remnants, pulsar wind nebulae, binary systems, star clusters, the Galactic Centre, active galactic nuclei, starburst galaxies and possibly new classes of VHE emitters, including dark matter). Three key-questions will be explored with CTA:

- The origin of cosmic rays and their role in the universe,
- The nature of particle acceleration in systems containing black holes,
- The ultimate nature of matter and physics beyond the Standard Model.

The first topic refers to the physics of galactic cosmic accelerators such as pulsars and , supernovae, and gamma-ray loud binary systems. The interaction of accelerated particles with their environment and their cumulative effects at different scales, from star forming regions to starburst galaxies, will be investigated. A better understanding of the VHE emission from active galactic nuclei (AGN) or possibly from gamma-ray bursts (GRB) will help to track down the origin of ultra-high energy cosmic rays. This question is also related to the second topic, the acceleration mechanisms of charged particles close to (super-)massive black holes, and the nature of these particles. GRB, as well as galaxy clusters, are promising candidates for VHE emission, which should be accessible with the increased performances of CTA. Probing the infrared extragalactic background light (EBL) with VHE gamma-rays from distant sources and the search for signals from dark matter will provide important input into our understanding of cosmology, while the search for Lorentz invariance violation using VHE flares at high redshifts will test the fundamentals of physics.

CTA presents a logical evolution of the currently operating experiments H.E.S.S., MAGIC and VERITAS, experiments with up to five telescopes, which have launched the cosmic exploration at VHE after the pioneering works by Whipple, HEGRA, CAT and other experiments. CTA will consist of two arrays of several tens of telescopes to provide an unprecedented sensitivity and sky coverage by the use of a new generation of telescopes. CTA will be the first VHE facility operated as an open, proposal-driven observatory, analogous to optical ones, that shall be available for the whole scientific community.

In the next section we argue for the need of a new kind of telescope to cope with the aforementioned scientific goals. We then provide details on the performance of an ideal dual mirror telescope in the framework of CTA (third section) and describe the telescope we are designing to fulfil these performances (fourth section). We conclude by exposing the future work and the schedule of our project.

2. WHY A SCHWARZSCHILD-COUDEUR TELESCOPE?

VHE gamma-rays are detected indirectly through the mostly ultra-violet Cherenkov light emitted from cascades of charged particles (air showers) they trigger upon interaction with the atmosphere. The geometry and energy of the air shower are reconstructed from its image, taken with several telescopes to improve the stereoscopic view, and are used to derive the arrival direction and energy of the primary gamma-ray. At energies of a few 10 to a few 100 GeV, the Cherenkov signals from air showers are weak and telescopes with large mirror surfaces are required to capture them. At energies of a few 10 to a few 100 TeV, the Cherenkov light emission is strong, but the detection is limited by the low statistics of the usually steep energy spectra of the astrophysical sources. In this domain, telescopes may have small

mirror areas, but they need to cover a large area on the ground. For this reason, CTA will consist of different types of telescopes of different sizes. A few large-size telescopes (LSTs), with parabolic dishes, will cover the lowest energies; a few tens of medium-size telescopes (MSTs), of Davies-Cotton (D-C) design, are optimised for the TeV energy range; and many tens of small-size telescopes (SSTs), of D-C or S-C design, will cover the highest energies up to 100 TeV.

Cherenkov telescopes operate generally in a photon starved regime. To avoid contamination of the air shower image with the night sky background, the exposure must match the duration of the Cherenkov light pulse, of the order of a few nsec. Therefore, unlike in conventional optical astronomy, the image on the camera, corresponding to the indirect signal from a single gamma-ray, cannot be improved through increased exposure. This motivates the development of optical systems with very large primary mirrors, having diameters in the range of 10–30m. In addition, the optical systems of Cherenkov telescope must be composed of the minimal number of optical elements to circumvent light loss [11, 12, 13, 14]. For this reason, the first Cherenkov telescopes were designed according to the Davies-Cotton (D-C) optical formula, which is based on a single spherical reflector segmented into individual mirrors. Initially imagined to concentrate solar energy for power production, the optical quality of the D-C allowed the discovery of the first sources in the VHE domain. All the current IACT arrays use either D-C or parabolic designs. The latter minimize time dispersion of the Cherenkov signal and are thus preferred for the largest telescopes, such as the LST component of CTA. The D-C design is the baseline for the MST component.

In these designs, the rapidly increasing effect of optical aberrations with the off-axis angle presents a major disadvantage, if one aims at a wide FoV. Especially for the SST component of CTA, a wide FoV is of great interest, since it permits to capture images of air showers at large distances from the telescopes, since air showers at the highest energies provide relatively strong signals. This allows a larger spacing of the SST part of the telescope array, and thus an increased effective area for the same number of telescopes. Moreover, in order to accurately estimate the background that is subtracted from the gamma-ray signal from an astrophysical source, a wide FoV is generally required to have within the same field both the putative source and a few equivalent regions of empty sky. This can be a constraint in particular for extended galactic sources, which will be the main target at the highest energies.

Moreover, in the D-C and parabolic designs, the camera must be situated in the focal plane of the single reflector and when the size of the reflector is increased, to allow a larger field of view, the size and weight of the camera and its distance from the dish increases. This implies strong constraints on the mechanical structure of the telescope.

