Status of the Small-Sized Telescopes programme for the Cherenkov Telescope Array Observatory

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ABSTRACT

The Cherenkov Telescope Array Observatory (CTAO) will include telescopes of three different sizes, the smallest of which are the Small-Sized Telescopes (SSTs). In particular, the SSTs will be installed at the southern site of CTAO, on the Chilean Andes, and will cover the highest energy range of CTAO (up to ~300 TeV). The SSTs are developed by an international consortium of institutes that will provide them as an in-kind contribution to CTAO. The optical design of the SSTs is based on a Schwarzschild-Couder-like dual-mirror polynomial configuration, with a primary aperture of 4.3m diameter. They are equipped with a focal plane camera based on SiPM detectors covering a field of view of ~9°. The preliminary design of the SST telescopes was evaluated and approved during the Product Review (PR) organised with CTAO in February 2023. The SST project is now going through a consolidation phase leading to the finalisation and submission of the final design to the Critical Design Review (CDR), expected to occur late 2024, after which the production

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and construction of the telescopes will begin leading to a delivery of the telescopes to CTAO southern site starting at the end of 2025-early 2026 onward. In this contribution we will present the progress of the SST programme, including the results of the PDR, the consolidation phase of the project and the plan up to the on-site integration of the telescopes.

Keywords: Observatories, Atmospheric Cherenkov Telescopes, Telescopes, Cameras, Mirrors, Opto-mechanical instrument design, Control System, CTAO, SST

1. INTRODUCTION

When a VHE gamma-ray interacts with the atoms and ions in the upper layers of the atmosphere, it induces a cascade of secondary particles that propagate through the atmosphere for many kilometres at a speed greater than the speed of light in the air. These particles emit Cherenkov light, forward-beamed with an aperture angle of about one degree. A Cherenkov light event consists of a time-correlated multi-photon image with a typical time scale of ~10 ns. Cascades originate at an altitude of ~10 km above the ground and create a pool of light on the ground with a radius of ~120 m. Ground-based telescopes with large reflectors focus the light onto an imaging camera. Such Cherenkov cameras must be highly pixelated, cover a large field of view, and be able to detect UV/blue light down to the single photon level with exposure times of about a billionth of a second. To provide high imaging sensitivity over a wide energy range from a few tens of GeV to a few hundreds of TeV, the Cherenkov Telescope Array Observatory (CTAO, see website link at https://www.cta-observatory.org and reference [1]) will be based on sub-arrays of three different types of telescopes: large (LST, 23 m diameter [2]), medium (MST, 12 m diameter) and small (SST, 4 m diameter [8]). They are located in two observing sites, the northern one in La Palma, Canary Islands, and the southern one in the Chilean Andes in the Paranal region. The southern CTAO site includes LSTs, MSTs and SSTs. In particular, the current alpha-configuration foresees the construction and installation of 37 SSTs with the deployment of the first 5 telescopes by 2026.

The SSTs are being developed by an international consortium of institutes that will provide them as an in-kind contribution to CTAO. This consortium currently includes more than 20 Institutes from Italy, France, Germany, UK, Switzerland, Netherlands, Japan, Australia, and Brazil, and it is open to the inclusion, where possible, of more participants from the wider CTA community.

The SSTs are based on a modified Schwarzschild-Couder-like dual-mirror polynomial optical design, with a primary mirror of 4 m diameter, and are equipped with a focal plane camera based on SiPM detectors covering a field of view of ~9°. They are sensitive in the band from ~0.5 TeV up to ~300 TeV, providing the Observatory with sensitivity to the highest energies. The current SST concept has been validated by the development of the prototype ASTRI-Horn dual-mirror Cherenkov telescope [4], the first telescope of the ASTRI mini-array project [5] and a Cherenkov camera based on SiPM sensors called CHEC-S [6]. The overall telescope properties are summarised in Table 1.

Table 1. overall main properties of the Small-Sized Telescope (SST)

Small-Sized Telescope (SST)	
Optical Design	modified Schwarzschild-Couder
Primary reflector diameter	4.3 m
Secondary reflector diameter	1.8 m
Effective mirror area (including shadowing)	>5 m2
Focal length	2.15 m
Total weight	<17.5 t
Field of view	>8.8 degrees
Number of pixels in SST-CAM	2048
Pixel size (imaging)	0.16 degrees
Photodetector type	SiPM
Telescope data rates (before array trigger)	>600 Hz
Telescope data rates (readout of all pixels before array trigger)	2.6 Gb/s
Positioning time to any point in the sky (>30° elevation)	70 s
Pointing Precision	< 7 arcsecs

2. SST PROJECT DESCRIPTION

The telescope can best be described in terms of its functional breakdown.

The high-level Product Breakdown Structure (PBS) (Figure 1) includes the main elements that allocate the functions and sub-functions.

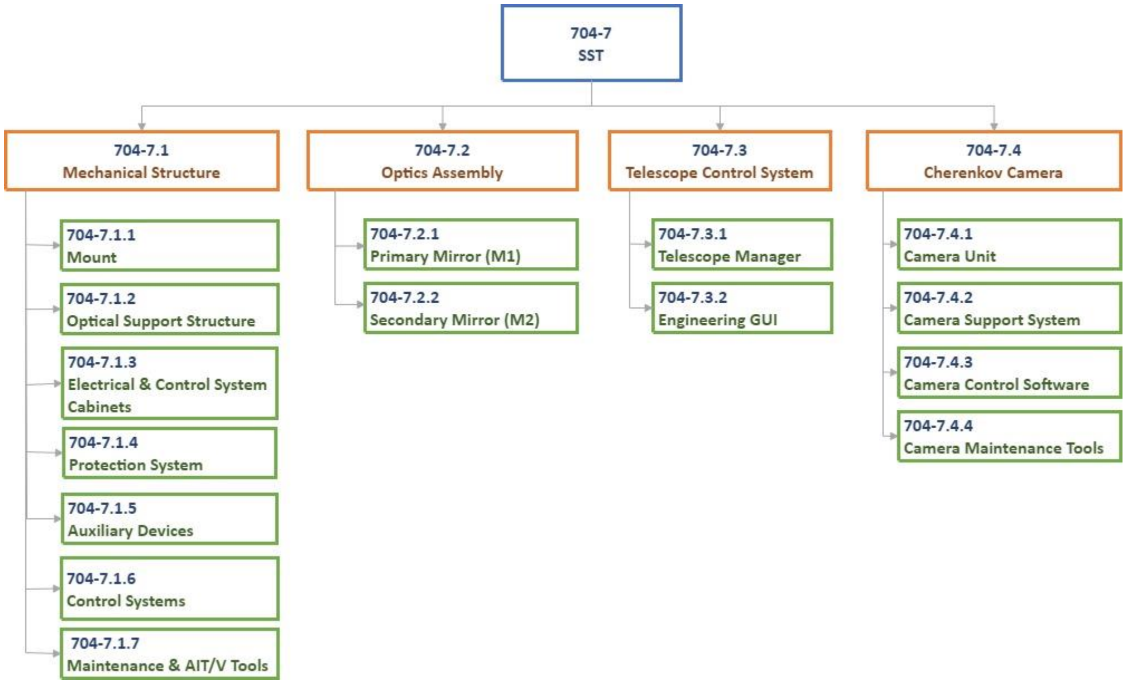

Figure 1. Telescope Product Breakdown Structure

The responsibilities of the SST Consortium are described in the following bullet points.

