SST Mechanical Structure: Design Report

SST-MEC-DSR-001

Version 2b

Prepared by:		
Gino Tosti (INAF)	Gino Tosti	SST-STR SE
Latest Release Checked by:		
Salvatore Scuderi (INAF)	Salvatore Scuderi	SST-STR PM
Alessio Trois (INAF)	Alessio Trois	SST-PRO PRM
Nicola La Palombara (INAF)	Nicola La Palombara	SST-PRO PRQM
Approved by:		
Gianpiero Tagliaferri	Gianpiero Tagliaferri	SST-ESC

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1. Introduction

1.1. Scope & Purpose

This document is the SST Mechanical Structure Design Report, describing the structural, mechanical, and electrical design of the SST Telescope Mechanical Structure (SST-MEC).

This document outlines the entire design of the SST structure. The description is divided into five main parts, which respectively describe the following topics:

- Introduction
- Telescope mechanical structure design overview
- SST-MEC Structural items design description
- SST-MEC Mechanisms design description
- Electrical design
- Telescope Protection System

1.2. Applicable Documents

1. [AD1] SST-MEC-SPE-002 SST-MEC Requirement Specification
2. [AD2] CTA-ICD-SEI-000000-0016 ICD between the CTAO-SOUTH Power Distribution System and Small Sized Telescopes (SST)

1.3. Reference Documents

1. [RD1] SST-MES-TRE-001 ReportAnalysisDishM1_Iss1_1
2. [RD2] M1 Dish opt1 CAD Model 550-ME-000-00
3. [RD3] M1 Dish opt1 FEM Model 550-SST-MEC-MAT-200_v12
4. [RD4] SST-MEC-ANR-008 SST-MEC Structural Analysis report
5. [RD5] SST-DSR- Optical Design Report

1.4. Definition of Terms and Abbreviations

1.4.1. Abbreviations and Acronyms

ACADA	Array Control and Data Acquisition System
AIT	Assembly Integration and Testing
AIV	Assembly Integration and Verification
ASTRI	Astrophysics with Italian Replicating Technology Mirrors
BKO	Bridging phase Kick-Off
CAD	Computer Aided Design
CDR	Critical Design Review
COTS	Commercial off the Shelf
CTA	Cherenkov Telescope Array
CTAO	Cherenkov Telescope Array Observatory
FAR	Final Acceptance Review
FRC	France Contribution
DR	Delivery Review
DVER	Design Verification Engineering Review
ERIC	European Research Infrastructure Consortium
ESC	Executive Steering Committee
IKC	In Kind Contribution
INAF	Istituto Nazionale di Astrofisica
INSU	Institut National des Science de l'Univers
KO	Kick-Off
MPIK	Max-Planck-Institut für Kernphysik
OP	Observatoire de Paris – PSL, CNRS
OSS	Optical Support Structure
PA	Product Assurance
PBS	Product Breakdown Structure

PM	Project Manager
PMC	Pointing Monitoring Camera
PR	Product Review
PO	Project Office
PR	Product Review
PRM	Programme Manager
PRR	Production Readiness Review
QA	Quality Assurance
RAMS	Reliability, Availability, Maintainability & Safety
SE	System Engineer
SST	Small-Sized Telescope
SST-MEC	Telescope Mechanical Structure
TRR	Test Readiness Review
WBS	Work Breakdown Structure

1.4.2. Glossary

TERM	**DEFINITION**
"As Built" Configuration	The as-built configuration or applied configuration is defining the as-built status per each serial number of Configuration Item (CI) subject to formal acceptance.
"As Designed" Configuration	The as-designed configuration or Applicable configuration is defining the current design status of a Configuration Item (CI)
AIV	AIV is the Assembly Integration and Verification, which is referred to the integration activities related with the verification of the system or sub-system. In the framework of SST for briefness this term also includes the Assembly Integration and Testing which is related with the integration activities and testing to be performed during the integration at system and subsystem levels
Baseline	Set of information which describes exhaustively a situation at a given instant of time or over a given time interval.
Change	Vehicle for proposing modifications to an approved baselined data or the business agreement.
Configuration	Functional or physical Characteristics of a product defined in configuration definition documents subject to configuration baseline.
Configuration Item	Aggregation of hardware, software, processed materials, services, or any of its discrete portions, that is designated for configuration management and treated as a single entity in the configuration management process. **NOTE:** A configuration item can contain other lower-level configuration item(s).