Finally, an optical system that has both large aperture and high f-ratio (ie field of view) leads to large plate scale, typically 50 mm per arcmin. This implies large and expensive cameras, consisting usually of at least several hundred photo-multiplier tubes, with the drawback of an enlarged effect of vignetting.

An ideal Cherenkov telescope would provide a small plate scale, a large diameter and a large FoV. As explained in [7], increasing the aperture diameter to improve the light-gathering power unavoidably results in a corresponding decrease in the f-ratio, in turn amplifying all primary aberrations, such as spherical aberration $\propto 1/f^3$, coma $\propto \delta/f^2$, as well as astigmatism and field curvature $\propto \delta^2/f$, with δ being the field angle. For a given plate scale, an aplanatic design radically outperforms the single reflector designs in terms of the effective light gathering power, the ability to accommodate a wide FoV, and the amount of time dispersion (in the case of the D-C)

To achieve the enhancement in the performances it is necessary to develop telescopes based on an aplanatic optical formula that minimises the aberration over a large FoV. This precisely was the aim of Schwarzschild's studies at the end of the nineteenth century when he developed a dual mirror optical formula. Despite the very promising performance of this aplanatic formula, without any coma and spherical aberrations, and an optimisation proposed by Couder at the beginning of the twentieth century, it has never been built. The Observatoire de Paris, represented by the LUTH and the GEPI, and the University of Durham, Liverpool and Leicester) are proposing to build such a telescope to demonstrate that it is technically possible to achieve the theoretically predicted performances. The objective of this work is to propose to the CTA consortium a new kind of telescope able to enhance all key performances at the same time instead of only the

light collecting power to the detriment of the uniformity of field of view, as in the case of the single reflector telescopes. The S-C prototype also aims to demonstrate that a significant reduction in the cost of the SST telescopes can be achieved for this design (smaller camera, lighter structure...) compared to the baseline D-C option.

3. THE CHALLENGES OF BUILDING AN S-C TELESCOPE

As we intend to develop a prototype of S-C telescope in the frame of CTA, we have derived the high level scientific requirements of CTA in the frame of a dual mirror telescope. They are gathered in Table 1.

Optical		Mechanical	
Designation	Value	Designation	Value
Field of view	9°	Pointing precision	< 7 arcsec
PSF	0.1° @ 80% ^(a)	Tracking precision	< 5 arcmin ^(d)
Mirror diameter	4 m	Source localisation	< 5 arcsec
Pixel size	6x6 mm ²	Slew speed	> 90°/min
Plate scale	0.025°/mm	Reliability of operation	97 % of the observational hours ^(e)
Angular resolution	0.02° ^(b)	Total lifetime	30 years
Throughput	> 60% ^(c)	Night lost for maintenance	< 3 observational nights/yr
Effective mirror area	> 5 m ²	Cost running	< 312 person.hours/yr
		Unit cost	< 250,000 euros
		Power consumption	< 10 kW

Table 1: Scientific requirements for the S-C telescope under construction at the Meudon's site of the Observatoire de Paris. ^(a) PSF size is determined by the area in which 80% of the energy is spread. ^(b) The angular resolution depends on the energy; we give here the most constraining. ^(c) The throughput includes the vignetting. ^(d) This precision includes the systematic and the statistic errors. ^(e) About 1500 observational hours per year are foreseen for CTA.

These optical and mechanical specifications have been derived in three levels which are “essential” (the minimum we can afford), “optimal” and “goal”. They give to the system engineering team the range in which each parameter must be situated in order to allow for an optimisation of the various budgets without back-looping permanently with the scientific team. This important scientific work is essential to get a reactive technical team to the unavoidable changes in the specifications in a project that has the size of CTA.

Table 1 presents the most constraining requirements. The optical requirements have been derived in optical surfaces by Zemax simulation whereas the mechanicals ones have been transformed in high level technical requirements for the engineering team.

However beyond these technical specifications, CTA requires to build two arrays of telescopes which, indeed, imply to take into account the environment, the array control and the consistency through all the whole CTA projects namely:

- Each telescope must be ordered independently to optimise the scientific targets and their ability to point and track any cosmic source whatever the target of the other telescopes is.
- The telescope must be operated from a remote control room.
- The telescope must be compliant with the existing camera (volume, weight...) and provide their positioning in their focal plate with the proper accuracy.
- The telescope must have a parking position that minimise the wind effective area to resist to a wind speed up to 200 km/h.
- The telescope must cope with the power supply that will be available on site (10 kW maximum per telescope).
- The maintainability must be made with less than 6 person.hours per week and must not let the telescope unavailable more than 3 observational nights per year.

- The telescope life time shall be at least 30 years without any protection against the environmental conditions.
- Each part of the telescope must be subcontracted.
- The choice of materials and software must be compliant with others CTA telescopes.

Moreover, the environmental conditions also constrain the telescope design. CTA will consist in two sites, in the north and the south hemispheres, each one having several dozen of SST telescopes. In order to be compliant with the future CTA requirements related to the site location, we designed the SST-GATE telescope to be compliant with the most constraining parameters over the 4 sites still in competition. The specific cost as well as maintenance specificities will be recorded in order to give to the Project Committee the real cost of our prototype once the site will be chosen. The environmental conditions are gathered in TableTableau 2.

