Automatic performance budget: towards a risk reduction

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ABSTRACT

In this paper, we discuss the performance matrix of the SST-GATE telescope developed to allow us to partition and allocate the important characteristics to the various subsystems as well as to describe the process in order to verify that the current design will deliver the required performance. Due to the integrated nature of the telescope, a large number of parameters have to be controlled and effective calculation tools must be developed such as an automatic performance budget. Its main advantages consist in alleviating the work of the system engineer when changes occur in the design, in avoiding errors during any re-allocation process and recalculate automatically the scientific performance of the instrument. We explain in this paper the method to convert the ensquared energy (EE) and the signal-to-noise ratio (SNR) required by the science cases into the "as designed" instrument. To ensure successful design, integration and verification of the next generation instruments, it is of the utmost importance to have methods to control and manage the instrument's critical performance characteristics at its very early design steps to limit technical and cost risks in the project development. Such a performance budget is a tool towards this goal.

Keywords: Performance budget, Small Size Telescope, Cherenkov SST-GATE, system engineering, CTA, Cherenkov, Gamma-ray astronomy, Very High Energy

1. INTRODUCTION

Astronomy has really moved forwards when instruments arrived to improve the eyes performance. This story began in 1609 when Galileo used a Lipperhey's discovery, a tube with two lenses that magnified the images [1]. Pointing this new instrument to the sky, Galileo reported the presence of mountains on the moon and the existence of the Jovian satellites [3], unexpected facts at this time.

During the four following centuries, instrumentation has always improved its capabilities to see farther and fainter in order to fulfil the very demanding scientific requirements that point toward a better angular resolution, an enhanced signal-to-noise ratio (SNR), a longer lifetime and more versatility. These improvements rendered the instruments more complex and more expensive during the last decades whatever the wavelength domain. In the radio, SKA (Square Kilometre Array) represents the next generation of telescope array while in the visible, the ELT (Extremely Large Telescope) announces a new generation of versatile instruments with complex adaptive optics systems to take advantage of the large diameter of the telescopes and their high angular resolution. The VHE (Very High Energy) domain follows the same way by preparing CTA (Cherenkov Telescope Array) [3]. Such a large array of telescopes is mandatory to detect the atmospheric air showers generated by gamma-ray arriving at Earth from the most powerful cosmic-ray sources, and will certainly open the last unexplored energy domain in the astronomy (E > 10 TeV).

To successfully realise this next-generation of telescopes and instruments, it is of the utmost importance to control the cost of the development, the complexity of the systems and the duration of the project. Tools, such as the automatic performance budget, are mandatory to reach these goals. They allow a system engineer:

- To shorten the development phases by optimizing the feed back loop between the engineers in charge of the design and the achieved specifications.
- To allocate automatically the budget errors within the overall instrument with the help of general rules that depend on the behaviour of the system (telescope or instrument).
- To have an update of the expected scientific performance rapidly each time a change occurs in the design.

- To avoid human errors when changes are made in the allocation. This is very important for complex projects (e.g. including adaptive optics systems) in which flowing down a change can rapidly become very complex.

Moreover, building an automatic performance budget gives a better understanding of the instrument to the system engineering during the earliest phase because it ensures to detect all the links between the different parameters that influence the systems. It is also a driver to detect the technological stoppers.
In this paper, we will focus on the automatic performance budget created for SST-GATE, a prototype telescope under construction for CTA. We will first explain what a Schwarzschild-Couder telescope is (section 2) and derive it in major technical specifications (section 3). In section 4, we describe the SST-GATE telescope before explaining how to build an automatic performance budget (section 5) and using SST-GATE as an example (section 6).

2. WHY A SCHWARZSCHILD-COUDER TELESCOPE?

Cherenkov telescopes operate usually in a photon starved regime and, to avoid contamination of the air shower image with the night sky background, the exposure must match the duration of the Cherenkov light pulse (a few nanoseconds). Therefore, the image of the air shower cannot be improved by increasing the exposure time. This has motivated the development of optical systems with large (~2m) to very large (~28m) primary mirrors for the VHE domain, having diameter larger than 20 metres. Moreover, a minimum number of optical elements is mandatory[*] to circumvent light loss ([4], [5], [6], [7]). For this reason, the first Cherenkov telescopes were designed according to the optical concept of Davies-Cotton (D-C), which is based on a single mirror made of spherical segments arranged in a spherical shape. Despite its intrinsic optical aberrations, the D-C allowed the discovery of the first sources in the VHE domain. All the current IACT (Imaging Atmospheric Cherenkov Telescope) arrays use either D-C or parabolic designs. The latter minimise time dispersion of the Cherenkov signal and are thus preferred for the largest telescopes.

The mostly ultra-violet light pulse triggered upon interaction of the VHE gamma-rays with the atmosphere are detected indirectly from cascades of charged particles (air showers). Their geometry and energy 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 as explained above. At energies of a few 10 to a few 100 TeV, the Cherenkov light emission is stronger, but the detection is limited by the low statistics of the usually steep energy spectra of the astrophysical sources. In this domain, telescopes can 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. A few large-size telescopes (LSTs), with parabolic dishes, will cover the lowest energies; a few tens of medium-size telescopes (MSTs), based on the Davies-Cotton (D-C) design, are optimised for the TeV energy range; and many tens of small-size telescopes (SSTs), spread over several km^2, will cover the highest energies up to 100 TeV.

Due to the physics of interaction, the most energetic gamma-rays create air showers that illuminate an area several square kilometres in size and an ideal Cherenkov telescope would provide, in addition of its large diameter, a small plate scale and a large FoV. Especially for the SST component of CTA, a wide FoV is of great interest, since it enables the capture of images of air showers at large angular distances. This allows a larger spacing of the SST component 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 field of view (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. As a consequence, D-C telescopes are not an obvious solution as explained in [8]: 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. Such an optical system that has both a large aperture and a high f-ratio (i.e. field of view) leads to a large plate scale, typically 50 mm per arc minute. As a consequence, the size and the weight of

[*] For a discussion of different IACT designs, see for example A.M.Hillas, 2013, Astropart. Phys., 43, 19 or M. Actis, G. Agnetta, F. Aharonian et al. (CTA Consortium), 2011, Exp. Astron. 32, 193.

the camera increases as well as its distance from the dish. These large and expensive cameras consist usually of several hundred photo-multiplier tubes, with the drawback of an enlarged effect of vignetting of the FoV and increasing the constraints in the mechanical structure that holds the camera.

Thus, for a given plate scale, an aplanatic design such as the Schwarzschild-Couder dual-mirror radically outperforms the usual single reflector designs in terms of the effective light gathering power, the ability to accommodate a wide FoV, and the amount of time dispersion. Finally, with its small plate scale of 0.7 mm per arc minute, it allows the use of small cameras which alleviates the constraints in the mechanical structure.