TERM	DEFINITION
Deviation	Written authorization to depart from the originally specified requirements for a product prior to its production.
Firmware	Firmware is software programmed onto an electronic device which is treated like a pure hardware.
Executive Steering Committee	The SST Executive Steering Committee (ESC) is the high-level decision-making body which will manage the strategic direction of the Programme and will oversee progress and facilitating global collaboration among the participating groups.
Institutes	Research Institutes involved in the SST Programme.
Contractor	Industry involved in the SST Programme which has a contract with an institute
SST-PRO	It is the team composed by Institutes and Contractors responsible, involved in the production of SST telescopes elements, which coordinate the project level activities.
Hardware	Hardware is a single or an assembly of physical electronic devices which cannot be changed in its user environment.
Item	Any part, component device, sub-unit, unit, equipment, or device that can be individually considered.
Model	Physical or abstract representation of relevant aspects of an item or process that is put forward as a basis for calculations, predictions, or further assessment useful for the preparation of SST production
Partners	are those entities taking responsibility for IKC delivery by signing IKC agreements with CTAO, plus any organization identified by these signing entities as playing an essential role in SST delivery. The institutes are the partners of the CTA-SST consortium.
Product	A product (hardware, software, service) required in the frame of the program and included as element of the product tree having a unique identifier. A product may be deliverable or not.
Product Breakdown Structure	Hierarchical structure depicting the product orientated breakdown of the project into successive levels of detail down to the configuration items necessary to deliver the required functions. The Product Breakdown Structure (PBS) in general is influenced by Institutes/partners decisions to group certain products or by program history. It identifies products and their interfaces; it serves as the basis for the WBS
Service	Service is the result of at least one activity necessarily performed at the interface between the SST consortium and CTA and is generally intangible.
Software	Set of computer programs, procedures, documentation, and their associated data.
SST-E2E	The SST end-to-end telescope, or simply SST, will consist of the SST Structure and the SST Camera (including all mechanics, mirrors, auxiliary devices and required software), integrated and commissioned on-site including all required documents. It ends at (and integrates into CTA via) the system interfaces specified by the CTA PBS.
SST Consortium	The SST Consortium then consists of the Partners and their associated Teams, where a Team is a set of individuals within a single organisation at a single location (such as a university group).
System	An entity of products assembled or working together for a well-defined specified purpose. In SST the term system can be utilised in alternative to Telescope End-to-End.
Sub-System	Like a system but a lower level. In SST the SST system is composed by the subsystem SST-MECH, SST-OPT, SST-TCS and SST-CAM.
Waiver	Written authorization to use or release a product, which does not conform to the specified requirements
Work Breakdown Structure	Hierarchical representation of the activities necessary to complete a project.

2. Small Size Telescopes Overview

When a VHE gamma-ray interacts with the atoms and ions in the upper levels of the atmosphere, it induces a cascade of secondary particles which propagates over many kilometres at a speed higher than the speed of light through the atmosphere. These particles emit Cherenkov light, forward-beamed with an opening angle of about one degree. A Cherenkov light event consists of a time-correlated multi-photon image with a typical timescale of ~10 ns. Cascades originate at an altitude of ~10 km above ground and create a light pool on the ground of ~120 m radius. Telescopes placed on the ground, containing large reflectors, focus the light to and 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 levels with exposure times of approximately a billionth of a second. To provide a high imaging sensitivity over an extensive energy range, from a few tens of GeV up to a few hundreds of TeV, the Cherenkov Telescope Array Observatory (CTAO, see web page link at https://www.cta-observatory.org) will be based on sub-arrays with three different types of telescopes: large-sized (LST, 23 m diameter), medium-sized (MST, 12 m diameter) and small-sized (SST, 4 m diameter) telescopes. They are distributed in two observing sites, the Northern one in La Palma, the Canary Islands, and the Southern one in the Chilean Andes in the Paranal area. The CTAO Southern site includes LSTs, MSTs and SSTs. It currently envisages the construction and installation of 42 SSTs (30 of them are object of this SoW).

The SSTs are developed by an international consortium of institutes that will provide them as an in-kind contribution to CTAO. The SSTs rely 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 developing the prototype dual-mirror ASTRI-Horn Cherenkov telescope and the first telescope of the ASTRI mini-array project and a Cherenkov camera based on SiPM sensors called CHEC-S. Table 2-1 reports the main properties of the Small-Sized telescope (SST).

Table 2-1: Small-sized telescope main properties

Small-Sized telescope (SST) main properties:	
Optical Design	modified Schwarzschild-Couder
Primary reflector diameter	4.3 m
Secondary reflector diameter	1.8m
Effective mirror area (including shadowing)	>5 m^2
Focal length	2.15 m
Total weight	<17.5 t
Field of view	>8.8 deg
Number of pixels in SST Camera	2048
Pixel size (imaging)	0.16 deg
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)	70s
Telescope Post Processing Pointing Precision	< 7 arcsecs

3. Telescope Mechanical Structure overview

The mechanical structure of the SST telescope is based on a common Elevation-over-Azimuth mount.

The Telescope raw Elevation angle (EL) is measured with the horizon as reference (0° EL), while the zenith is set as 90° EL. The Telescope raw Azimuth angle is measured from zero at West to -270° at North in clockwise direction and to +270° at South in counter-clockwise direction.