Parameter	Observing conditions	Critical conditions	Emergency conditions	Survival conditions
Temperature range (°C)	-10 to +40	-15 to +45	-20 to +50	<-20 to > 50
Wind speed range (km/h)	0 to 50	50 to 65	65 to 100	>100
Humidity range (%)	5 to 95	5 to 95	5 to 95	0 to 100

Tableau 2: Climate conditions assumed to design the SC prototype.

In the critical situation, the telescope can observe but with degraded performance. Velocities and accelerations of movements are reduced to 70% of their nominal capacities. In the emergency scenario, velocities and accelerations of the movements are reduced to 10% of their maximum capacities and the telescope must return to its parking position. Under survival conditions, the telescope is parked and cannot be moved.

All these additional constraints have guided the opto-mechanical design described in the next section. For instance, the telescope will remain without any protection so each system shall be sealed or placed in a hermetic box to prevent any water damage. A long duration life-time requires choosing long-life equipment with a mature technology or it means to design the telescope in order to make the maintenance rapid and easy. Moreover, the electronic architecture must use long-life components that shall still exist in 30 years.

The prototype we are building will be situated at the Meudon’s site of the Observatoire de Paris and will be devoted to measure the performances an SC telescope can achieve. Once this operation will be done (phase A), it will be used for testing scientific cameras such as the CHEC one – developed by a UK-US-Japan consortium – as well as for student training and outreaches (phase B). Some equipment are specific to each phase. We split the cost and the procurement catalogue for each phase, the first being dedicated to telescope building and to make it available for observation (including the maintenance). The second one is devoted to the specificity of our prototype and includes all the equipment and parts related to the outreaches. For instance, considering the use of our telescope for our own research program in Meudon and for educational trainings, and in order to decrease the maintainability cost, we will get a shelter.

4. THE UK-FRENCH TELESCOPE DESIGN

4.1. High level conceptual design

The high level technical requirements derived from the scientific specifications led us to the functional diagram presented in Figure 1. One can see that the telescope can be described in 6 different elements:

- The FSS (Foundation and Slab Structure) will support the telescope weight and will provide the torque resistance.
- The AAS (Alt-Azimuthal Structure) provides the ability of the telescope to point in any direction in the sky and to track any scientific source with the required accuracy in the limit of the environmental conditions (wind speed up to 50 km/h). It also has the function to support the optical part of the telescope.
- The elevation structure (including several functions, see the PBS in Figure 2) which gathers all the movable parts (mirrors M1 and M2 plus their supporting structure and the camera),

- The TCA (Telescope Control and Alignment) which is in charge of controlling the whole telescope adequately to perform the scientific operations.
- The SDS (Software Data System) will operate the telescope, the data storage and all the operations to perform the alignment.
- The PSS (Protective Shelter Structure) which will protect the telescope during its outreach life.

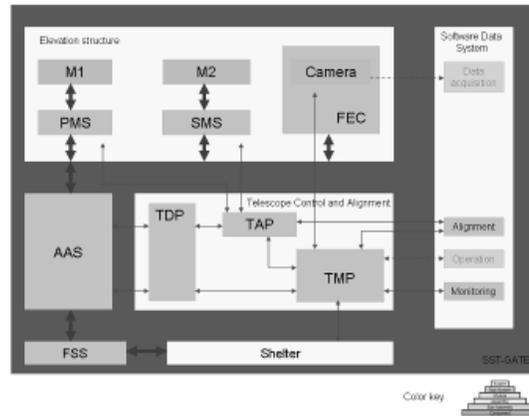


Figure 1 : Functional diagram of the UK-French design. See text and Figure 2 for the meaning of the acronyms.

Name	Id Acronym
SST-GATE Prototype	SG-SST
1 Telescope Mechanical Structure	SG-MEC
Foundation and Slab Structure	SG-FSS
Alt-Azimuthal Structure	SG-AAS
Mast and Truss Structure	SG-MTS
2 Telescope Optics	SG-OPT
Primary Mirror Structure	SG-PMS
Secondary Mirror Structure	SG-SMS
3a Scientific Detector (Cherenkov)	SG-SDT
Focal Plane Instrumentation	SG-FPI
Camera Alignment System	SG-CAMS
Mechanical Interface between Camera and the scientific camera Holder	SG-MCH
Data Acquisition Hardware	SG-CAH
Supplies	SG-SUP
3b Optical camera	SG-FEC
Detector	SG-DMS
Supplies	SG-SUP
Mechanical Interface between Optical camera and Scientific camera Holder	DG-IOS
Data acquisition Software	SG-MOH
4 Telescope Control and Alignment System	SG-TCA
PLC	SG-PLC
Monitoring	SG-TMP
Driving	SG-TDP
Alignment	SG-TOP
Safety	SG-SAF
Weather Station	SG-WSA
Technical Archive	SG-TAR
5 Protective Shelter Structure	SG-PSS
Shelter	SG-SHL
Shelter Control	SC-SCT
6 Maintenance Devices	SG-MAD
AIT Facilities	SG-AIT
Maintenance	SG-MAI
Global Safety	SG-SAV

Figure 2: Two first levels of the PBS developed for the UK-French prototype.

For cost reasons we have preferred an alt-azimuthal structure instead of an equatorial one because the latter requires an additional pillar. Moreover, it constraint the orientation of the parking position to the East or to the West which are not necessary the less windy directions on the future CTA sites.