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. One reason can be the particular shape of the mirror required to perform the optical quality. The Observatoire de Paris, represented by the LUTh and the GEPI 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 consists in proposing 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 with this design, thanks to a smaller camera and a lighter structure compared to the baseline D-C option. These are exactly the constraints an automatic performance budget helps to deal with.

3. THE CHALLENGES OF BUILDING A S-C TELESCOPE

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

Table 1: The scientific requirements for an S-C telescope to be built at the Meudon's site of the Observatoire de Paris. [(a)] The PSF size is determined by the area in which 80% of the energy is spread (EE). [(b)] The angular resolution depends on the energy; we give here the most constraining for the design. [(c)] The throughput includes vignetting. [(d)] This precision includes systematic and statistical errors. [(e)] Averaged over one year.

Optical		**Mechanical & Maintenance**	
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	< 7 arcsec
Pixel size	6x6 mm²	Slew speed	> 90°/min
Plate scale	0.025°/mm	Reliability of operation	97 % of the observational time[(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 presents only the most constraining requirements. The optical requirements have been derived in optical surfaces by Zemax simulations whereas the mechanical and the maintenance ones have been transformed in high level technical requirements for the engineering team.

From a general point of view, the high level requirements may be derived into different levels i.e. “essential” (the minimum the equipment must perform), “optimal” and “goal”. These levels give to the system engineering team the range in which each parameter must be situated in order to perform an optimisation of the various budgets without back-looping permanently with the scientific team. This important scientific work is essential to get a technical team reactive to the unavoidable changes in the specifications in a project. For SST-GATE, the principle is identical even if the manner slightly differs as the optical and the mechanical specifications that are not fixed to one value (i.e. FoV, throughput, etc) have been derived into “minimum” (the values displayed in the table i.e. FoV = 9°) and “goal” which means that these values must be better whenever it is possible (i.e. FoV > 9°).

In addition of these technical specifications, the project must take into account the common requirements that encompass all the CTA telescopes:

- Each telescope must be pointed independently to optimise the scientific targets and their ability to point and track any cosmic source whatever the targets of the other telescopes.
- A telescope must be operated from a remote control room.
- A telescope must be compliant with the existing camera (volume, weight…) and provide their positioning in their focal plate with the proper accuracy.
- A telescope must have a parking position that resist to a wind speed up to 150 km/h[†].
- The maintainability must be performed with less than 6 person.hours per week and must not let a telescope unavailable more than 3 observational nights per year.
- The telescope's life time shall be at least 30 years without any protection against the environmental conditions.

Moreover, the environmental conditions also constrain the telescope design. 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 environmental parameters over the four sites in competition during the design phase of the telescopes. The specific cost and the maintenance specificities have been recorded in order to give to the CTA Project Committee the real cost of our prototype once the site will be chosen. These environmental conditions are gathered in Table 2.

Table 2: Climate conditions assumed to design the S-C prototype (CTA requirements).

Parameter	Observing conditions	Critical conditions	Emergency conditions	Survival conditions
Temperature range (°C)	-15 to +25	-20 to +40	-20 to +40	-20 to +40
Wind speed range (km/h)	< 36	< 50	< 50	<120
Humidity range (%)	2 to 90	2 to 100	2 to 100	2 to 100

In the critical situation, the telescope can observe but with degraded performance. Velocities and accelerations of the movements are reduced to 70% of their nominal capabilities. 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.
In addition to the performance requirements, 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. For the long duration life-time, it requires choosing long-life equipment with a mature technology. It also means to design the telescope in order to make the maintenance quick and easy.

4. THE SST-GATE TELESCOPE DESIGN

4.1. Conceptual design

The high level technical requirements derived from the scientific specifications led us to the functional diagram presented in Figure 1. This functional analysis helped us to split the telescope in six parts as independent as possible to reduce and to simplify the interfaces. This is motivated to ease the procurement, the tests and the mounting of the telescope on the site which will be situated far from any facility. The corresponding PBS (Product Breakdown Structure) is thus composed of six main functions, as described in our High Level Technical Requirements.

- The FSS (Foundation and Slab Structure) will support the weight of the telescope and will provide the torque resistance to the wind.
- The AAS (Alt-Azimuthal Structure) provides the ability of the telescope to point at any direction in the sky and to track any scientific source with the required accuracy in the limit of the environmental conditions (see Table 2). It has also the function of supporting the optical part of the telescope and its counterweight.
- The elevation structure (which includes several functions) gathers all the movable parts: the mirrors M1 and M2, their supporting structure (MTS), the camera and the counterweight.
- The TCS (Telescope Control System) which controls the basic functions of the telescope and the safety operations.

[†] This wind speed is for the site of the prototype (Meudon). It is higher than the CTA requirement.

- The PSS (Protective Shelter Structure) will protect the telescope during its outreach life.
- Maintenance devices that are needed to maintain the telescope in operation during its life-time.

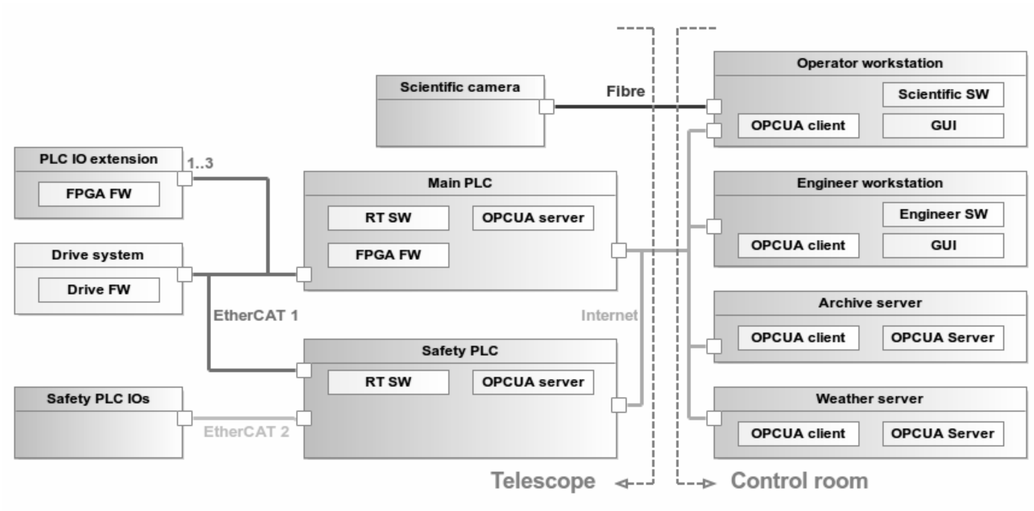

Figure 1: Functional diagram of the SST-GATE telescope.