The first level decomposition of the SST-MEC is shown in Figure 2-1:

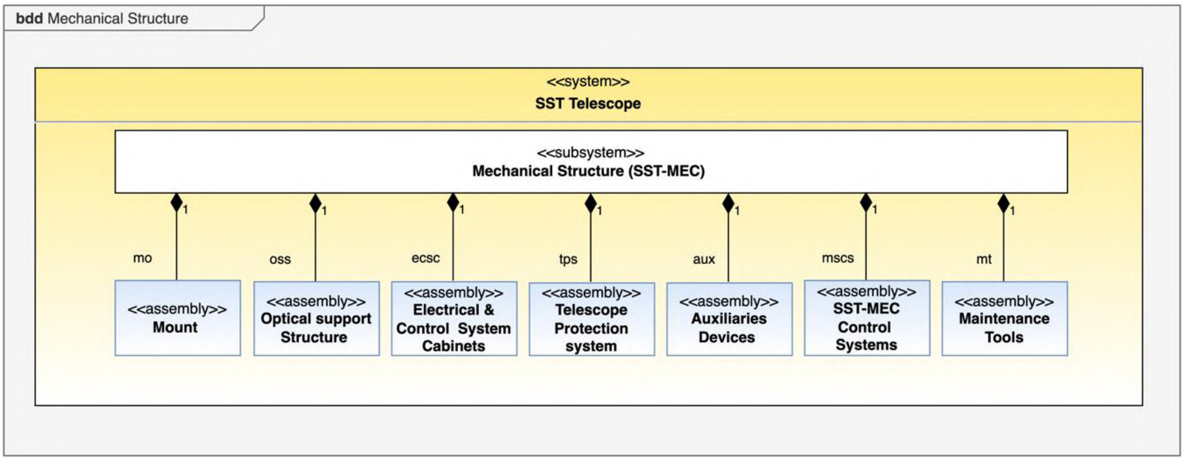

Figure 3-1: SST-MEC decomposition

- **Mount**: The Mount includes the Base structure and the Fork. Itis the part of the SST-MEC that allows the motion of the Optical Support Structure around the Azimuth and Elevation axes. The conical base fixes the telescope to the foundation by means of 24 M30 anchor bolts. On top of the base, a crossed-roller slewing ring with external gear allows the motion of the mount around the azimuth axis of the Elevation Structure. Two electrical cabinets, one for power supply and one for control hardware, are mounted on the Fork (the main structural component of the elevation structure) and thus they can rotate around the azimuth axis to reduce the number of moving cables.
- **Optical Support Structure:** The Optical Support Structure (OSS) comprises the M1 and M2 supports, along with the central tube supporting the Camera, and the Mast composed by three legs connecting M1 to M2. Counterweights are foreseen to balance the OSS about the Elevation axis. It is mounted on the elevation axis that is supported by two elevation bearing groups. The OSS can rotate around the elevation axis by means of a mechanism consisting of a ball screw mechanical jack. The OSS M1 Dish with its mirror segments is positioned above the Elevation axis, then the presence of a ballast mass is necessary. Counterweights are supported by three pipes. A central tube standing on the centre of the M1 Dish supports the Cherenkov Camera at its top. The M2 Support Structure is connected to the M1 Dish by a tripod. The M2 support Structure comprises a the M2 mirror itself, and an active optics system. Finally, the Pointing Monitoring Camera (PMC), which provides information about the instantaneous pointing direction of the telescope mount, is located at the top the M2 support.
- **The Electrical and Control system cabinets** comprise the two Electrical cabinets (the Telescope Power Cabinet for power supplies and the Telescope Control Cabinet for control hardware), cabling, and various electrical boxes.

- **The Telescope Protection System** consists in the external Lightning Protection system, the internal Surge Protection system and the Telescope safety system.
- **Auxiliary devices** comprise the SST-MEC Condition Monitoring system, the M1 calibration system, the Optical Camera, and the Stellar Intensity Interferometry Instrument. The M1 calibration system is a set of removable actuators that are installed on the telescope just to perform the alignment of the M1 segments.
- **The SST-MEC Control System** controls all the functions of the SST-MEC, including the main axes drive systems.
- **The Maintenance tools** are all those special tools and devices needed for maintenance operations to be performed on the SST-MEC.

The CAD model of the telescope, integrated with Camera and optics, is shown Figure 2-2.