- *SST Telescopes:* It is the whole contribution of the SST Consortium to CTAO. It consists in the provision of all the equipment necessary to perform the imaging of the Cherenkov Light, providing the telemetry, both scientific and engineering, and guaranteeing an autonomous management of the telescope equipment.
- *Mechanical Structure (SST-MEC)*: The Telescope Mechanical Structure includes all the hardware, software and documentation that allows the telescope to point to different parts of the sky with the required performance. All mechanical parts (structural elements, bolts, screws, bearings, gears, springs, bumpers, accessories) needed to support the telescope optics to collect light are part of the SST-MEC. The SST-MEC provides the motion capabilities that allow the Telescope to point and track over its specified range. All of the EEE sub-systems included in the SST-MEC are provided with power and communication connection lines. The SST-MEC is fixed to the concrete foundation by means of anchor bars. The SST-MEC also includes the control hardware/software related to the SST-OPT.
- *Optics Assembly (SST-OPT):* The Optics Assembly (Optics) includes the primary and secondary mirrors.
- *Telescope Control System (SST-TCS):* The Telescope Control System (TCS) is the interface between the telescope and the CTAO facility. The TCS includes a telescope engineering GUI to operate the SST telescope in stand-alone mode during installation, calibration and maintenance activities.
- *Cherenkov Camera (SST-CAM):* The SST Camera includes all the activities related to the design development and implementation of the detection cameras, including all the related hardware and software subs-systems (with the associated documentation). The camera system of each telescope makes possible the Cherenkov signal detection, images acquisition, digitisation, trans project and pre-processing. The SST Camera system is modular; consisting of a number of subsystems. These modular subsystems greatly simplify the organisation and division

of activities within the production phase, and also form the basis of the international SST Camera Project (SST Camera).

Each of these subsystems is described in the following sections.

2.1 The Mechanical Structure

The current Mechanical Structure baseline selected for the SST is the outcome of a project initiated in 2011 as a "flagship project" funded by the Italian Ministry of University and Scientific Research (MUR). This project is named ASTRI and is led by the Italian Istituto Nazionale di AstroFisica (INAF). It started with developing a prototype Cherenkov telescope of the 4-m class, called ASTRI-Horn[4], relying on an innovative dual-mirror optical configuration based on a polynomial-modified Schwarzschild - Couder design previously proposed by Vassiliev et al., [7], for IACT telescopes.

After the successful realisation of the ASTRI-Horn prototype, the ASTRI team moved toward implementing 9 other telescopes, named the ASTRI Mini-Array [4]. This mini-array was supposed to be a pathfinder for the Southern site of CTAO, also representing the first seed around which the SST array would have been developed. However, the ASTRI schedule, dictated by the funds availability and time frame in which they had to be spent, was ahead of the CTAO site construction schedule. Therefore, in 2019, INAF and the Instituto de Astrofisica de Canarias (IAC) agreed to install the ASTRI Mini-Array at the Teide Astronomical Observatory in the Canary Islands of Tenerife.

The Mechanical Structure includes all the hardware and software that allows the telescope to point at different positions in the sky and achieve the required performance. All the mechanical parts (structural elements, bolts, screws, bearings, gears, springs, bumpers, accessories, etc.) needed to support the telescope optics to collect light are part of the Mechanical Structure. The CAD model of the telescope is shown in Figure 2.

The mechanical structure of the SST telescope is based on a common elevation-over-azimuth mount. The elevation angle is measured with the horizon as the reference (0 degrees EL), while the zenith is set at 90 degrees EL.

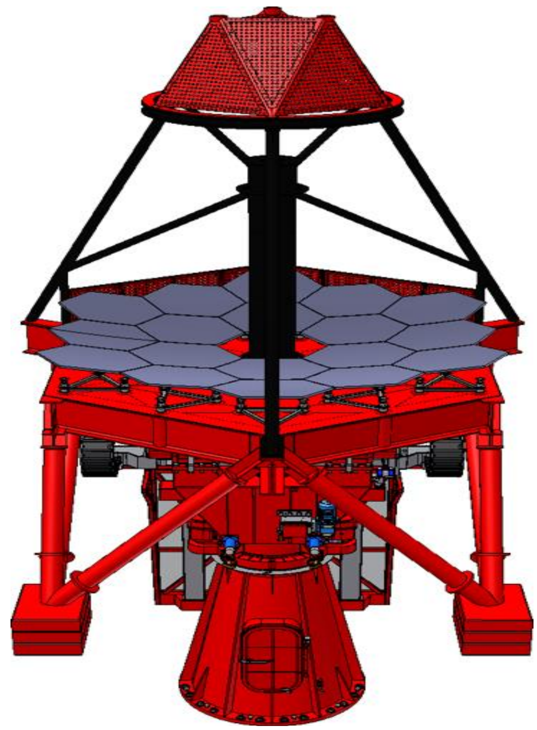

Figure 2: 3-D model of the SST telescope structure

A conical base fixes the telescopes to the foundation by means of 24 M33 anchor bolts. At the top of the base, a cross-roller slewing ring with an external gear allows the azimuth movement of the mount and supports the azimuth fork. The two electrical cabinets, a power cabinet and a control cabinet, are mounted on the azimuth fork and rotate along the azimuth axis to reduce the number of moving cables. Two elevation bearing groups support the elevation part of the telescope, called the Optical Support Structure, and the elevation motion is allowed by a mechanical ball screw jack. As the M1 dish with its mirror segments is positioned above the elevation axis, the presence of a ballast mass is necessary. The counterweights are supported by three tubes. A central tube standing on the M1 dish supports the Cherenkov camera at the top, while a tripod supports the M2 unit. The M2 unit consists of a support structure, the M2 mirror itself and an active optics system. The telescope's local control software controls all the functions of the mechanical structure, including the drive systems for the main axes.

Finally, the Pointing Monitoring Camera (PMC), which provides information on the current pointing direction of the telescope mount, is located at the top of the M2 support.

2.2 The Optics Assembly

The SST optical design is based on a slightly modified dual-mirror Schwarzschild-Couder configuration (see Figure 3). Unlike the Davies-Cotton configuration, which has a spherical mirror profile, as in the case of the MST and LST telescopes, the SST mirror profile is aplanatic and it is described by an aspherical polynomial function (see [9]). This solution allows us to derive a good imaging capability over a larger field of view (while it introduces a small on-axis degradation with respect to the classical Schwarzschild-Couder design). Such a configuration can be obtained even for small focal ratios, facilitating the construction of compact telescopes and reducing the overall size of the camera. In the case of SST, the focal ratio is F=0.5 with a plate scale of 37.5 mm/°. Since the Cherenkov pixel is approximately 0.16°, with an equivalent focal length of 2155 mm the SST optical design provides a usable field of view greater than 8.8° in diameter and an effective area of ~5 m^2.