The shelter is not part of the CTA requirement but it will allow mounting the telescope whatever the weather conditions in Paris. Moreover, our telescope will be used for outreach and science education after the prototyping phase and a shelter will alleviate the maintenance operation for the Observatory of Paris. Following our proposal the concept of a shelter for all the SST's is now being considered by the CTA consortium as a solution to reduce the cost of the maintenance.

A major driver in the design of a telescope is the combination of the movements to point at the sky. We have followed the CTA requirements and designed an alt-azimuthal structure because the mechanical tracking accuracy is not very demanding (5 arc minutes on sky). Moreover, an equatorial mount would have imposed a parking position toward the East or the West which are not necessarily the best directions with respect to the statistic wind direction in the future CTA site.

4.2. The optical structure

The telescope is based on a Schwarzschild-Couder optical concept as discussed in Section 2. It is composed of a primary mirror (M1) having a diameter of 4 metres and a secondary mirror (M2) of 2 metres diameter. The camera is located between the two mirrors which is significantly different from the classical D-C telescopes. With this construction, the light of any object is shadowed by the M2 mirror, its supporting structure (named MTS for Mast and Truss Structure) and the detector before being collected by the M1 mirror as shown in Figure 4.

The detecting surface of the S-C optical formula optimised for CTA is a disc of 362 mm in diameter. A distance of 510.7 mm separates the M2 mirror and the detector while the M1 and M2 mirrors are separated by 3561 mm. These distances, as well as the shape of the mirrors have been designed to offer the smallest PSF over the whole field of view of 9°. The scientific camera paves the focal plane with a matrix of pixels of about 6 x 6 mm^2 which leads to an angular resolution of 9 arc minutes. This poor angular resolution permits to get a large FoV with mirrors relatively simple to manufacture. As a result for SST-GATE, the PSF depends on the field angle and ranges from 3 arc minutes to 6 arc minutes. The mirrors have a shape described by a 16th order polynomial with a tolerance Peak-to-Valley of 20 µm and 50 µm respectively with respect to the theoretical shape.

An intuitive mechanical design for this kind of telescope consists in fastening the M1 and the M2 mirrors to the same mechanical structure. In this case, the distance between the mirrors M1 and M2 associated with the weight of M2 (about 130 kg with its supporting structure) would create an important momentum and would generate a variable flexure with the elevation angle. As a consequence, different segments would change position with respect to each other, degrading the optical performance of the telescope. A second consequence of this relative movement of the mirrors is the shift of the optical direction with respect to the mechanical one, which impacts the pointing accuracy of the telescope.

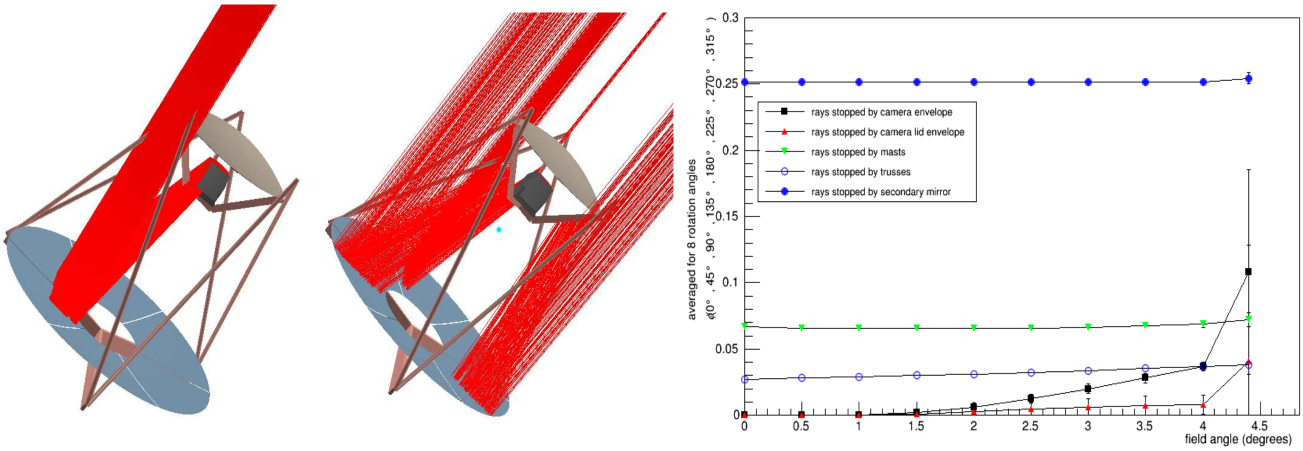

Figure 2: Shadowing due to the M2 mirror, the Mass and Truss Structure (MTS), composed of 6 rods arranged in a Serrurier-like configuration, and the detector. Off-axis illumination (left) and the on-axis (centre) are displayed. The fractional loss of photons versus the field angle due to the shadowing contributor is shown (right). Key colour is black bullet for ray stopped by the camera envelope, the red for the camera lid, green for the masts, open blue for trusses and blue for secondary mirror. Credit: Cameron Rulten.

The classical solution consists in stiffening the structure to reduce its flexure and to prevent deformations of the M1 mirror. This heavy and costly solution increases the shadowing of M1 and do not solve totally the problem. On SST-GATE, we developed a novel concept which consists in fastening the M1 and the M2 mirrors by independent structures: the M1 dish and the MTS respectively. Both are fixed as close as possible to the elevation structure (see Figure 3). Hence, the flexure of the MTS due to the mass of M2 does impact upon either the pointing direction of M1 or its shape. We alleviate the mechanical constraints and we ensure that the M1 mirror will look in the same direction as the mechanical structure, reducing the shift of the pointing direction. This solution has also the advantage of rendering the MTS lighter for better performance because it has to support the minimum possible weight and it reduces the shadowing of M1.

Following the same philosophy, the M1 mirror is split into 6 petals to lower the manufacturing cost and to ease the mounting operation. These petals are moved (1 degree of freedom) and oriented (2 degrees of freedom) individually to tune the telescope. These petals with their actuators are maintained by the M1 dish structure (PMS – for Primary Mirror Structure – in the PBS) to achieve an M1 mirror that behaves as a whole. This dish is fastened directly in its centre to the elevation structure of the telescope.

The split of the structures that support the mirror M1 and the mirror M2 with the separation of the M1 mirror into six petals increase the complexity of the performance budget as it must take into account the tip, the tilt and the defocus for (1) the mirror M2, (2) the mirror M1 as a whole and (3) the six petals. This explains why in Figure 5, four boxes are required for the dual-mirror telescope. Two are mandatory for the mirrors as a whole and two others for the petals, one for each mirror. Indeed, as the design is cost driven, we have foreseen in the performance budget the possibility of having petals also for the M2 mirror to let the system engineer test this option without changing anything in the structure of the performance budget. If the M2 mirror is monolithic, the values of this branch become null.