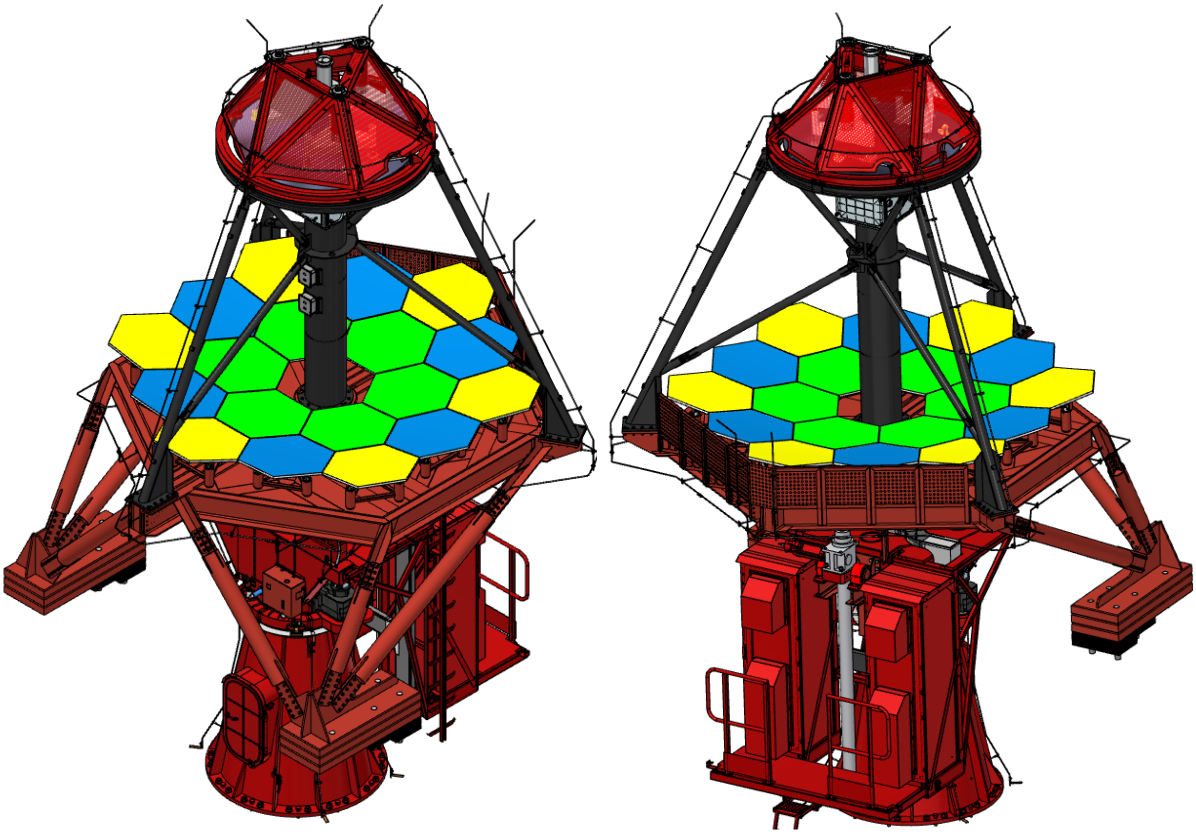

Figure 2-2: SST CAD model

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4. SST-MEC Structural items design description

4.1. Mount Assembly

Mount includes two main structural elements:

- The Azimuth Structure
- The Fork

The main component of the Azimuth structure is the Base. It is fixed to the foundation by means of 24 M30 anchor bolts. The Azimuth bearing is mounted on the top of the base.

Material considered for the Base is common S355J2 painted steel; only shields are made of aluminium to reduce the weight.

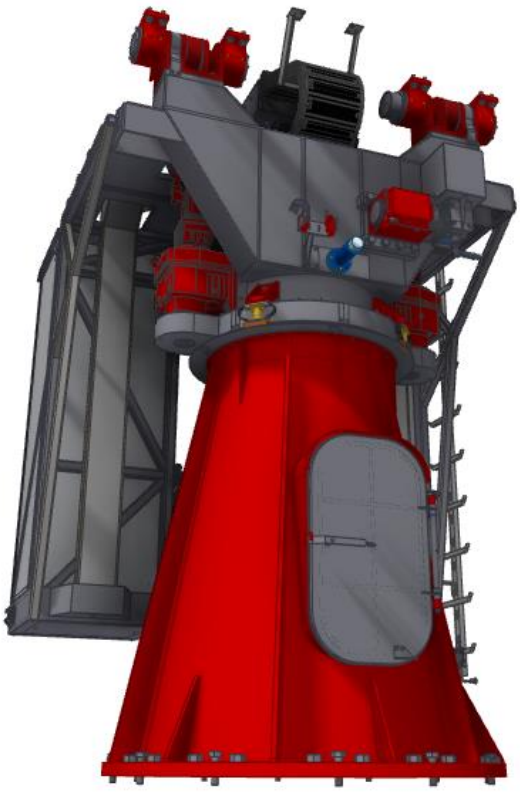


Figure 4-1: Mount subassembly

The base coordinate system (fixed) foresees:

- X axis horizontal and parallel to EL axis (towards West),
- Y axis horizontal and oriented opposite to the base access door side (towards South),
- Z axis oriented vertically towards up, coincident with AZ axis.

The Elevation fork coordinate system foresees:

- X axis is horizontal and parallel to EL axis oriented towards EL encoder side,
- Y axis is horizontal and oriented towards the electrical cabinets side,
- Z axis oriented vertically towards up, coincident with AZ axis.

4.1.1. Base Structure

The Base structure consists of a cone, which links the foundation to the Azimuth bearing. For these reasons the interfaces imposed by the foundation anchor bolts and the bolts required by Azimuth bearing are essential to establish the correct shape of this item. The cone shape guarantees the best compromise between proper transmission of the loads of the telescope to the foundation and the lowest mass necessary. Ribs are implemented to distribute loads in the desired way and at the same time to improve deformation stability and stiffness where required.

Figure 4-2: Base

Furthermore, it guarantees to provide access to the volume contained inside; this aspect is essential for providing access to the items installed inside of the base for their sensitivity to the weather agents (for example: azimuth encoder, cables, azimuth switches etc.). Thanks to that, encoder heading alignment and maintenance procedures are possible and at the same time can be carried out safely.