The 4.3 m diameter primary mirror is segmented as shown in Figure 3. The full reflector consists of 18 segments (the central one is not used). The segmentation requires three segments with different surface profiles, indicated by different colours in the figure. The segments have a hexagonal shape with a face-to-face size of 85 cm. A 9 mm gap separates each segment from the next one to facilitate the mounting and alignment operations.

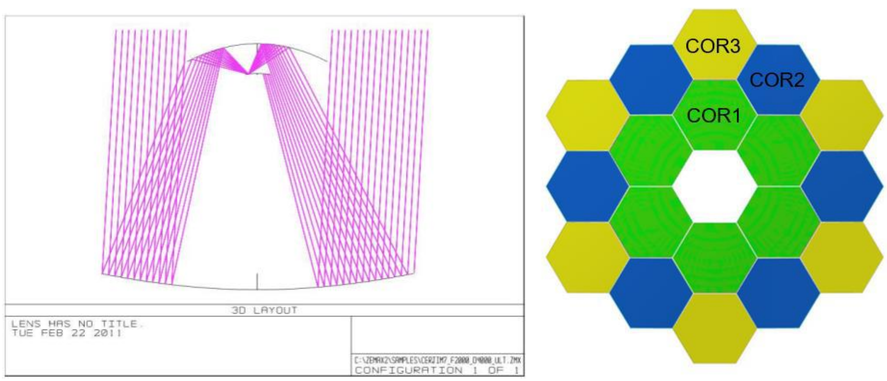

Figure 3: left: the SST optical system; right: tessellation of the primary mirror M1; the 18 segments are divided into three groups, identified by the colours, with a different surface profile

Each segment is equipped with three actuators, to correct for the tip/tilt and piston misplacements of each element. An active alignment system (actuators, controls, etc) will be installed only during the integration; once the mirrors have been aligned, the dynamic system is removed, and only a passive fixed system remains. The active system can be re-used each time the mirror system needs to be realigned, but this is estimated to be very infrequently. The segments of the primary mirror are made using a glass cold slumping technology, where the correct mirror shape is obtained by bending a thin glass foil on a mould with the correct profile. An aluminium honeycomb is then bonded to the bent film and a second thin glass film is bonded to the other side of the honeycomb. Finally, a suitable reflective coating is applied to the outer surface of the first curved glass sheet. The result is a stiff and lightweight mirror that meets the requirements of Cherenkov Telescopes. This technique was developed by INAF-Osservatorio Astronomico di Brera in collaboration with the Media Lario s.r.l. and was successfully used for the MAGIC-II telescope ([12]) and then for the ASTRI telescopes ([10]). It will also be used for the MSTs at the northern site of the CTAO. This approach is based on a cost-saving replication process, which is very attractive for CTAO due to the large number of mirrors to be produced, and provides lightweight mirrors with shape errors within a few microns, fully satisfying the requirements.

The secondary mirror, M2, is based on a monolithic substrate with a diameter of 1.8 m, produced by the hot slumping technique. A mandrel of the correct shape is placed in an oven with a flat glass foil on top; at high temperatures, the glass foil bends and takes the shape of the mandrel. The M2 mirror is mounted on the M2 support, which allows tip/tilt/piston adjustment to fine-tune the overall alignment of the SST telescope optical system. This approach has already been well proven with the implementation of the ASTRI-Horn and the first ASTRI mini-array telescope [11].

2.3 The Telescope Control system

The Telescope Control System (TCS) is the software manager, implemented by the SST consortium, and interfaces internally with the mount software, developed by an external contractor, and the camera software, and externally with the Array Control and Data Acquisition System(ACADA [13]).

The main blocks of the TCS are shown in Figure 4.

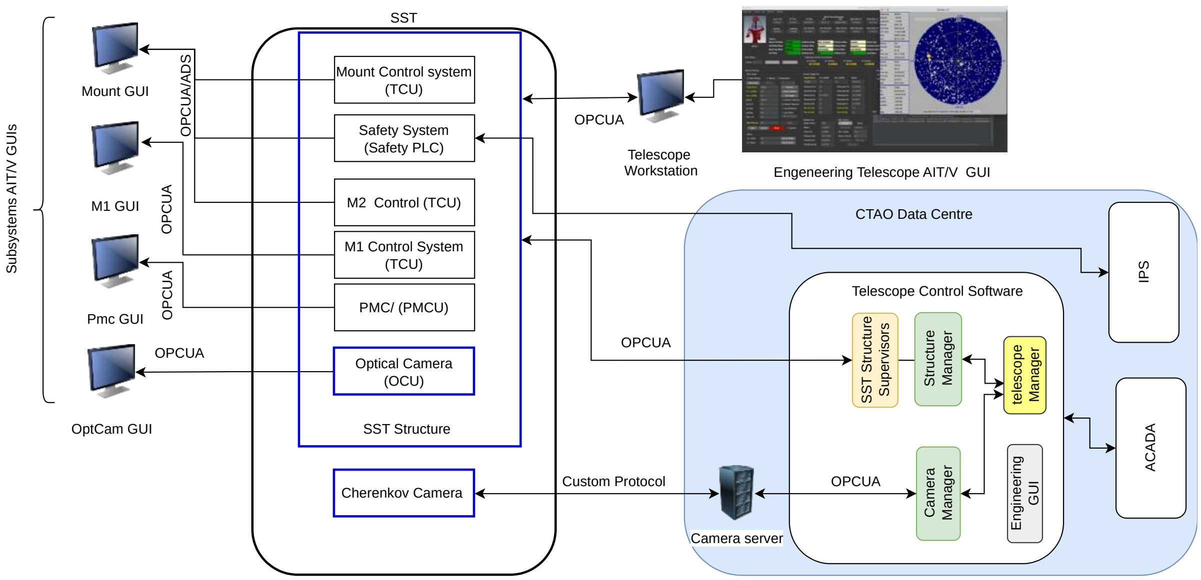

Figure 4: The Telescope Control System Architecture

The TCS also includes:

- Telescope Engineering to operate the SST Telescope in standalone mode during installation, calibration and maintenance activities;
- the Supervisors of all control systems installed on board each telescope.

2.4 The Cherenkov Camera

The SST Camera comprises all the hardware, software and documentation associated with Cherenkov image detection, digitalisation, transmission and pre-processing. Figure 5 shows the CAD model of the SST Camera.

The SST Camera is modular, consisting of a number of subsystems whose components have been prototyped with CHEC-S [6] and are now been designed to the final configuration.