There is only one box for the 6 petals instead of six boxes because we want to determine the mean behaviour of the telescope (see section 5.1) so the allocation for the petals are identical as they are filled in term of standard deviation with a zero mean.

4.3. The mechanical structure of the telescope

The performance budget point of view

As we can see in Figure 3, the telescope has the classical design of an alt-azimuthal mount. A tower places the elevation axis high enough to allow the telescope to go down to -5° in elevation despite a diameter of 4 metres for the primary

mirror. On this tower is fixed the AAS which is composed of the azimuth rotation, the fork and the elevation sub-systems. The tower and the azimuth bearing have been chosen with a diameter smaller than 700 mm to reduce the cost. The fork enlarges the general footprint of the telescope to get a sufficient room for the bosshead – the central piece of the telescope – within the elevation structure. All these sub-systems are represented in the performance budget by (1) their interfaces, which consists in an allocation to take into account the uncertainties of the mounting and of the alignment of the different parts and (2) by the errors they induce in the telescope movement (flexure, non-circularity of the movement, etc.). These errors are gathered in the box named “Mechanics” in Figure 5.
To ease the maintenance and to optimise the spare policy, a minimum number of bearings have been used in the telescope. The azimuth and the elevation driving systems have been studied via trade-offs to solve the cost-maintenance-hazard equation. The baseline consists in using bearings to define the rotation axis. This solution is less efficient for slow movements than the oil film but it is imposed by the CTA requirements. A complex assembly has been designed to allow a smooth movement on both axis despite the harsh environment (for instance the precise encoders must be protected against dust and humidity) and the intrinsic limited accuracy of industrial bearings. As a consequence, the AAS, which gathers all these equipments, will be an assembly of 73 mechanical parts.
We emphasize that this sub-system is involved in the model of the telescope, a set of nine values that characterises the imperfections of the movement of the optical axis when the mechanical structure of the telescope moves. The AAS represents 5 of the 7 values and is the major contributor of the discrepancies (box named “control loop” in the performance budget).
Each driving system will be an assembly of a crown wheel moved by a worm gear and electric motors. A servo-motor wired with EtherCAT to the SST-GATE backbone will complete this assembly. The accuracy of the control loop has been estimated with the datasheet of the manufacturers and is also part of the performance budget to estimate the absolute pointing accuracy of the telescope.
Finally, as requested by the CTA requirements, the elevation movement will range from -5° to +91°. The azimuth will range from -90° to +450° with respect to the parking position.

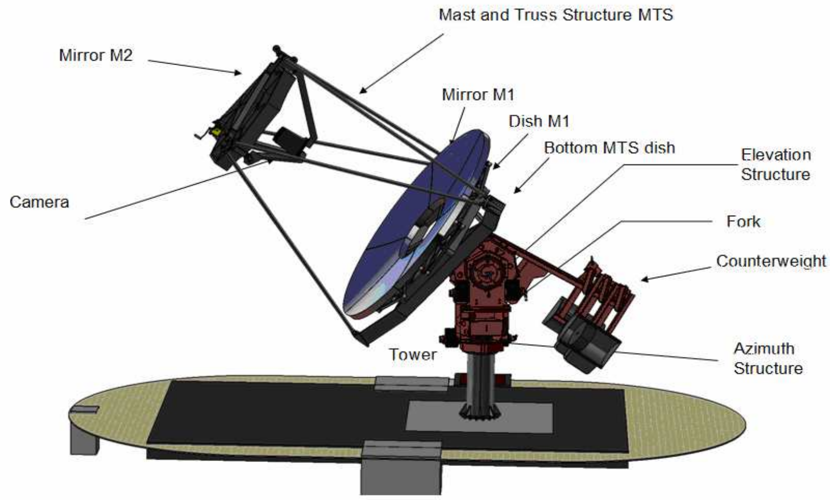

Figure 3: Conceptual design of the SST-GATE telescope.

Mechanical description of the telescope

The counterweight is fixed at the back of the bosshead while the optical parts are situated in front of it. The MTS (Mass and Truss Structure) starts from the bosshead and holds the M2 mirror as well as the detector. As mentioned in section 4.2 the PMS is fastened to the elevation axis and is located at 2.5 metres above the ground. The design has been made to minimise the torque due to the wind. It also eases the maintenance because most of the elements are reachable at human

height. Hence, we have implemented a mechanism to make the M1 rotate as a whole to allow the petals being changed without any scaffolding or ladder. This decreases the risk to break a mirror and reduces the time required for the maintenance operations.
The AAS (Alt-Azimuthal Structure) has to support several constraints which must not cause any irreversible damage or deformation. The first load is the combination of the compression due to the mass of the MTS and the counterweight (4 tons) plus the pressure the wind generates on the structure. If this load exceeds the Euler condition (53 500 kN for the steel grade S355 used for the telescope), a buckling may occur in the AAS, creating a permanent deformation which may require disassembly of the telescope for repairing before mounting and aligning it again. We considered a maximum wind speed of 150 km/h for this effect with a laminar profile which is the worst case because we neglect the edge effect of the ground (where the wind speed is null). Finally, we took into account the snow and the ice as specified in the CTA requirements (20 mm of ice and 500 mm of snow on the ground).
The AAS must also resist to the torsion due to an emergency stop of the azimuth or the elevation drive. The strains must not exceed the elastic limit for the steel to avoid permanent deformation. We use in the model a deceleration from the maximum speed (0.3°/s) to zero within 0.1 second.
The FEA (Finite Element Analysis) shows that the maximum constraints in the design are always situated at the bolts because they are linked with 3 points instead of the total surface of their washer. Despite this assumption, the constraints never exceed 50% of the steel grade S355 yield stress. The compression load (77 kN) is well lower than the Euler condition which suggests that no buckling will occur. We carefully modelled the bosshead which links the MTS with the elevation structure to ensure that the flexure of this mechanical part is small enough to be neglected in the discrepancy between the mechanical and the optical pointing directions. Earthquake hazards have been modelled with a horizontal acceleration of 0.25g (about magnitude 6 on the Richter scale) and a vertical acceleration of 0.35g according the CTA requirements and injure neither the structure nor the ball bearings.

The lifetime is an important parameter since it shall be at least 30 years. The major contributor is the varying period and strength of the wind. As no data are available on such a long period for the sites that are candidates, we made some assumptions (period down to 0.1 second, speed up to 150 km/h) and found that the maximum stress (270 MPa) is low enough to consider the fatigue of the material negligible. The modal analysis shows that the first two modes occurs at about 3 Hz and are the bending of the optical structure around the elevation axis and its perpendicular axis. At this frequency, the structure may not be excited by the wind.