The functional analysis helped us to split the telescope in as independent as possible parts in order to simplify the procurement, the tests, the feasibility and the mounting. That explains why the PBS (Product Breakdown Structure) is composed of 6 main functions, as described in our High Technical Level Requirements. The first and the second level are showed in Figure 2.

4.2. Trade-offs

When the cost, the maintainability and the life-time are the drivers to build a telescope, without sacrificing the performances, a certain number of trade-offs must be solved to determine the best design. We pointed out:

- The kind of material (aluminium, steel or carbon fibre).
- The different parts that require a safety system redundancy.
- The fastening system of the camera.
- The camera removing.
- The risk analysis of the mirror procurement.
- The size of the alt-azimuthal fork.
- The use of a single or double motor in the AAS.

The choice of the material is essential because it largely impacts the cost. Indeed, a metallic structure is heavier than a carbon fibre one and will require a more expensive foundation. As the CTA arrays will be situated in deserts, this item may increase rapidly. In the other hand, designing and mounting carbon fibre structure is complex due to (1) the difficulty to find companies that provides several profiles in this material and (2) the strong dependence of the characteristics with respect to the dimension (along the fibre or not). The steel won this trade-off with a small advantage compared to the aluminium option, thanks to the low price of the material considering the product market and due to the easiness of manufacturing and mounting steel pieces.

In terms of safety, we identified that the elevation axis would need a safety system in addition to a passive return mechanism. Actually, a failure of this axis may generate an undesirable movement that could be dangerous for telescope integrity and for human beings during the maintenance activities. If a redundant elevation axis could be an interesting idea, it is not relevant in the frame of CTA, because this solution does not solve the problem of a failing motor leading to a blocking axis or a failure of power supply (a battery is foreseen for each telescope, but no requirement is available). This explains why we choose a passive mechanical system plus an electric engaging mechanism. In case of an electrical failure, the elevation motor is disengaged and the passive system makes the telescope able to go to its parking position without help. This solution works for any of the previous hazard situations.

Having the detector between M1 and M2 is an advantage as it provides a lighter camera compared to the DC telescopes. Nevertheless it imposes to be able to remove the detector for maintenance. We found an innovative solution that avoids any human intervention in the telescope and thus minimise the optics hazards. It consists in two connections “kneecap” and one “punctual” – all fastened to the M2 mirror – that allows the detector to rotate while the telescope is in its parking position (see Figure 3). This method won the trade-off as it cumulates several advantages: the camera is situated at a height of about one meter so that it facilitates the operations by limiting the amount of staff needed, the equipment required and the human, M1, M2 and camera hazards. It is also lighter than the three other solutions considered.

The mirror procurement trade-off was the most difficult to solve because there is no suppliers capable of making mirror cumulating several meters in diameter, a relatively complex shape, a small radius of curvature and a low cost. Fortunately, some laboratories are working on this topic for CTA. The IRFU has succeeded in making mirrors with the appropriate radius of curvature (about two meters) with a variant of the cold-slumping method. The M2 mirror is under procurement for our prototype.

The diameter of the M1 mirror makes it difficult or impossible to be produced in one part if we want to remain in the cost envelope so a tessellated option is considered in all prototypes. The LAM laboratory (Marseille, France) works on the hydro-forming method which consists in applying a pressure on a pre-rectified metallic sheet to get the desired shape and form. Petals mirrors could be made by this method. However this technology will not be available soon enough for our prototype. Electro-forming is another solution but the mirror transportation from US represents a too high cost for one telescope. We are so investigating the feasibility of M1 with the CEA technology which has the advantages of being feasible and very light.



Figure 3: Picture simulated of the camera removing after full rotation while the telescope is in its parking position

Two other trade-offs have been made on the alt-azimuthal system. The first one deals with the size of the fork which could be either long with a small tower or the reverse. The trade-off significantly concludes for the small fork which allows lower axial stresses compared to a long fork configuration. In addition, a small fork is lighter and less expensive at the first order, so this configuration is compliant with CTA requirements.

The last trade-off consists in the use of single or double motors for the alt-azimuthal system. We decided on the use of a single motor in order to simplify the control of the elevation and azimuthal systems and because the MTBF (Mean Time Between Failure) of the foreseen motors is larger than 10,000 hours (8 years of observation). Indeed, two motors imply a higher accuracy in the control and the synchronization and would not offer an easier solution in the case of a power breakdown.

4.3. The telescope design

4.3.1. The Alt-Azimuthal Structure

The AAS has to support several constraints which must not cause any irreversible damage or deformation. The first load is the compression due to the mass of the MTS. If this load exceeds the Euler one, a buckling may occur in the AAS and will imply to unmount the whole telescope to repair the permanent deformation. The second load is the torsion due to a brutal stop of the azimuth or the elevation drive. The strength must remain in the steel elastic domain. The third constraint is the bending load caused by the wind. We considered a maximal wind speed of 200 km/h for this effect. Unfortunately, period and strength of the wind are not constant so we have to take the fatigue damage into account that implies to add a security coefficient in the calculation of the wind load. We also assumed the worst case of a laminar profile for the wind which is also included in the security coefficient.

Several kinds of AAS have been analysed in our preliminary study in which the elements have been modelled by circular steel tubes. It showed that the internal stresses follow a linear function with the mass of the MTS and that it increases with the square of wind speed, as theoretically expected. It also allows us performing a rough analysis of several

possibilities in order to choose the best kind of structures among: conic and cylindrical tower, fork structure made by steel tubes or reinforced and long or short fork. In addition to the mechanical performance, the criteria for choosing the AAS design were the mechanical performance, the cost, the maintenance cost and the safety hazards.