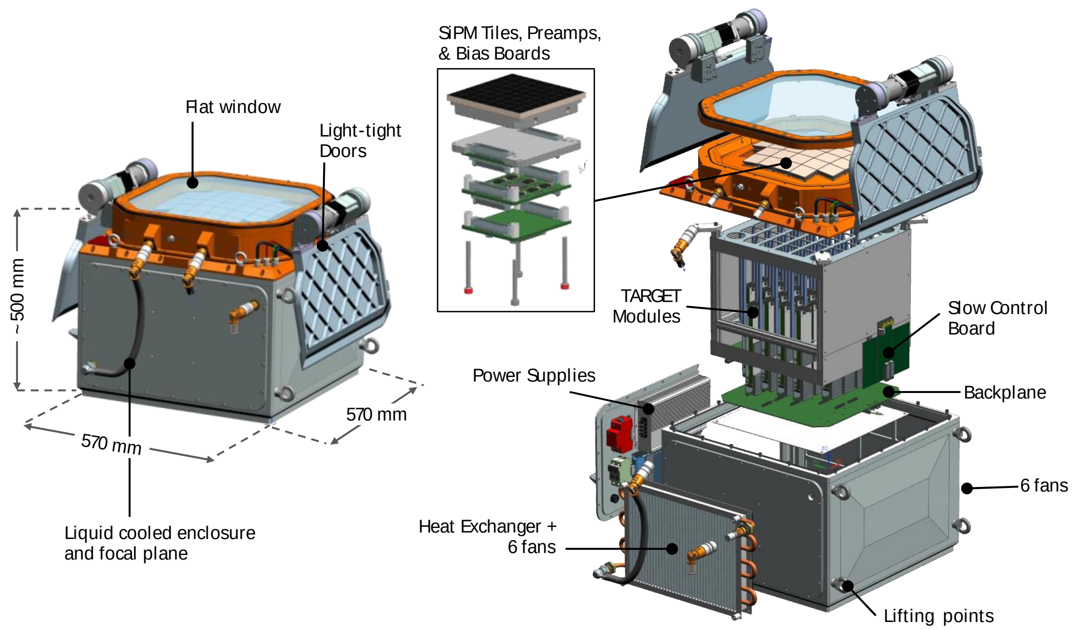

Figure 5: Overview CAD model of the SST Camera.

The Cherenkov Camera includes:

- Camera Unit
- Camera Support Systems
- Camera Software

Camera Unit

The Camera Unit is the main part of the SST Camera that is installed on the Telescope Structure. It is a photon-counting device consisting of an array of 2048 Silicon Photo-Multipliers (SiPM) and associated electronics responsible for self-triggering, fast (1 GS/s) digital waveform capture and nanosecond event timing. The Camera Unit design can record Cherenkov shower images with a good signal to noise ratio even in the presence of high levels of night-sky background light (NSB), being able to operate up to a rate of 1200 Hz.

The Camera Unit consists of the following items:

- Enclosure (ENC): The mechanical assembly housing the camera Focal Plane Assembly (including photosensors), and the Electronics Rack Assembly (which in turn houses the TARGET Modules). The Enclosure includes a heat exchanger and fans, a second set of fans and the camera power supplies, all mounted to removable panels. The Enclosure is sealed and water tight. All power and data connectors are located in the Power Panel. The Enclosure forms the mechanical interface to the Telescope Structure, attaching directly via the Telescope Interface Plate. The Enclosure measures approximately 50 cm x 50 cm x 50 cm and is made from machined Al. components. The ENC accepts an AC 230 V input connection for power, a multi-core fibre connection for data and control and refrigerant fluid inlet and outlet.

- Focal Plane Assembly (FPA): A liquid cooled, curved plate that holds all 32 SiPMs tiles in place, with a sealed, coated entrance window and door system. The chosen SiPM technology is 50 μm, "LVR3", provided by Hamamatsu Photonics. To minimise optical cross-talk, each SiPM will be used uncoated. SiPMs are connected to the focal-plane readout electronics that provide an interface to the TARGET Modules. Preamplifiers and interface boards are also connected to the SiPMs. The SiPMs are mounted on the liquid-cooled plate providing temperature stabilisation. The coated entrance window protects the SiPMs. A motorised door protects the window from adverse weather and dust, and the SiPM from daylight. The FPA also houses an internal camera illumination system to self-calibrate the camera.
- Electronics Rack Assembly (ERA): It consists of a mechanical rack, housing a Backplane board for camera-level triggering and read out, a Timing Board for precision time stamping, a SCSA (Slow-Control Sub-Assembly) for controlling the camera doors, the camera power distribution and monitoring of the environment inside the camera. The cabling connecting these boards is also part of the Electronics Rack.
- TARGET Modules (TMs): the 32 TARGET Modules are 3-board assemblies providing the first level of triggering and the digitisation of signals from the SiPM assemblies. Each module includes one FPGA, four TARGET sampling and four triggering ASICs.
- Focal Plane Illumination Assembly (FPIA): a system providing the illumination of the front of the camera for calibration and monitoring purposes. It is based on an LED Flasher system prototyped for CHEC-S. It is installed in the CU, with potential connection via fibre to an under-lid leaky fibre (part of the FPA), to a diffuser for illuminating M2 and to a fibre connected to a diffuser at M2. Alternatively, a second LED Flasher system is to be installed in the back of M2, for illuminating the camera directly. Finalisation of design choice is pending tests.

Camera Support Systems

The hardware items associated with the Camera located at the Telescope, but not part of the Camera Unit, including the camera chiller, pipework and any external cabling.

- Chiller Assembly: The camera chiller, heater and associated pipework. The Chiller and Heaters are commercially available units housed in a cabinet; the pipework is routed via the structure and connected to the Camera Unit;
- Cabling: All cabling external to the Camera Unit and attached to it. Such cabling is routed via the Telescope Structure.

Camera Software

All the SW installed on the Camera Server will be used to locally control and operate the camera and acquire the data it produces. It can be further divided into:

- Camera Local Control System: it is the software providing the camera control, and interfacing to the telescope control system via OPC-UA. It also provides Monitoring and Service data to the Telescope Control System and/or directly to ACADA.
- Camera Data Acquisition System: it is the software that acquires the Event data produced by the camera and uploads it directly to ACADA in R1 format.

3. SST PROJECT STATUS AND ORGANISATION

While waiting for the final formalisation of the CTAO organisation, which is expected to occur in 2024, we are now in the "**Consolidation Phase**", which started in June 2023 and will end with the Critical Design Review at the end of 2024.

In summary, the overall project timeline is divided in four main phases:

- Bridging (Closed)
- Consolidation (Current)
- Production
- On-Site AIT/V (Assembly, Integration, Testing and Verification)

Details of the tasks to be performed and completed in each phase are given below.

3.1 Bridging Phase (Closed)

During the bridge phase, the SST consortium was organised to manage all phases efficiently: a consortium board responsible for the implementation of the SST programme, composed of representatives of the lead partners, and a programme office responsible for the coordination of all day-to-day technical activities. The plans for management, PA, safety, development, AIT/V have been consolidated. The preliminary design has been consolidated following technical discussions with the CTAO, and thermo-structural analyses have been carried out to demonstrate the reliability of the system in the environment in which the telescopes will operate, with particular reference to earthquakes, which are a key reliability issue.

During the Bridging Phase, several trade-offs were performed to improve the SST. The most relevant trade-off for the scope of this SoW was the optimisation of the M1 dish design [14].