For the system engineering team, such a model is important to update the major changes of the design and to verify that the design remains in the requirements. Even if an automatic performance budget makes possible a dialogue with the optical (thanks to a database of PSF simulations) and the mechanical engineer (via the interfaces), the link with the final mechanical performance is inaccessible without FEA.
This validation of the design led us in spring 2014 to launch several call for tender for the manufacturing of the AAS. The first elements have arrived on the site (see Figure 4).

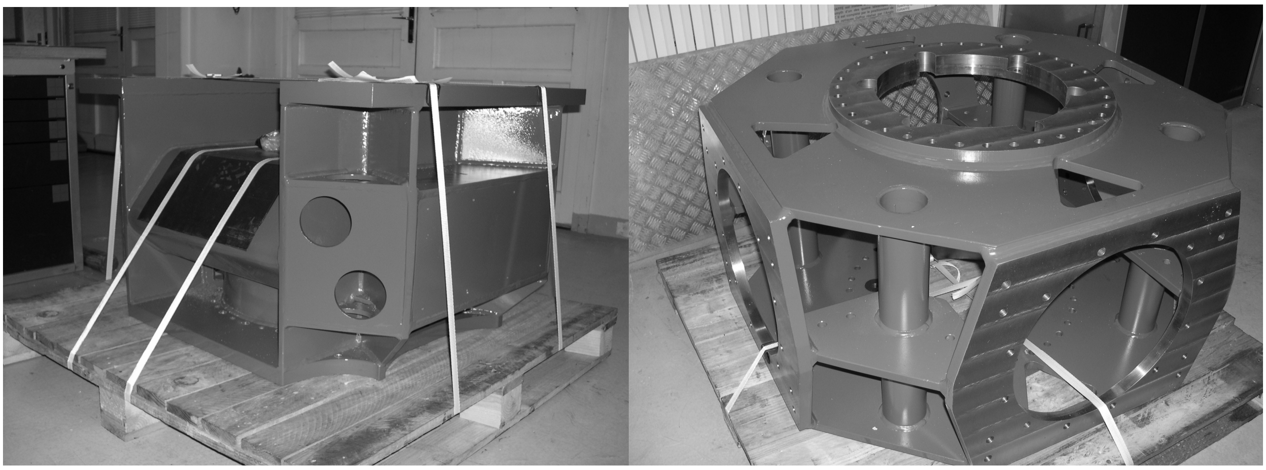

Figure 4: Image of the fork (left) and the bosshead (right) at the Observatory of Paris before their mounting.

5. HOW TO BUILD A PERFORMANCE BUDGET?

5.1. What is a performance budget?

System engineering is an interdisciplinary approach that aims to identify the stakeholder needs and their interfaces to transform them into a technical description capable of satisfying the minimum requirements regarding the cost and time constraints. The goal is to optimise the resources of the project, at the earliest phase of the design, in order to quickly define how the instrument will look from both a technical and scientific point of view.

To do so, it is of the utmost importance to be able to determine the consequence that may impact upon the scientific objectives if there is any change in the design. Considering that the technical developments are more and more complex to fulfil the requirements while the delay to design an instrument decreases this brainstorming phase needs powerful tools. One of them is the performance budget which encompasses the error budget by including an estimate of the scientific performance of the instrument and helps to determine the impact of a technical change in the design. As we are designing a telescope for a

large number of scientific sources we are interested in its mean behaviour and not in a particular case. Thus, all the allocations are distributed in terms of 3-sigma values (for statistical parameters) and in terms of maximum value (for the others) which represent the range in which the parameters can evolve.

The building of a performance budget starts with the understanding of the scientific requirements and their derivation in technical specifications. In the framework of CTA, the telescopes have two **main scientific drivers** that are the **SNR** (Signal to Noise Ratio), related to both the PSF (Point Spread function, which is the response of an optical system illuminated by a point source) and the different noises, and the **direction reconstruction**. Indeed, the telescopes do not see directly the scientific source but the light of the showers generated by the incoming cosmic-ray. The direction from which the light of the shower comes for each telescope allows retrieving the direction of the cosmic-ray direction. The more accurate the determination of the shower, the more precise the calculation of the scientific source on the sky. By continuing this reasoning, the system engineer follows the links from the scientific drivers down to the components and progressively builds his performance budget. The links represent how the system behaves and must be described by equations or by look-up table for the non-linear cases.

Hence, in the case of a “manual” performance budget, the system engineer has to perform all these calculations when a change occurs in the design. This task can be difficult for complex instruments or for those that require specific skills such as adaptive optics. On the contrary, an automatic performance budget re-calculates the allocation and flow up the changes up to the scientific requirement level. The system engineer can immediately see if the new performance fulfils or not the scientific requirements. This tool prevents also for human errors during these phases, making the automatic performance budget a powerful and kind solution.

5.2. Why an automatic performance budget?

An error budget consists of allocating to each sub-system the margins the engineers can afford to design their sub-systems. This ensures a technical optimization but has two drawbacks: the system engineer works at “constant volume” and he has no vision of the impact of a change on the scientific requirements. For instance, a large allocation, say 1 mm, for a detector in an instrument implies that the image will not necessarily be perfectly centred onto the detector but this has no consequence on the spectral resolution. On the contrary, allocating an additional millimetre on the position of a mirror in an instrument can degrade dramatically the PSF quality. The impact on the science requirement depends on the project and on the parameter considered. With an error budget, a permanent feed-back loop with the instrument scientist of the project is mandatory to ensure that the science requirements are always fulfilled. It is a long duration process which hinders to work rapidly when the system engineer wants to test several configurations of the instrument (or of the telescope).

If the System Engineer creates a performance budget, the available budget due to the scientific requirement is flowing down into the different sub-systems. As the latter are linked to the global scientific performance, the consequence of any change in the allocation of a sub-system can be evaluated in term of science. In this case, the System Engineer continues to loop with the Instrument Scientists. The action can be long but the decision can be made by scientific considerations.

If now the System Engineer makes an automatic performance budget, the physical links between the sub-systems are described by equations or look-up tables so that the global performance is automatically re-evaluated. The System Engineer can make a decision and accept or reject a technical change without looping permanently with the instrument scientist. This speeds the development phase up and makes the System Engineer able to test different scenarios of an instrument or a telescope in a short duration to mark the first phases of the project study.

This promising system requires from the scientific team to give to the system engineer the ranges in which the scientific parameters can evolve (for instance fixing the lower bound of the wavelength range to [350-380 nm] instead of fixing a unique value of, say 360 nm). It also assumes that the different LUTs (Look-Up-Table) are available (for instance how the PSF evolves with the decentring of the optical elements). But it has a major advantage: to do such a performance budget, the system engineer must list all the links between the different parameters to be sure to ask for all the LUTs he needs. This leads him/her to define some priorities in the simulations, data and parameters that mostly characterises the instrument.