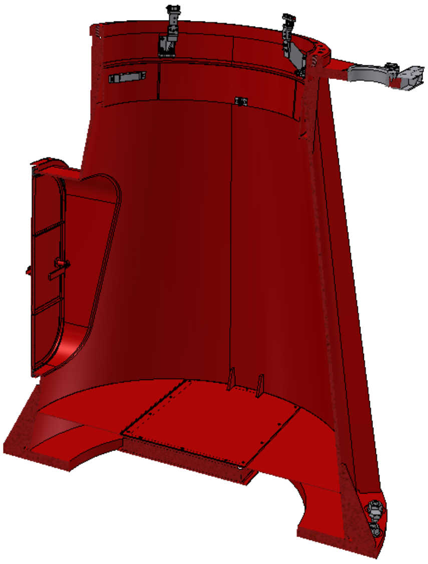


Figure 4-3: Base section view

The access door of the base ensures safe local operation and maintenance, as it is connected to the interlock chain by means of a proper safety switch, which is an electromechanical switch monitoring the rotation of the door hinge. The door can be locked in the open position by means of a latch.

The base door is locked in the closed position by means a padlock interface on the door handle. This is just to prevent access to the telescope base and is not related in any way to the safety switch. Also, an internal handle is present to ensure the possibility of opening the door from inside the Base.

Figure 4-4: Base door detail

The structure is studied in detail in order to provide the alignment of every single item it hosts. In particular for the azimuth encoder the interfaces provide to install simple aligning devices which simplify drastically the mounting sequence and time.

The bush of the stow pin is located in Azimuth (Az) position angle of +90° and it consists in a sheet of metal able to bear the survival conditions imposed.

Figure 4-5 The stow-pins realized for the ASTRI Mini-Array telescopes

4.1.2. The Fork

The Fork main structure is one of the key structural elements, as it provides support and interfaces for these following essential subsystems:

- Azimuth bearing
- Elevation bearings
- Azimuth ratio-motor drives
- Elevation actuator drive
- Azimuth and Elevation stow pins
- Azimuth and Elevation switches
- Azimuth cable chain and Elevation cable wraps
- Elevation bumpers
- Support for the electrical cabinets.
- Ladder to access the Fork platform