Despite a conic tower offers more stability than a cylindrical one, we chose the latter for cost reasons, and we compensate the lower performance with a larger thickness. Concerning the fork mount, an assembly of tubes can be sufficient but it is expensive to integrate because of the welding manpower and the maintenance frequency. We chose a closed fork mount in order to (1) reinforce the fork structure, (2) simplify the welding operations and (3) close the fork so that the maintenance is minimal inside.

A fine analysis has been performed by Finite Element Method (MD.Patran, MD.Nastran) to choose the best solution. The corresponding model is shown in Figure 4. The fork mount is made of an assembly of steel tubes, stiffened by 15 mm thickness steel sheets. The tower has a diameter of 530 mm and is 15 mm thick.

In this model, the bottom of the tower is clamped while its top is submitted to the combined effects of the MTS mass and the wind. The elevation subsystem is modelled by a single point located at its centre of gravity with the corresponding mass of this assembly. This point is linked to the top of the AAS with 24 points by a MPC (Multi Point Constraint) element (RBE3) in order to define a relationship between the degrees of freedom of the 24 previous points and those in the centre of gravity of the elevation assembly.

We focused these analyses on the static behaviour, the eigenmodes and the buckling load. The static analysis shows that the internal stresses remain lower than the steel yield stress times the security factor. It also shows that the deformation is located in the fork part and not in the tower. The long fork shows a lower stiffness while it is heavier (1.9 tons instead of 1 ton). This last result means that a short fork is stiffer than a long fork and it confirms our trade-off choice of a short fork.

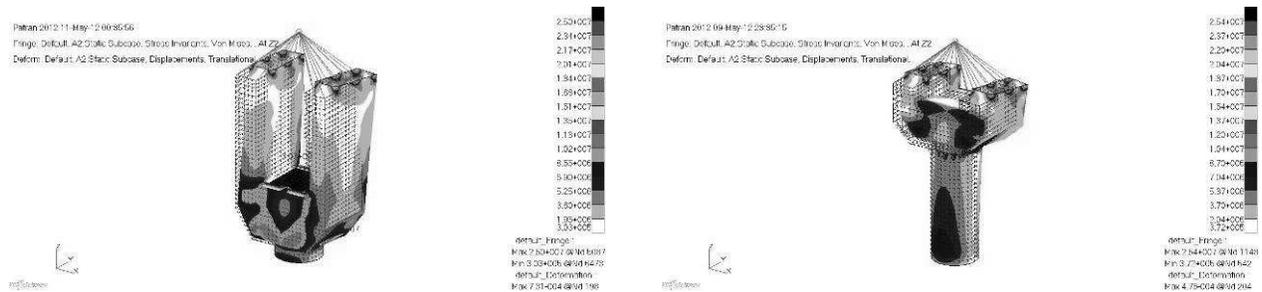


Figure 4: Von Mises stresses for equivalent long fork and short fork

The modal analysis also shows that the first two modes are the bending of the tower and occur at about 75 Hz. At this frequency, the structure is not excited by the wind. The following mode is a torsion mode and occurs at 188 Hz. Regarding the buckling analysis, the Euler load (53 500 kN) is greater than the compression load (35 kN) and no buckling should occur.

4.3.2. The optical structure

The telescope is based on a Schwarzschild-Couder optical formula as discussed in Section 2. It is composed of a primary mirror (M1) with a diameter of 4 meters and a secondary mirror (M2) with a diameter of 2 meters. The camera is located between the two mirrors which is significantly different from the classical DC telescopes. The detecting surface will be a disc of 362 mm in diameter. A distance of 510.7 mm separates M2 and the detector.

The telescope is composed of the PMS (Primary Mirror Structure) which holds the mirror tiles, their actuators, the supporting structure and the counterweight. The SMS (Secondary Mirror Structure) is related to M2 and consists of the actuators and the frame structure. The PMS and the SMS are maintained at the proper distance by three tubes of 100 mm in diameter (named MTS for Mast and Truss Structure). We chose kneecaps to fasten the SMS to the MTS and “pivot” at the interface between M1 and the MTS in order to ease the mounting procedure.

The PMS is fastened to the elevation axis and is located at 2.5 meters above the ground. The design has been made to minimise it so that the torque due to the wind is lowered. It also eases the maintenance because most of the elements are reachable at human height. We remind that our telescope will have an elevation range from -5° to $+185^\circ$ in order to (1) proceed to the alignment (theodolite method) and (2) access to any part of the mirrors at human height. Finally, it allows removing easily the camera (see further).

The azimuth and elevation driving system have been studied via trade-offs to solve the cost-maintenance-hazard equation. The baseline consists in using ball bearings to define the rotation axis. This solution is less efficient for slow movements than the fluid film but fluids are forbidden by the CTA requirements. Each driving system will be an assembly of a crown moved by a worm gear and an electric motor. A servo-motor wired with Ethernet to the SST-GATE backbone (see section 4.4) will complete the assembly. As requested by the CTA requirements, the elevation movement will range from -5° to $+90^\circ$ to address the CTA requirements and $+90^\circ$ to $+185^\circ$ to perform a simpler maintenance of the telescope. The azimuth will range from -90° to $+450^\circ$ with respect to the parking position.