The Bridging Phase was concluded with by the Product Review (PR), held in February 2023, where the preliminary design of the SST Telescopes has been presented.

Product Review

The PR was the milestone closing the SST Bridging Phase, before entering the SST Design Consolidation Phase and it was organised by the SST consortium, with the active participation of CTAO both as reviewers and as part of the Decision Making Authority. During the review the design of the projects/subsystems was presented together with the status of all verification and validation steps. Although the SST design was verified by prototypes, it was expected that the outcome of the PR would identify any missing areas requiring further elaboration and provide advice as input to the SST design consolidation phase (in particular for serial production and AIT/V plans).

The Product Review was carried out with specific consideration of the development status achieved by the SST program based on the following elements:

- An SST Structure prototype, inherited from ASTRI-Horn Cherenkov telescope, has been produced and tested extensively in Catania, Serra La Nave, during the years 2014-2020 [4];
- A Camera Unit prototype (CHEC-S SiPM) [6];
- ASTRI Mini Array/ASTRI1 Structure prototype [5].
- Trade-Offs analysis have been done during the bridging.

The Review Board's assessment of the Data Package submitted for the PR was very positive. The SST design showed an appropriate level of maturity, with prototypes providing confidence in the proposed design. No show-stoppers were identified and all actions issued were considered non-critical and normal work for a project.

Specific recommendations were made by the Review Board for activities related to structural and finite element analysis. One of the objectives of the review was to authorise the early procurement of the long lead item for the Cherenkov camera. The Review Board carefully considered the risks involved and found them to be acceptable.

Finally, the SST design was considered sufficiently mature for its current phase and ready to enter the considered phase.

3.2 Consolidation Phase (Current)

The outcome of this phase is the final SST design, optimised for simplicity, maintainability, and cost. This phase will also produce the final plans and documentation for the Production and AIV Phases. The Design Consolidation Phase is expected to be completed with the passing of the Telescope CDR in late 2024.

Starting from the Consolidation Phase KO (occurred on June 7, 2023) and until the Telescope Critical Design Review the preliminary design of the Telescope and its subsystems, approved by the Product Review, will be consolidated and finalised. All the analysis and simulations to confirm the chosen design will be carried out. All HW models required to confirm the selected design will be produced and tested.

During this phase, industrial contractors will be involved to support the development and production of the mechanical structure and the optical system.

Mechanical Structure Status

The Telescope verification strategy uses prototypes for the main subsystems, engineering, and qualification models. As mentioned above, the electro-mechanical structure of the ASTRI Mini-Array has been defined as the baseline configuration of the SST structure and has been designed based on the SST requirements.

Given the strong commonality between the ASTRI Mini-Array and the SST Array, and the fact that the ASTRI team is also largely present in the SST team, we are directly experimenting all the procedures necessary for fabrication, integration, verification, transport of the telescope from Europe to the remote observing site, on-site integration and associated AIV/AIT (Assembly, Integration, Verification and Testing) activities. This means that we directly verify all the steps required to go from a telescope design to a fully assembled and operational telescope at the observing site. This allows us to put the construction of the SST array on a very solid footing.

The electromechanical structure of the first ASTRI Mini-Array telescope has been integrated and tested at the Teide Astronomical Observatory (Tenerife, Canary Islands) in 2023.

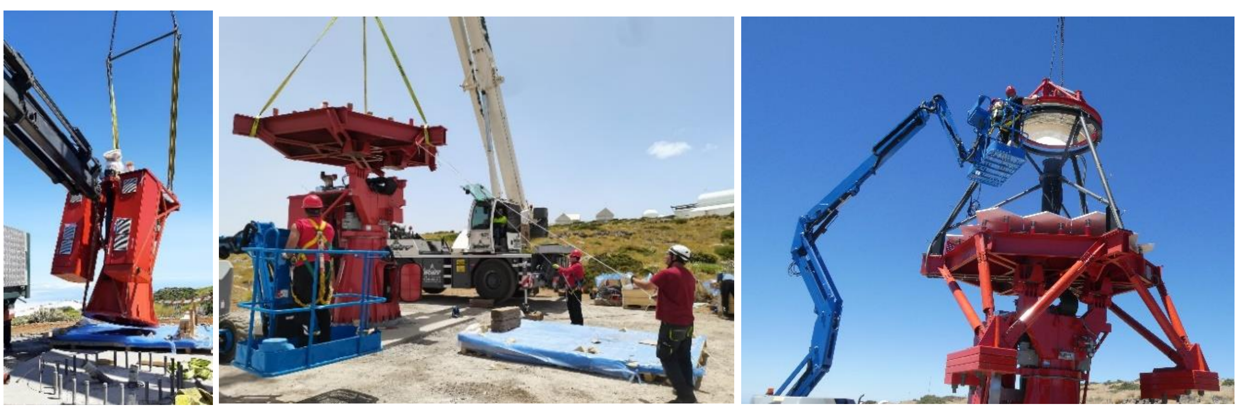

Figure 6. Mounting of the first ASTRI Mini-Array telescope at the Teide observatory. Left: The mounting of the base of the telescope on the foundation. Centre: The mounting of the M1 dish on the azimuth fork. Right: The mounting of M2 support structure (courtesy of EIE Group).

Figure 6 shows some stages of assembly and integration on the first telescope of the ASTRI Mini-Array. The assembly process takes between two and three weeks, including cabling and integration of the M1 segments.

Once the integration process was complete, the acceptance tests of the telescope began. The tests had to verify that the telescope met all the requirements. Interface requirements to the site infrastructure (foundation, power and communications) and to the optical systems (M1 and M2 mirrors) were the first to be verified. Functional requirements were the next to be verified (motion range, repositioning time, axes speed and acceleration) and then the operational requirements, mostly related to states transitions, error and alarms reporting and handling. Finally, the telescope performance requirements were verified. Pointing and tracking performance have been measured using an auxiliary CCD camera mounted on the top of M2 support structure (the Pointing Monitoring Camera) and was found to meet the requirements (<35 arcsec RMS for pointing and <6 arcmin RMS over 600 s). Once the telescope was fully tested, we started the alignment of the optics. The optical alignment system of the ASTRI mini-array telescopes and later of the SST telescopes consists of 54 removable M1 actuators (3 for each of the 18 panels), 3 M2 actuators and an optical camera placed at the focal plane of the telescope and equipped with a CMOS detector to image stars. Figure 7 shows the images of a star produced by the single mirrors of corona 2 and also the result of the aligning procedure.