5.3. Towards a versatile and automatic performance budget

It is possible to go further in the concept of a performance budget by making it versatile with the different science cases and the various physical parameters that can influence the performance of an instrument. Indeed, the science requirements usually consist of several science cases for which a change in the technical design has not the same impact. If the system engineer can select the science case in its performance budget, he/she is able to visualize the gain in the different science cases and determine if the change is valuable or not. Such a performance budget is also a very powerful tool to discuss with the various stakeholders in order to make decisions on an instrument when it overtakes the system engineer's ones. Moreover, if the system engineer can go through the phase dimensions of the parameters that influence the performance, he/she can help the engineers in charge of the design to choose the best way to reach the technical goals. For SST-GATE, we do not have several science cases but we do have to deal with numerous technical parameters including the FoV, the position of the mirrors, their tilt with respect to the telescope axis, the relative position and tilt of the tiles that compose the mirrors and the relative position of the mirrors. It has also to deal with the uncertainties of the alignment process of a novel optical layout, with a very specific shape of the mirrors that leads to additional constraints and with the behaviour of a telescope during 30 years. We will see in section 6 how these different parameters are treated.

Building an automatic performance budget requires some care. Firstly, the system engineer has to carefully partition the instrument. This task consists in splitting the instrument in several blocks that can be considered independent and for which the design can be performed as a whole. This aspect is very important because a set of optical components to be tuned do not require the same error allocation that the sum of the allocation required by each optical component considered individually. This is because some optical components can compensate the aberration due to others. Thus, partitioning an instrument has several advantages: it limits the number of interfaces to be managed, it alleviates the error budget and it gives some room to the design engineers to find the best possible solution taking into account the technical requirements. On the contrary, if the allocation is done for each component, the risk is to over-constraint the system and to compel the designers to eliminate some attractive solutions.

With a primary mirror of 4 meters in diameter made by an assembly of tiles and a scientific camera held at 3 meters from its Alt-azimuthal movement, SST-GATE cannot be mounted sequentially like a single instrument. Based on the experience of the team, the partition of the telescope consists of the tower, the AAS (Alt-Azimuthal System which includes the movement of the telescope) and the optical part, itself being split into the two mirrors, its supporting structure and the counterweight. This makes the production of each module independent, in which the internal alignment errors can be compensated for during its assembly operation. Consequently, each module generates an end-product (mechanical interface or an optical field) that can be easily measured and used for the assembly and for the alignment operations. The mounting operation is also easier since the modules can be assembled directly. An allocation in the error budget for their alignment that simply includes the tip-tilt and a bi-dimensional shift of the modules is sufficient for two adjacent blocks.

The system of units has to be chosen with care too. From an optical designer point of view, the WFE (Wave Front Error) is a very important parameter whereas in mechanics, engineers use millimetres for their dimensioned sketches as well as for the tolerances for the positioning and for the alignment of the optical components. On the opposite, the two scientific drivers in SST-GATE are estimated in fraction of energy (named EE for Ensquared- – or Encircled- – Energy, no unit) and in direction (angle, in radians). To make additions, the different parameters must be expressed in the same unit as far as possible. To do so, we have implemented a unit exchanger module that is able to convert the optical unit (wave front error in rms) in fraction of energy or in deviation in the focal plane (equivalent of the direction in the sky). This point is very important because it creates a feedback loop in the performance budget that does not exist in an error budget because the global allocation is manually estimated for (perhaps) each change in the design. An advantage of an automatic performance budget can be emphasized here: the system engineer is ensured that any change is taken into

account from the impact on the scientific drivers to the allocation in each sub-system.
The parameters that drive the performance budget have to be carefully selected. The performance criterion for science is the Signal to Noise Ratio. At the same level, the VHE domain requires to determine the direction of the incoming beam once the shower has been detected. These two criteria mainly depend on the optical elements (the two mirrors of the telescope) but, unfortunately, it is not possible to enhance both at the same time because the science drivers are linked to other parameters (detector noise, pixel size of the detector, etc.) and do not behave in the same way. An optimisation is thus required to fulfil as far as possible the science requirements while ensuring feasible mirrors in the industry with the allocated budgets (mass, volume, cost…).

6. BUILDING THE PERFORMANCE BUDGET OF SST-GATE

6.1. Rationale

To guide the performance budget allocation, sub-science parameters have been considered as part of the trade-off studies in SST-GATE. For the signal part, the throughput is not the only parameter that will influence the overall performance of the system. The EE (Encircled Energy) is also a crucial parameter for which the science must give an estimate. For the direction reconstruction, the movement of the telescope, the pointing accuracy and the mechanical flexure of the telescope are important drivers for which the science must also give a goal.
Another important parameter is the field of view (FoV) of the telescope that must equal at least 9° to be compliant with the CTA requirements. For any optical system, such a large FoV implies some aberrations that degrade the PSF (and then the EE). As the relation between the EE and the FoV depends on the mirror shape, it cannot be derived easily without extensive optical simulations. This is the same with the tip-tilt and the decentering of the mirrors that compose the SST-GATE telescope.
In the next sections, we will describe the SNR model that was developed by the system engineer and that allows analysing immediately the impact a change in the design generates on the overall performance of the instrument despite its complexity. This model automatically takes into account all the conversions between the parameters listed above. This aspect is very important because it allows the team to observe the change in the performance of the system immediately with any change in the input parameters. It also becomes possible to re-allocate performance and error budgets dynamically to the various system building blocks. As we have seen earlier, this would not be possible using the traditional methods. In the next section we will describe how the team has created this model.

6.2. Flowing down the scientific requirements

The SNR
The SNR is the composition of the signal to be measured, decreased by the transmission of the telescope and by the associated encircled energy (EE), and the different sources of noises (as stray light, moon light, camera noise…). The noises do not behave in the same manner. The camera noise is statistical due to the nature of the photomultipliers. The stray light is due to the light that is reflected by the elements of the telescope to the detector. This phenomenon occurs in certain situations that depend on the telescope state (azimuth, elevation, etc.) and the position of the source of light (for instance, the moon). There is also the halo of the moon due to the atmospheric scattering which is a systematic additional amount of light that varies with the date, the azimuth and the elevation. For a development phase, we do not need an accurate performance budget as we mainly wish to guide the design of a telescope to make it compliant with the requirements. Thus, we built a "worst case" performance budget to ease the calculations and to simplify its use. In this case, the stray light occurs at any time and the moon light can be switched on or off according the user wish. As a consequence, the camera noise is considered with its 3 sigma value to be compliant with this philosophy and the total noise becomes a simple addition of the three contributors. We have:

$$Noise = Detector\ noise + Stray\ light + Moon\ light \qquad (1)$$

And considering the discussion on the SNR above, we have:

$$Signal = Source\ Signal \times EE \times Throughput \qquad (2)$$

The throughput depends on the atmospheric absorption, the throughput and the absorption of the different optics involved in the telescope. The latter are technical parameters on which the System Engineer can play, according the companies found by the project to produce the optical elements.