As explained previously, the safety system is foreseen in this assembly for the two axes. It consists in a passive system that mechanically works against the movement generated by the motor. Thus, even in case of power supply or motor failure, the telescope returns to its parking position without any help. An electrical disengaging system is foreseen to free the axis in such a condition. This passive system has also the advantage of annihilating the play in the movement chain and will enhance the tracking accuracy.

4.3.3. Telescope behaviour

An optical simulation has been performed with Zemax (1) to optimise the mirror's shape, the distance between the optical surfaces to provide the best PSF over the whole field of view and (2) to define the sensitivity of the optical elements to a misalignment.

To perform the optimal PSF over the large field of view (9°), no simple shape fits the needs so a polynomial formula has been developed to express the height variation of the mirror's shape with respect to a sphere along the radius. The flatness error, which means the discrepancy that is tolerable between the real surface and the theoretical one, is about 10 mm for the M1 and M2 mirrors along the normal surface [8]. This is explained by the weak dependency of the PSF to this kind of movement. The sensitivity is a little bit more constraining in the other directions (2 mm) but remains easily feasible.

For cost reasons, the mirrors will be made by an assembly of tiles that must fit the mirror shape. In [8], the PSF degradation has been studied versus decentring, tilt and focus. The most constraining movement is the rotation along the axial and tangential axes of the tiles (0.1 mrad). This can occur only when the structure is locally deformed by a thermal gradient or a mechanical constraint. We will study in detail within the next months these two possibilities in order to implement a passive (preferred) or active corrective system to prevent local deformations larger than 0.1 mm at the scale of the tile (0.1 mrad times the typical tile size) and 0.2 mm at the telescope scale.

The consequence is very important in terms of mirror manufacturing because they can be made of several tiles to be assembled (M2 mirror) or not (M1 mirror) with no consequence on the optical performances. Having this kind of mosaic does not strongly constraint the movable mechanical structure of the telescope as it tolerates deformations and rotation at the scale of the mm which is usually manageable with passive mechanical solutions. This is the same conclusion for the distance because our prototype will be able to translate and tilt independently M1 and M2.

Finally, the optical quality is not sensitive to a variation of the distance between the optical elements. A displacement of ± 5 mm does not change the PSF's width by no more than 10%. We are thus confident for the telescope construction and the performance to achieve.

4.3.4. The shelter

The location of the telescope on the site of the Meudon's Observatory implies the use of a shelter in order to work on the telescope despite the environmental conditions. Moreover, after the optical performance test in 2014 the prototype will be dedicated to outreaches for which the shelter is required to minimise the maintenance during this phase. Finally, the Meudon site is classified, which requires integrating our telescope SST-GATE in the landscape

The shelter must fit with the following requirements, which come from the telescope, the location site and the lifetime:

- Due to the telescope, the shelter must have a minimal length of 6 meters, a minimal width of 5 meters, and a minimal height of 5 meters. The power supply must be lower than 5 kW.
- Due to the characteristics of the Meudon site, the maximal wind speed is 150 km/h, the maximum snow weight is 110 kg/m², it has to avoid the propagation of any tear and an M2 certification against fire hazard has to be considered for the telescope security but also, in our case, for the outreaches.
- Due to the safety and the lifetime (30 years), the opening and the closing of the shelter must be done only when the telescope is in parking position. It must be possible to operate manually the shelter in case of a power failure. A guarantee of a minimal lifetime of 10 years is required.

Four different concepts are in competition.

- Mobile garage: it is a rigid structure in galvanized steel with a coverage made with PVC fabric sliding to discover the telescope on two rails.
- Retractable garage: it is an assembly of four rigid parts (an aluminium structure protected with polycarbonate plates) sliding and stored one into each other.
- PVC dome: It is a dome with an oval footprint composed of a structure in aluminium and tubes covered with a PVC fabric; the opening solution is made by a full 180° rotation of the structure.
- Resin dome: It is a moulded resin parts which rotate and can be stored one into each other, each part is a portion of a sphere.

Currently, a call for tender is opened; decision will be made during the summer for an assembly and mounting within the 6 following months. The shelter option, first not considered by the CTA consortium, may be adopted for the SST telescopes.

4.4. Telescope Control

CTA will be composed of many distributed systems and sub-systems. The UK-French telescope control system has to be designed in such a way that its implementation in the CTA framework shall require as little developments as possible. With this objective in mind, the choice of standard industrial solutions can't be avoided; these have to provide reliable, scalable, manufacturer-independent, and long-term support systems.

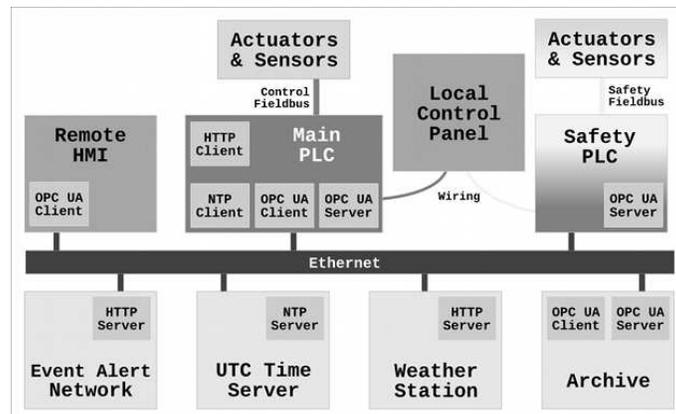


Figure 5: Communication architecture

For the implementation of the communication architecture, Ethernet is selected as the low-level layer and OPC UA as the software layer (see Figure 5). Other client-server protocols have to be added for instance the synchronisation. If a control software is used, this architecture may be integrated by using an interfacing layer such as DevIO in a CORBA environment to be compliant with the ACS environment.