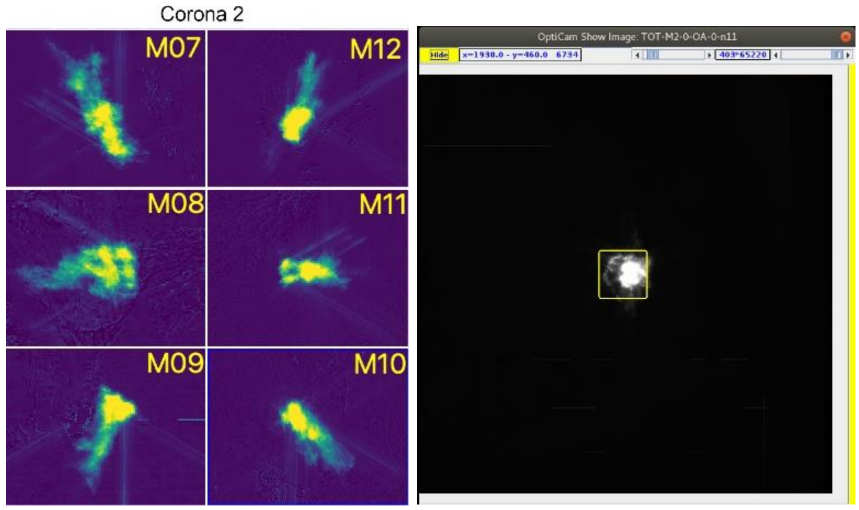

Figure 7. Left: images produced by the M1 mirrors of corona two. Right: the result of the alignment procedure. The linear dimensions of yellow square are 7×7 mm corresponding to the linear dimensions of a pixel of the ASTRI Mini-Array camera (courtesy of ASTRI project).

Detailed information on the performance of the first of the ASTRI Mini-Array Telescope can be found in [see Paper 13094-33 same conference].

During this phase, one tender for the industrial participation of a company was concluded. The bidder will finalise the design, carry out the final analysis with particular reference to the structural analysis, if necessary, produce sub-components prototypes to support any adjustments to the approved design and prepare documentation for the Critical Design Review.

During the next production phase, this bidder will manufacture 25 mechanical structures and will be responsible for the on-site integration of the telescopes.

Optics Assembly Status

Following the product review, the procurement of the optical elements for both the M1 segments and the M2 monolithic mirror has started.

As far as the M1 segments are concerned, the requirements have been frozen and all the paperwork has been prepared to allow the best manufacturer to be individuated on a tender basis, according to European law, in mid-2024. The applications received will then be evaluated on the basis of technical, economic and quality aspects and a winner will be selected to manufacture all the M1 segments. The first months of the activity will be devoted to the qualification and fine-tuning of all the parameters of the production processes, in order to arrive at the end of the consolidation phase with all the necessary information to support the CDR. As summarised in section 2.3, the manufacturing technology selected for the production of the M1 segments has already been successfully used in the past for ASTRI-MA, which has the same design as the SST. Therefore, the specific process is not expected to pose any problems and the main objective of the qualification is to verify the environmental requirements characteristic of the CTAO South site. Detailed preparation work has been carried out on product assurance and all the information relating to each individual segment will be collected in an individual identity card.

As far as the M2 mirror is concerned, the requirements have also been frozen and activities have started to set up a new dedicated production line in Italy. The selected technology has already been demonstrated in the past [4][5], but the need for a new production line requires some development activities. An oven has been specifically installed at the purpose and the first slumped M2 substrates have been realised with a mock-up mould to fine-tune the process parameters. The current results suggest a good process replication capability in line with the requirements; the final confirmation and qualification of the process quality is expected in a few months with an improved mould [see Paper 13100-126 in the same conference]. Until the CDR, it is planned to refurbish the used mould to the optical specification in order to qualify the process and prepare all the necessary procedures to allow the subsequent production of all the necessary M2 monolithic mirrors. Their number is considered compatible with the characterisation of each single mirror in terms of shape and reflectivity; therefore, no sample base characterisation is currently foreseen. In this case too, the individual identity card will be used to record and track all information relating to each individual mirror.

It should be noted that, wherever possible, tests are performed separately for the M1 and M2 mirror assemblies. However, the performance verification tests for the optical subsystem as a whole can only be completed at a higher level, after its integration into the telescope structure.

Telescope Control System Status

As far as the mechanical structure is concerned, the TCS is also derived from what has already been developed within the ASTRI project. At the beginning of the 'consolidation phase', and starting from the use cases, the requirements document, the product assurance plan and the development plan were consolidated. Based on the development plan, work started during the consolidation phase to adapt what had already been developed for ASTRI to SST and then to integrate the SW modules for camera control. The first tests will be carried out using the internal and external interface simulators. The final qualification of the TCS will take place during the integration of the first telescope in the factory, scheduled for mid-2025.

Cherenkov Camera Status

The development of the SST Camera is proceeding via the following model philosophy, prior to series production for CTAO.

- Mechanical camera (MCAM): Consisting of a full set of mechanics, including sealed enclosure and working door system. Internally MCAM contains all power supplies, fans, heat exchanger and slow control system. MCAM is used for interface, environmental and thermal tests.
- Camera Module (CM): A full SiPM tile (64 pixels), set of focal-plane electronics (SiPM bias supply and signal preamplification) and TARGET module. Several copies of CMs are made and tested prior to the next step. CMs are used to confirm charge, timing and first-level trigger performance.
- Quarter camera (QCAM): As MCAM, but equipped with 8 of the 32 CMs. A ¼ backplane provides the exact functionality of a full camera BP, for ¼ of the front-end electronics.
- Engineering Camera (ECAM): A fully equipped SST Camera. ECAM is used for final and full verification of the camera design.

MCAM, QCAM and ECAM are produced sequentially (but are physically unique) to allow design changes to be made between models.

MCAM has been produced (see Figure 8), and in November 2023 was transported to Tenerife for tests on the first ASTRI Mini-Array telescope (see Figure 9). The camera was successfully mounted and unmounted several times from the telescope, and the procedure carefully documented. The mechanical interfaces were all found to be correct. MCAM is currently undergoing thermal and environmental lab tests. Minor changes to the mechanical design and the slow-control cable connectors have been identified.

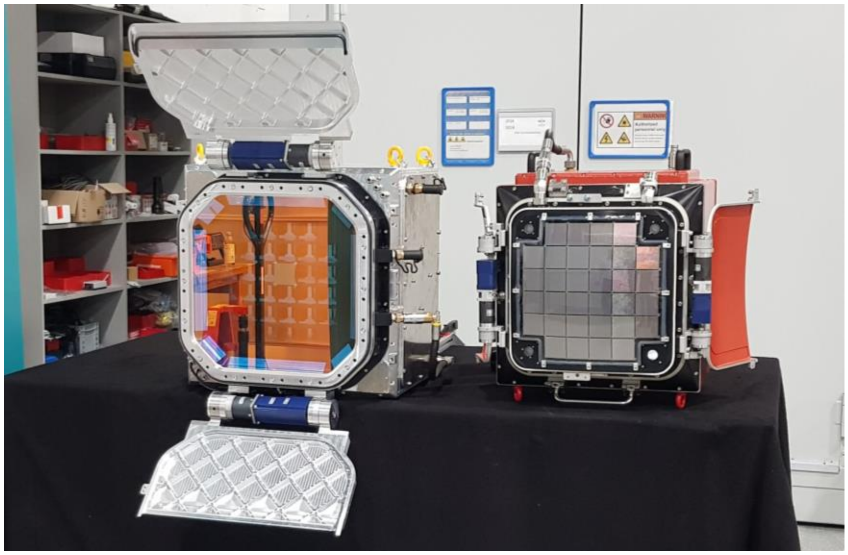

Figure 8: MCAM (left) next to the CHEC-S prototype

Figure 9: MCAM installed on the first ASTRI Mini Array telescope on Tenerife, with the camera and telescope team pictured below.