EE represents the fraction of the incoming energy that is concentrated within a certain radius on the focal plane. For SST-GATE, the EE equals 80% if we consider a PSF radius of 2 mm on-axis according to our optical design. It measures the quality of the optical alignment of the telescope as it produces the image quality. As we mentioned above, the EE is difficult to calculate. It depends on the atmospheric transformation of the shower signal (chromatism, turbulence, refraction) and on the combination of the optical elements themselves. A discrepancy in their shape, position or orientation worsens the EE. The PSF (or EE) determination implies to use a Fourier Transformation and to take into account the aberrations generated by the optical elements – which have a non-linear behaviour with the FoV – as well as the orientation of the mirrors with respect to the optical axis of the telescope. An additional complexity comes from the fact that the M1 mirror is split into 6 petals. This is illustrated in the Figure 5 where we only depicted the links between the optical elements and the science drivers – and not the others such as the chromatism – to simplify the scheme. We can see that the EE depends on the global mirror characteristics (position, orientation, shape) and on the characteristics of the tiles that compose the M1 mirror. As explained in section 4.2, we add the possibility to have a non-monolithic M2 mirror.
Integrating the Fourier transformation within the performance budget to make it automatic is a complex task. To simplify the interfaces, we created a database with Zemax simulations for different combinations of values for the parameters involved in the EE, namely the FoV, the tip-tilt (mirror and their tiles), the decentring of the mirrors and their tiles. Hence, according the value entered by the system engineer for each parameter, the performance budget interpolates within the database to get the appropriate value of EE. No action is mandatory by the optical designers and the system engineer can decide immediately if a change in the design is acceptable or not. This is the strength of an automatic performance budget.

The direction reconstruction
The direction reconstruction is simpler to describe because it is a simple geometric relation with the mirror orientation with respect to the telescope axis. It is sensitive to the thermal effects and to the mechanical errors but not to the discrepancies of the shape of the mirrors. It also depends on the accuracy with which the telescope has been aligned.

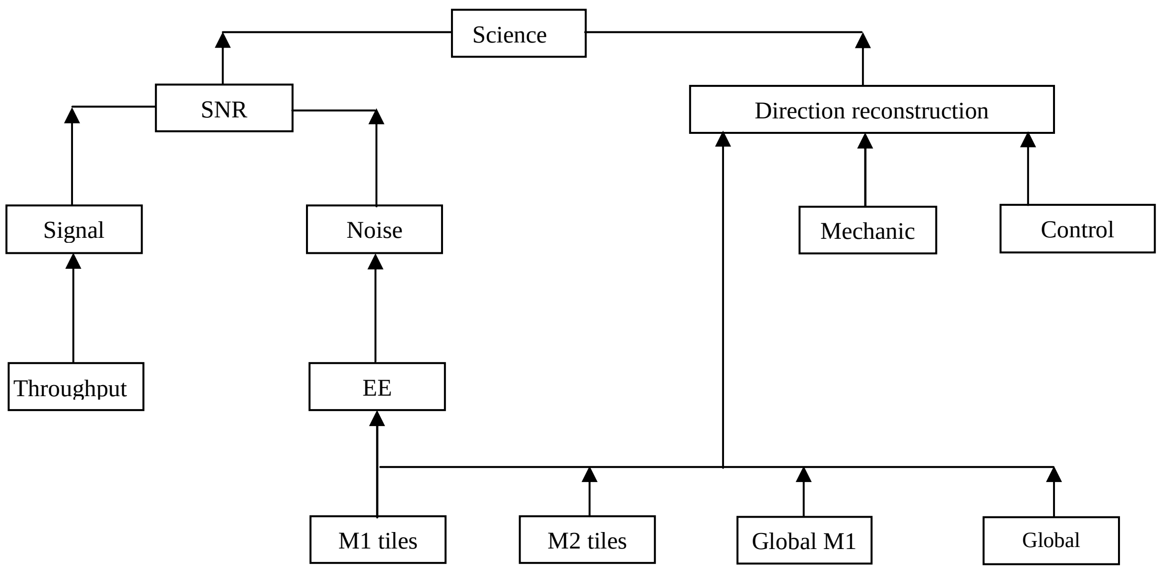

Figure 5: Scheme of the high-level structure of the performance budget for SST-GATE.

The calculation of the direction from which the cosmic-rays come from is related to the atmospheric effects (chromatism, turbulence, refraction) that change the path of the light according the wavelength, to the mechanical behaviour of the telescope (quality of the rotation, perpendicularity of the axes, etc.), to the control loop accuracy and to the optical elements. Indeed, an unknown misalignment of these components induces a movement of the focal spot onto the detector and an error on the direction reconstruction of the cosmic-ray.