For scalability and easy interfacing, the software will be based on Object-Oriented Programming (OOP); depending on the functions and the targets, LabVIEW, C++ and Java are preferred languages.

The environment of telescopes is always demanding in terms of temperature and altitude. In consequence the hardware has to be rugged: the considered main PLC is a NI CompactRIO, selected among different solutions.

5. EXPECTED PERFORMANCES

5.1. Alignment

For the SST-GATE prototype, the performances are measured by the PSF size and the ability of the telescope to track a scientific target on the sky within the 7 arcsec required by the scientific specifications.

From the Zemax simulation, the expected PSF over the field of view is presented in Figure 6. This performance is related to the mechanics (relative movement of the optical elements) and to the alignment (absolute position of the optical elements). We discussed in section 4 that the sensitivity to a mechanical deformation will be weak. A thermal-mechanical simulation will help us to identify the weaknesses of the design and to modify it to ensure the proper behaviour. Constraint gauges will also be installed in the telescope to make the telescope control able to compensate for the deformation.

For the alignment point of view, we intend to use to following procedure:

- To mount the PMS, the MTS and a sight in place of M2. With the M1's sight, we mechanically define the optical axis of the telescope. It has the advantage to link the optical axis position to the mechanical rotation axes.
- To mount the tiles on the PMS and align them by looking the image of a distant point source – aligned with the sights – in the image plane of M1.
- To mount the MTS then M2 with three reference lengths in order to place the M2 references parallel to the M1 ones.
- Same for the M2-detector distance.
- To look a star and refine the alignment according to the recorded PSF (to be minimised).

The use of reference length is possible for the SST telescope because the accuracy needed on the optical distances is larger than the millimetre. We remind that the M2's tiles will be assembled during the manufacture to alleviate the alignment procedure. We chose to identify the optical axis with the mechanical one because the error budget allocates a discrepancy between them of a fraction of millimetre which is reachable with classical mechanics.

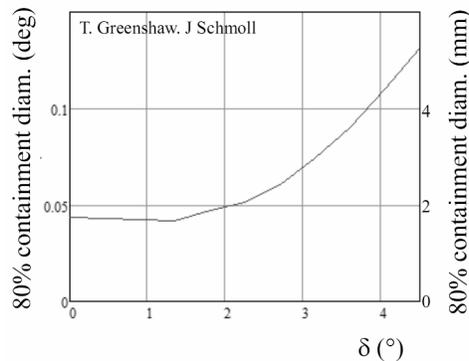


Figure 6: Expected SST-GATE PSF over the field of view. The pixel size of the scientific camera will be 0.2 degree.

We foresee to develop an elevation axis that ranges from -5° to $+185^\circ$ to ease the alignment of the Alt-azimuthal mechanical axes to the optical axis. Following the theodolite procedure to define the horizontal plane, we need to reverse the azimuth and the elevation angle (e.g. azimuth goes from 0° to 180° thus elevation goes from 0° to 180°) to look at the same direction in the sky but by changing the mechanical configuration. This capability enlarges the specifications with respect to the CTA requirements but it will ease the alignment process without any additional equipment.

As discussed in section 4, the mirrors must be moved in translation and tip-tilt in order to be tuned with respect to the optical axis (alignment procedure). Due to the tessellation of M1, we shrewdly assembled 4 tiles (two adjacent tiles per crown) to get 6 “big” tiles to be moved instead of 24. This reduced the number of actuators and, because single tiles are assembled four by four, the specifications for the M1 actuators become similar to the M2 ones, with strength of 1000 N for a stroke of 30 mm. We will thus provide a single kind of actuators for our prototype in order to optimise the cost equation.

5.2. Tracking performance

All the telescope assembly is involved in the tracking performance. The main identified parameters are presented in Table 3. We divided the error into systematic and statistic errors because the systematic errors can be compensated (if measured) whereas the statistical ones cannot be.

Systematic error	Statistic error
Horizontality of the azimuth rotation axis	Azimuth wobble
Perpendicularity between the azimuth and the elevation axes	Azimuth rotating smoothness
MTS deformation	Elevation wobble
Misorientation of the telescope optical axis with respect to the centre of rotation of the fork mount	Elevation rotating smoothness
	MTS vibration

Table 3: List of the main parameters that are involved in the source tracking performance.

A first errors budget has been established on the strength of the datasheet and on the method we foresee to position and to orient the different parts of the telescope. The estimate of the total statistic error equals 11 arcsec (no margin) so a discrepancy of 4 arcsec with respect to the requirements, if we consider that the all systematic errors can be corrected. The conclusion is that the orientation of the different parts will have to be refined by using reference stars. We are working on this aspect to prepare the AIT phase.