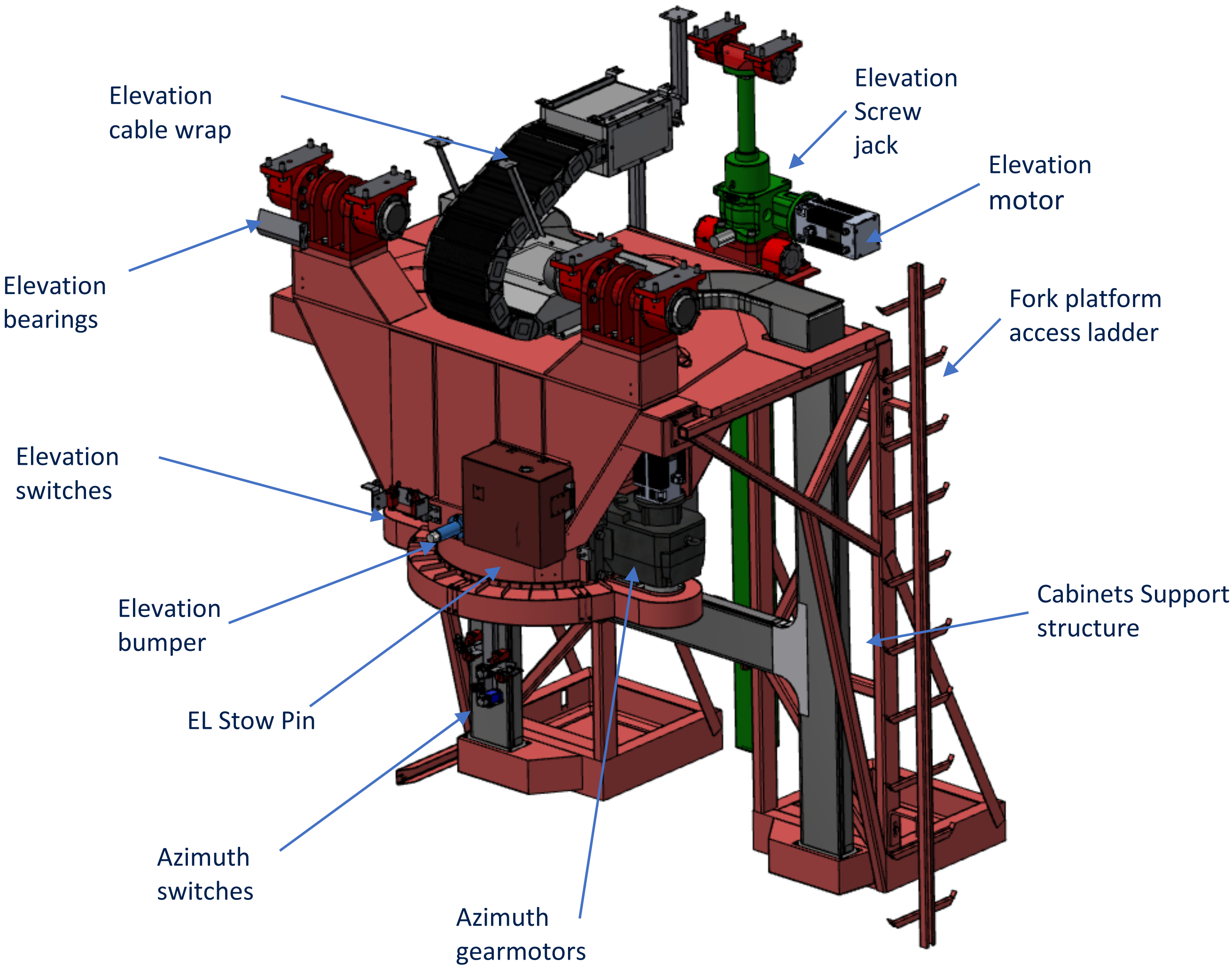


Figure 4-5: Fork structure

These items grant the motion of the telescope mount main axes as well as the telescope safety during survival conditions both from the personnel and hardware points of view. These are the reasons that make this item so critical for the entire telescope structure.

For all devices installed on the Fork (motors, stow pins, etc), alignment devices are present, which make the installation and replacement of such components easier. The alignment blocks are presented in the pictures here below:

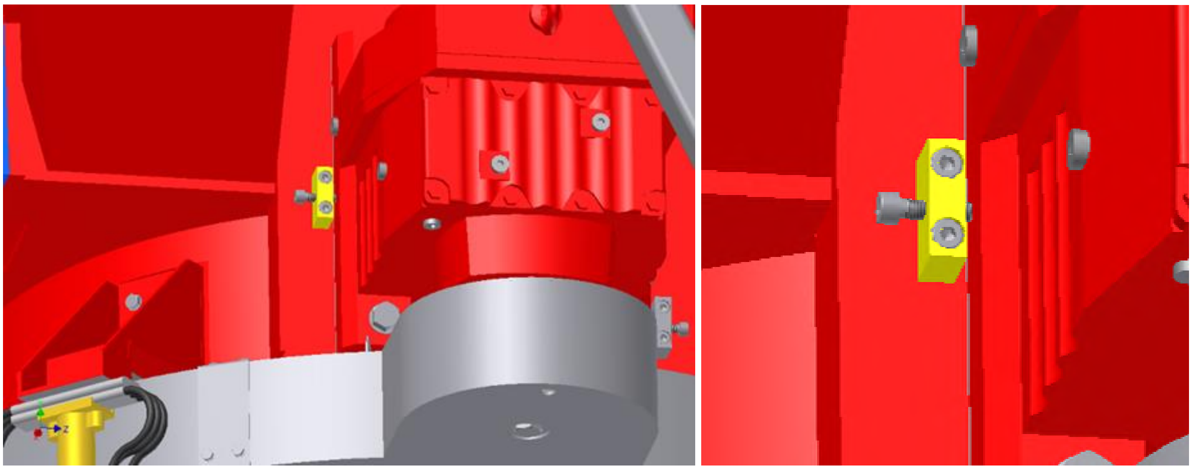


Figure 4-6: Fork alignment devices (components in yellow)

Elevation cable wrap is the key to provide power and communication for all telescope subsystems; in this contest, the fork main structure has a key role also in the cable routing as its shape has been defined to host cable trays and ways. The cabinets support frame has the role to provide interface for the electrical cabinets and at the same time grants the support for the cable trays and Elevation cable wraps.