Full CMs have been built and are under test at several institutes (see Figure 10), results are pending.

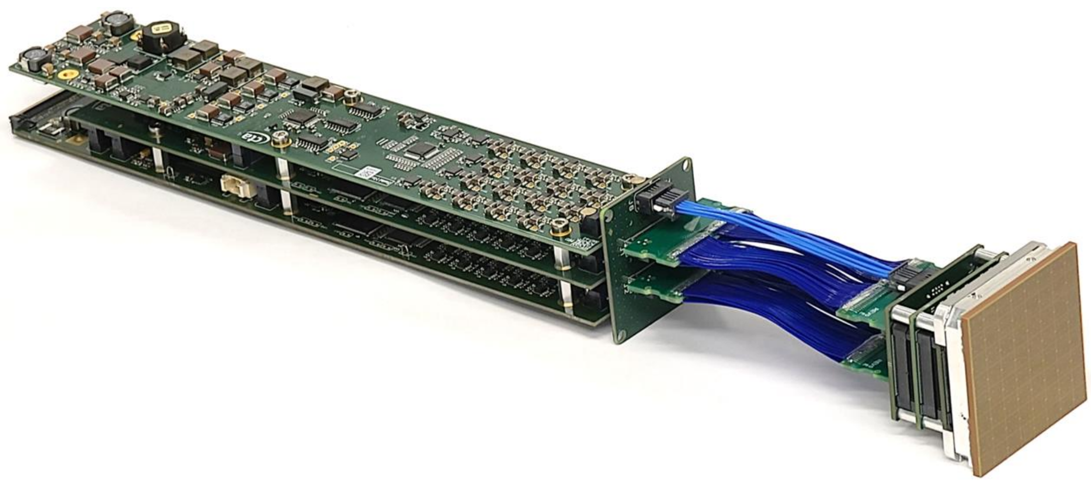

Figure 10: A single SST Camera Module, consisting of a 64-pixel SiPM tile, connected directly to PBCs providing SiPM bias voltage and signal preamplification. Flexible ribbon cables connect to the TARGET module, providing digitisation and first level triggering.

QCAM is due to be constructed in 2024. To date, all SiPMs for QCAM have been delivered and tested. CMs for QCAM exist and have been calibrated. A full set of mechanics has been built. Construction will take place in two steps: first the FPA (see Figure 5, all orange parts) will be integrated and tested, then once the QBP is complete, the full QCAM will be integrated. Following lab tests, the QCAM will be installed on the first ASTRI Mini Array telescope in Tenerife to perform on-sky verification tests. These tests will focus on:

- Verifying the optical alignment of camera mounted on the telescope
- Recording Cherenkov images from cosmic rays, and comparing parameter distributions to those expected from Monte-Carlo simulations
- Operation of the camera under extreme levels of night-sky background
- Extracting the pointing of the telescope using only data recorded by the Cherenkov camera.

Many parts for ECAM have been procured, including all SiPM tiles. Only once lab verification of the CMs has been completed, will procurement of front-end electronics take place. Development of the full backplane is taking place in parallel to QCAM build and tests.

In preparation for series production, early procurement of parts is underway for the first 5 cameras following verification. MCAM tests have allowed the production of all 5 sets of mechanical enclosures to proceed, along with procurement of fans, heat exchangers and power supplies. Following CM tests, ASIC and SiPM procurement are now proceeding. In this way, a balance between keeping to schedule and risk mitigation is achieved.

3.3 Production Phase

In this phase, the SST Partners will produce the elements of the SSTs (Structures, Cameras, TCS and Optics), to be delivered to the CTAO Southern site over approximately 3 years.

The first part of the production phase will start with the first telescope. The first telescope is considered as the SST qualification model and will be integrated in the factory to validate the I/Fs, to validate the M1 dish optimisations and the entire AIT/V process including calibration activities. For this scope, the first Cherenkov camera (ECAM), the optics and the TCS will be delivered to the industrial contractor, responsible for providing the mechanical structure, for integration into the telescope.

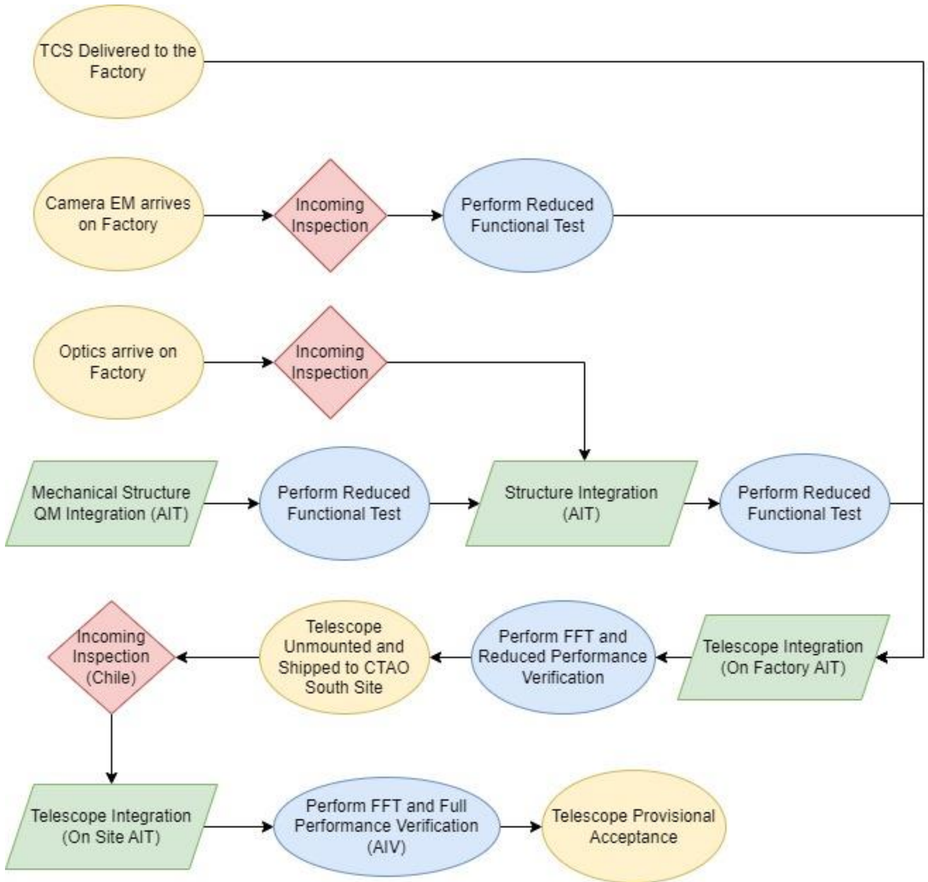

Figure 11: First Telescope Qualification AIT/V flow.