6. CURRENT STATUS OF THE PROJECT

As presented before, the SST-GATE telescope is an ambitious project using a new generation of optical design. The full design had to be created and optimized to fit the CTA requirement. Presently, the status of the project is well going considering the CTA schedule.

The main difficulties of the mechanical structure have been highlighted and solved. Doing so, we are now able to move to the building steps and to think about the control and monitor aspects, and to make a stiffer link with the science requirement considering the design.

6.1. The foundation

The project has been already brought to reality. Indeed, foundations of the telescope have been realized at the Observatoire de Paris in Meudon. The location has been chosen within the Meudon's site in order to be compliant with the observation constraints (other telescopes are in use), the environmental positioning and for an easiness of access and control.

Following the mechanical simulation, foundations have been made. It is composed of a large rectangular shape of about 5x6 m² and a stiffer square has been built in order to support the telescope itself. Power supply, Ethernet and fibre cables could be easily provided to the telescope thanks to the already built gallery which links the telescope to the dedicated control room.

6.2. Future work

As presented in the previous paragraphs, the main aspects of the telescope structure have been frozen; the validations have been made by successful mechanical analysis. In order to frozen definitively the mechanical design, further simulations will be made concerning the alt-azimuthal structure and the dishes of mirror M1 and M2. The telescope would be then slightly optimized. The risk analysis which is currently done would help us to complete the mechanical design and the definition of the software control. Last optimisation of the structure will be done by the parallel analysis in terms of mechanical and thermal simulations scheduled for the end of the year and the beginning of 2013. The goal will be to decrease as possible the weight and amount of steel in the structure in order to decrease the cost and assembling effort.

Moreover, the telescope design will be analysed through the scientific point of view. Currently, the scientific simulations we are performing show the various dependencies of the PSF but further work remains to take into account the entire structure of the telescope. For instance, the tubes connecting the camera to the mirror M2 create an obscuration on the detector that lead to a lower PSF quality. Thus, telescope design has to be related to the science quality that we want to obtain.

In the same way, alignment process which guarantees the required optical quality of our telescope has to be analysed through both the mechanical and science simulations. The error budget of the mechanical parts would have an influence on the PSF and must be taken into account as soon as possible.

Based on these studies, we would be able to build the telescope progressively by the beginning of 2013, starting with the alt-azimuthal system which is almost fixed now.

Moreover, the procurement of the shelter will be an important milestone for us because it will be the very first step of the construction allowing a continuous work on the site during the winter; power would be provided to test the well working of the shelter by the end of this year, and later on to test the functionality of the telescope drive.

Following the alt-azimuthal structure achievement, the whole telescope would be progressively built, for instance the mirror M2 should be received and mounted by the end of the summer 2013.

7. PERSPECTIVES AND CONCLUSION

CTA is presently a really challenging project in both technical and scientific aspects. The Observatoire de Paris is involved to demonstrate that a new generation of telescope based on Schwarzschild Couder design is a really good solution to achieve the resolution needed by CTA requirement.

From a technical point of view, the telescope is almost fixed in its mechanical design, advances in control, monitoring and alignment systems as software, hardware and components are under studies or procurement and will benefit from the definitive frozen structure due at the end of the year. Analyses are currently done to finalise and optimise simulations and the telescope will be built in current 2013.

In addition to prove the S-C design concept, the SST-GATE team has proposed since 2011 to use our prototype as a camera test bench. We are currently taking into account the camera designs – especially the CHEC camera one. This particularity devotes our design to be fully compliant with others CTA teams. For instance, the camera holder has to fit with all SST cameras from both a mechanical and an electrical point of view.

Moreover, the telescope is devoted to a long life of use in Meudon thanks to the research teams interested by this

innovative telescope but also by the educational outreaches which positively drive the manufacturing requirement of our telescope like the need of low cost of maintenance and the procurement of a shelter that represents an interest directly usable for CTA.

8. ACKNOWLEDGMENTS

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REFERENCES

- [1] J.A. Hinton & W. Hofmann, "Teraelectronvolt Astronomy", *Ann. Rev. Astron. Astrophys.*, 47:523 (2010).
- [2] CTA Consortium, "Design Concepts for the Cherenkov Telescope Array", *Experimental Astronomy*, 32, p 193, 2011.
- [3]. Bernl'ohr, K., et al., "Theoptical system of the H.E.S.S. imaging atmospheric Cherenkov telescopes. PartI: layout and components of the system", *Astropart.Phys.* 20,111–128(2003).
- [4]. Fernandez, J., et al.,Optics of the MAGIC telescope, AppendixA of J. Barrio, et al., "The MAGIC Telescope", MPI-PhE/98-5, Max-Planck-Institut für Physik (1998).
- [5]. Weekes, T.C. et al., "VERITAS: the Very Energetic Radiation Imaging Telescope Array System", *Astropart. Phys.* 17 ,221–243 (2002).
- [6]. Kawachi, A., et al., "The optical reflector system for the CANGAROO-II imaging atmospheric Cherenkov telescope", *Astropart. Phys.*, 14, 261–269 (2001).
- [7] Vassiliev V., Fegan, S., Brousseau, P., "Wide field aplanatic two-mirror telescopes for ground-based gamma-ray astronomy", *Aph*, 28, 10 (2007).
- [8] J. Rousselle, "Schwarzschild-Couder Telescope: Study of non-linear optical system", General CTA meeting, Amsterdam, 14-18 May, 2012.