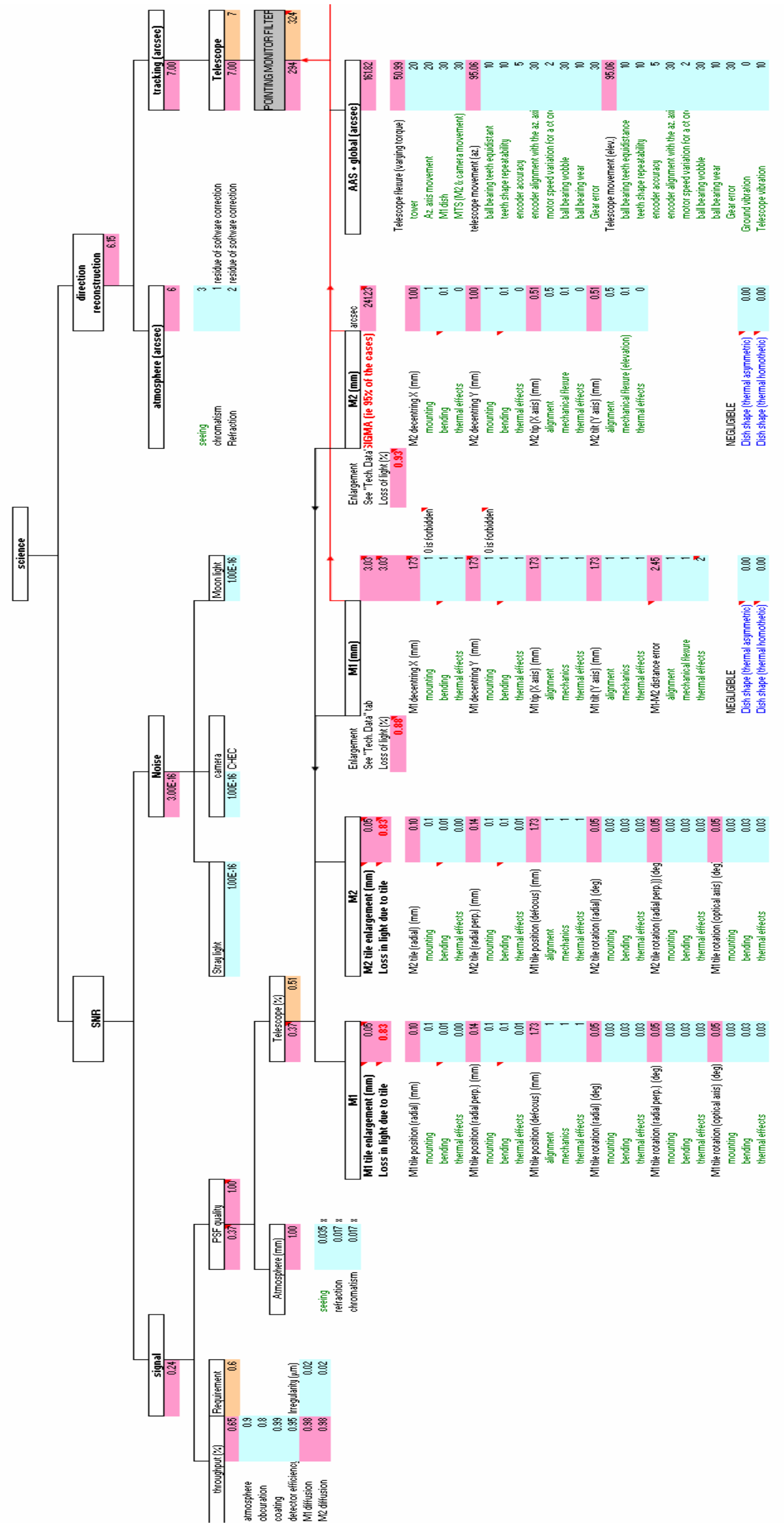

Figure 6 : First sheet of the performance budget of the SST-GATE project.

The control loop

The intrinsic accuracy of the control loop creates a small bias between the real direction along which the telescope points at and the one required by the science. It is lower than 1 arc second after comparison with the IMCCE‡ service.

As we explained above, the telescope is a complex set of mechanical parts that will be mounted with certain uncertainties that come from the manufacturing process and the accuracy of the metrology tools. This will lead some errors that are listed in Table 3. If these errors are not taken into account, i.e. if one considers that the telescope is perfectly aligned, with perpendicular axes, a variable discrepancy between the scientific source and the pointing direction of the telescope will permanently degrade the measurements. A model of the telescope must be created to take into account these imperfections. The method consists in taking several dozens of pictures of the sky in the area where the telescope is supposed to observe to create a map of the discrepancies between the pointing direction of the telescope and the exact position (usually, we use an astronomical source that may be situated at the centre of the focal plane if the telescope was perfectly aligned.). This set of discrepancies is inverted to get the numerical values of the parameters listed in Table 3. With these values, it becomes possible to create the model of the telescope as explained in 4.3.

Table 3 : List of the parameters and their name in [9] involved in the telescope model for an alt-azimuthal mount.

Designation	**Name**
Roll index error	IA
Pitch index error	IE
Vertical Deflection	FLOP
OTA/pitch non perpendicularity	CA
Roll/pitch non perpendicularity	NPAE
Roll axis	AW
Misalignment	AN

The performance budget

The performance budget of SST-GATE is presented in Figure 6. The four left columns at the bottom of the performance budget are the boxes named M1 tiles, M2 tiles, Global M1 and Global M2. The fifth column is dedicated to the AAS sub-system and the sixth (not visible in Figure 6) is for the control loop. The column at the extreme left gathers values for the throughput (atmosphere and optics). The other cells are used for other effects, such as chromatism, and to calculate the scientific performance (the upper cell of the performance budget).

7. CONCLUSION

SST-GATE is an example of how an automatic performance budget is crucial for the successful development of highly integrated instrument or telescope. Some optical elements impact on the two main scientific topics: the direction reconstruction and the SNR. By the way, they are not independent and the science performance must be considered as a whole. Indeed, a tilt of the mirror does not significantly degrade the PSF (or the EE fraction) but it does have a large impact on the direction reconstruction. This is the contrary to the case where the mirrors are decentered. Each scientific driver constrains the mirror specifications and finding a balance reasonable cost and alignment complexity too difficult is not easy. Thus several loops are required in order to optimise the balance between the two scientific topics, and this is where the automatic calculation proved extremely helpful.

For the same reason, a system engineer's work is made easier when a change in the allocation is mandatory. The performance budget re-calculates automatically and immediately the scientific performance and represents a powerful tool to discuss technical solutions with the engineers in charge of the design.

Finally, an automatic performance budget reduces the risk of human error because (1) all the calculations are done automatically and because (2) the sole human action consists in entering values in the error allocation tree.

Of course, building an automatic performance budget is longer than for a classical error (or performance) budget. But the amount of work is not very important especially if we compare it to the amount of work required to perform the

‡ IMCCE is a unit of the Observatory of Paris which is involved in the calculation of the Ephemerides.

calculation manually. Indeed, whatever the project, the system engineer has to split the system into sub-systems, to identify the link(s) between them and must determine how they interact and behave (via equations or simulations). The sole additional work towards an automatic performance budget consists in creating a database for the interpolations (if required by the complexity of the behaviour of the system) and to enter the equations that simulate the physical links between the different elements of the system. The third (and last) additional action consists in verifying that the calculations are performed properly.
So, when is it worth building an automatic performance budget? We think that the answer is always. Even on a small project (say 3-4 people involved), the time saved by an automatic budget can be discussed. The duration of the project is another parameter. If the design phase lasts several years, forgetting certain details on how the performance budget runs is unavoidable whereas with an automatic performance budget, the system engineer can use it at any time with no risk of mistake.

The context of the astronomy requires saving time and cost during the design, the construction and the exploitation phases while lengthening the lifetime and enhancing the performances. To succeed in this multi-dimensional goal, an automatic performance budget helps by shortening the design phase and ensuring that all the possibilities can be investigated in terms of scientific performance in a reasonable time because, precisely, the automatic performance budget delivers a result immediately.
Such an automatic performance budget has been already performed for another project and is being re-used for future project at the UK ATC for the MOONS project. We are thus confident that the use of this kind of tool will be generalised rapidly.

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