Figure 4-7: Cabinets support structure

4.1.2.1. Cabinets Access Platform

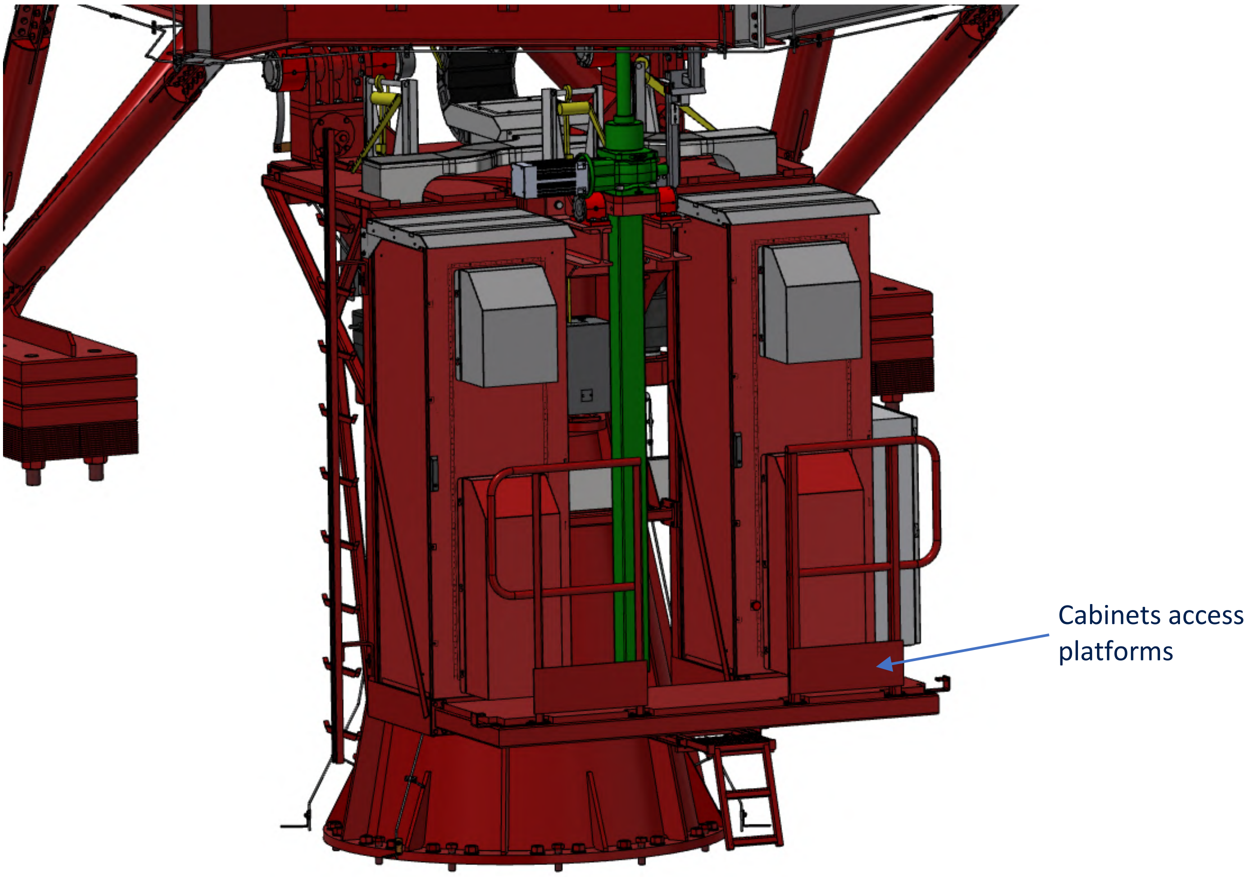


Figure 4-8: CAD model of the cabinets access platform

Electrical cabinets of the telescope are located at about 80 cm height from the ground, and they are 2m tall. During factory integration, on-site commissioning, and maintenance throughout the entire lifetime of the array, they often need to be accessed, and work must be performed onto them for quite some time.

A platform is provided to access to the cabinets without additional means, and a small retractable ladder is foreseen for easy climbing on the platform. The cabinets door opens in a symmetric way towards the external side, so that moving from one cabinet to the other is possible without having to close doors.

The railways are bolted to the access platform so that they can be removed in case of need, however the cabinet doors can be fully opened with the railways installed.

4.1.2.2. Access to Fork devices for maintenance

Maintenance on the heavy-weight devices installed on the Fork structure (the two azimuth motors and the two stow pins) can be performed by removing the devices from the telescope. The following figure show the anchoring points onto which a winch can be attached so to remove the devices from the telescope and lower them on the ground (grey support with yellow winches).