The telescope will be fully tested and its performance partially verified at the factory. Based on the readiness of the test results, the telescope will be disassembled and shipped to the CTAO South site. The successful completion of the test on the qualification model and the successful completion of QCAM on-sky verification tests (see section 3.2) will authorise the mass production of the SST telescopes.

During this phase, a further tender will be issued for the manufacture of a further 12 mechanical structures. The winner of this contract will also be responsible for the integration of the associated telescopes and will follow the same approach as the first, as shown in Figure 11. The Production Phase ends with the delivery of the last set of elements to the Southern site.

3.4 On-Site AIT/V Phase

The On-Site AIT/V Phase will start when the first telescope is available on site. The delivered subsystems will be installed and integrated on the foundation prepared by CTAO (see Figure 12). Each telescope will be commissioned and handed over to the CTAO. Due to the large number of telescope units, the production and on-site AIT/V phases will run in parallel. The AIT/V phase will end with the acceptance of the last set of SSTs by CTAO (~3.5 years from the start of the phase).

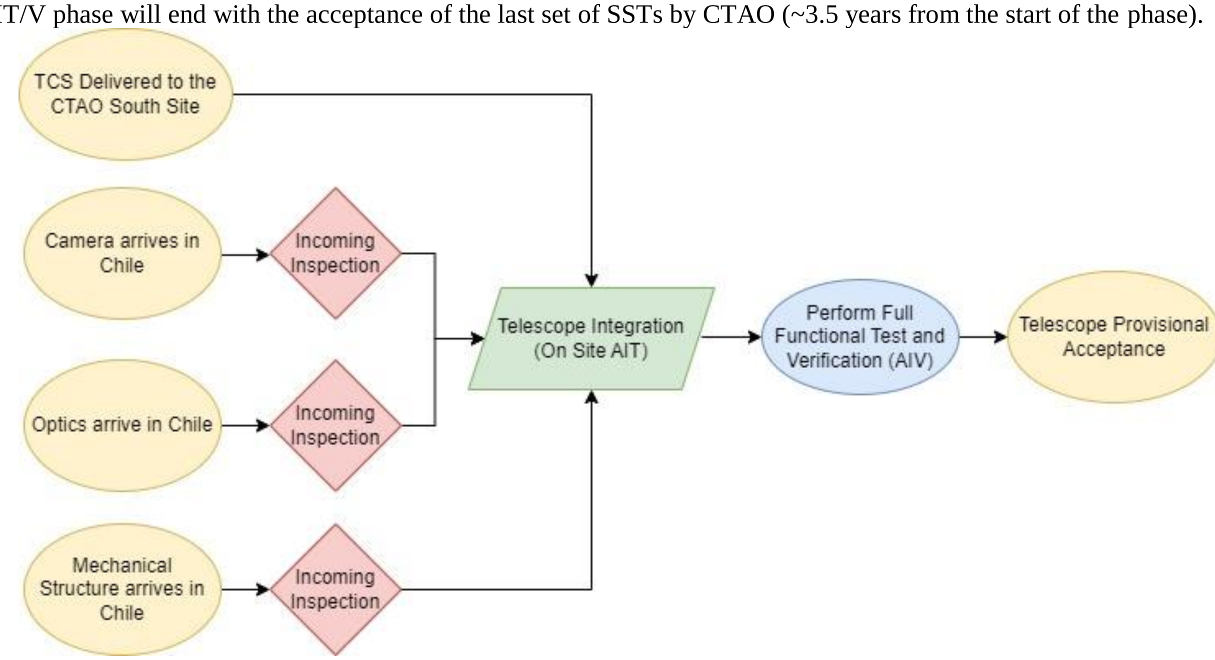

Figure 12: On-Site AIT/V flow

4. CONCLUSION

The international SST Consortium organisation has been consolidated to deliver the SST Telescopes as an in-kind contribution to CTAO. The preliminary design of the Telescopes was endorsed by CTAO at the end of the Bridging Phase. The SST project is currently in the Design Consolidation Phase, where all plans are being consolidated and the design and interfaces are being finalised through prototype testing and dedicated analysis.
The Consolidation Phase will be completed by 2024 with the Critical Design Review, managed by CTAO, which will formally authorise the production of the telescopes. The current schedule is for the first complete telescope to be ready for shipment to Chile by the end of 2025, the first five telescopes to be in place by 2026, and the full SST array of the alpha-configuration completed by 2028.

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REFERENCES

[1] Wild W., Ferrini, F., "CTAO – the world's first and largest ground-based gamma-ray observatory," https://doi.org/10.1117/12.2630255

[2] Mazin D., Cortina J., Teshima M., "Large Size Telescope Report," AIPC proc, Vol. 1792, issue 1 (2016) arXiv: 1610.04403

[3] Garczarczyk M., "The Medium-Sized Telescopes of the CTAO," https://doi.org/10.1117/12.2629857

[4] Pareschi G., "The ASTRI SST-2M prototype and mini-array for the Cherenkov Telescope Array (CTA)," proc. SPIE, vol. 9906, 99065T (2016)

[5] Scuderi S., et. al, "The ASTRI Mini-Array of Cherenkov telescopes at the Observatorio del Teide," JHEA 35, 52 (2022)

[6] Zorn J., et al., "CHEC—A compact high energy camera for the Cherenkov Telescope Array," Nuclear Inst. and Methods in Physics Research, vol. 936, 21 August 2019, Pages 229-230

[7] Vassiliev V., et al., "Wide field aplanatic two-mirror telescopes for ground-based γ-ray astronomy," Astroparticle Physics 28, 10-27 (2007)

[8] Tagliaferri G., et al, "The Small-Sized Telescope of CTAO," Proceedings of the SPIE, Volume 12182, id. 121820K 13 pp. (2022)

[9] Sironi G., "Aplanatic telescopes based on Schwarzschild optical configuration: from grazing incidence Wolter-like X-ray optics to Cherenkov two-mirror normal incidence telescopes," Proc. SPIE 10399, 1039903 (2017)

[10] La Palombara N., et al., "Mirror production for the Cherenkov telescopes of the ASTRI mini-array and the MST project for the Cherenkov Telescope Array," JATIS vol. 8, id. 014005 (2022), arXiv: 2201.08103

[11] Giro E., et al., "First optical validation of a Schwarzschild Couder telescope: the ASTRI SST-2M Cherenkov telescope," A&A 608, A86 (2017)

[12] Canestrari R., et al., "The ASTRI SST-2M prototype for the next generation of Cherenkov telescopes: structure and mirrors," Proc. SPIE 8861, 886102 (2013)

[13] Oya I., et al, "The Array Control and Data Acquisition System of the Cherenkov Telescope Array," doi:10.18429/JACoW-ICALEPCS2019-WEMPR005

[14] Dournaux J.-L., Bouley, F., Rébert, E., Huet, J.M., Sol H., et al.., "Mechanical optimization of the M1 Dish of the CTA-SST, the SST of the future Cherenkov Telescope Array," Proc. SPIE, (2022).