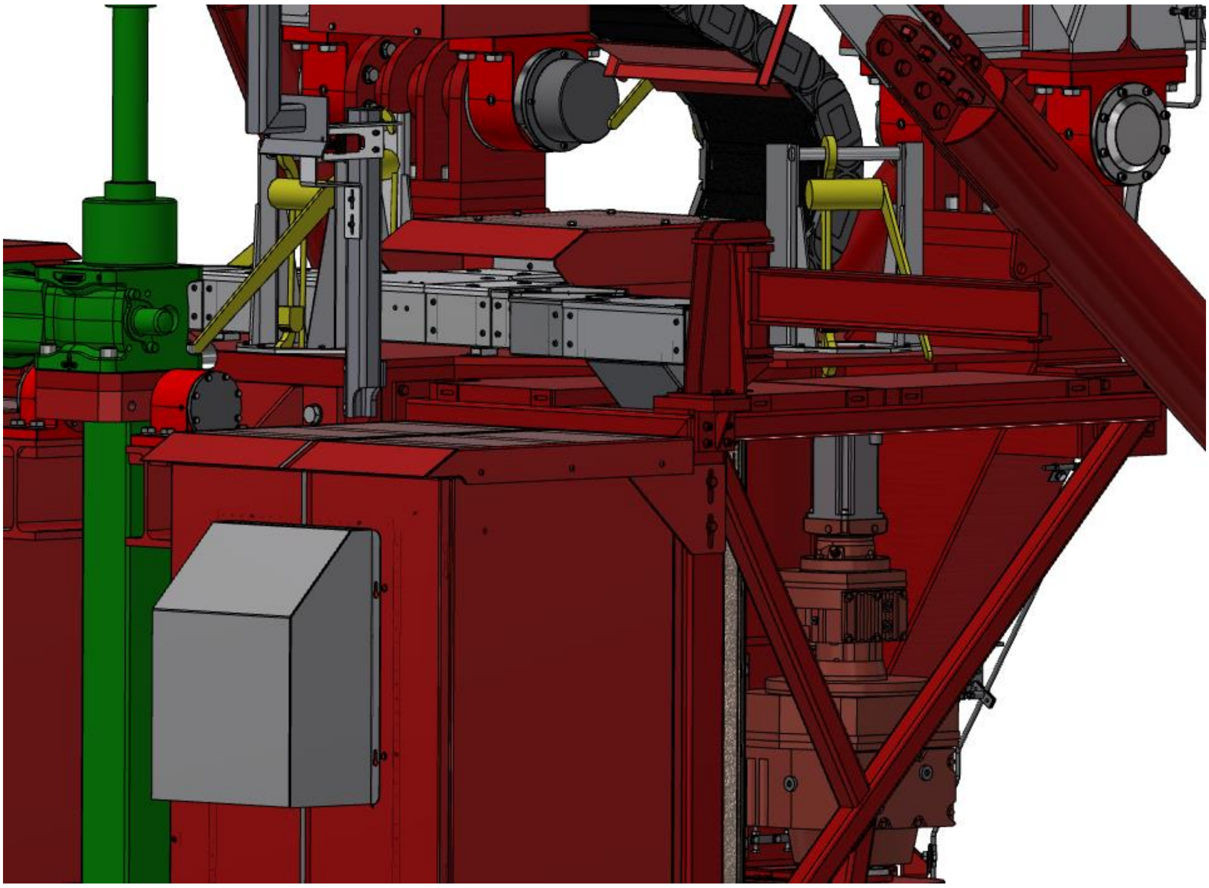


Figure 4-9: Fork devices handling

4.2. Optical Support Structure

The optical support structure includes: M1 dish, OSS Upper Structure, Counterweights, and M2 Support Structure.

The OSS coordinate system foresees:

- X axis is horizontal parallel to EL axis,
- Y axis is horizontal and oriented to point towards up when telescope is at EL=0°,
- Z axis oriented coincident with optical axis towards up when telescope is at EL=90°.

Figure 4-10: Optical Support Structure

4.2.1. M1 Dish, baseline design

The M1 Dish is a hexagonally shaped flat structure which has the task of supporting the telescope primary mirror. It also interfaces with the Elevation bearings and actuator on its rear side, and with the Mast and central tube on its front side.

Compared to the first SST prototype in Sicily, ASTRI-Horn, in the ASTRI Mini-Array baseline the primary mirror structure concept underwent a first round of optimization. Indeed, it had been reviewed entirely with respect to the prototype one, to:

- Reduce overall mass.
- Simplify its construction using standard steel profiles.
- Introduce M1 segments supports following a polar symmetry instead of a cartesian one.

The Dish is split in two halves to grant its transportability within a standard 40’ container volume.

The hexagonal shape of the Dish has been maintained, although, compared to ASTRI-Horn, it has been rotated by 60 degrees to reduce the number of masts from four to three and consequently simplify the M2 support structure and improve the accessibility to the Cherenkov Camera.

The structure main beams are three: one vertical and the other two are at 60 degrees from the vertical one, to provide support to the mast while actuators interfaces have reinforcing ribs to give stiff response and guarantee the adequate stability to keep the mirror segments in their position. Interfaces to elevation bearings and elevation actuator are very similar to the prototype ones.

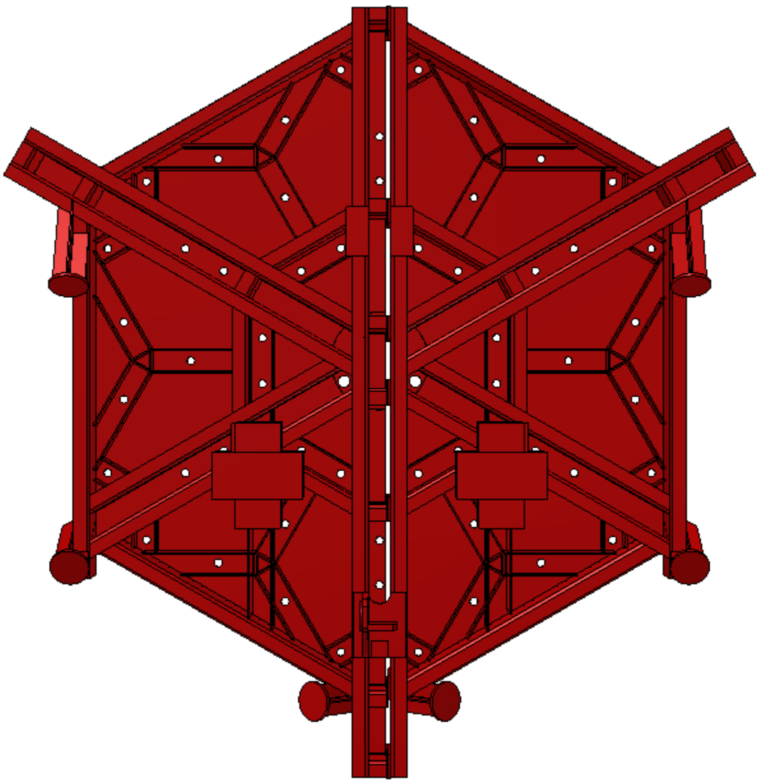


Figure 4-11: M1 Dish structure, ASTRI-Horn baseline

In correspondence with the central tube interface, two holes are provided for the electrical and fluids supply to the Cherenkov camera; fluids are necessary for Cherenkov Camera electronics cooling.

The elevation stow pin engages the Dish only in the elevation angle position of 0 degree (see Figures 3-1 and 3-5); for this purpose, a dedicated welded structure is fixed by means of bolts and nuts. The concept here is to have a stiff behaviour as well as a simple manufacturability.

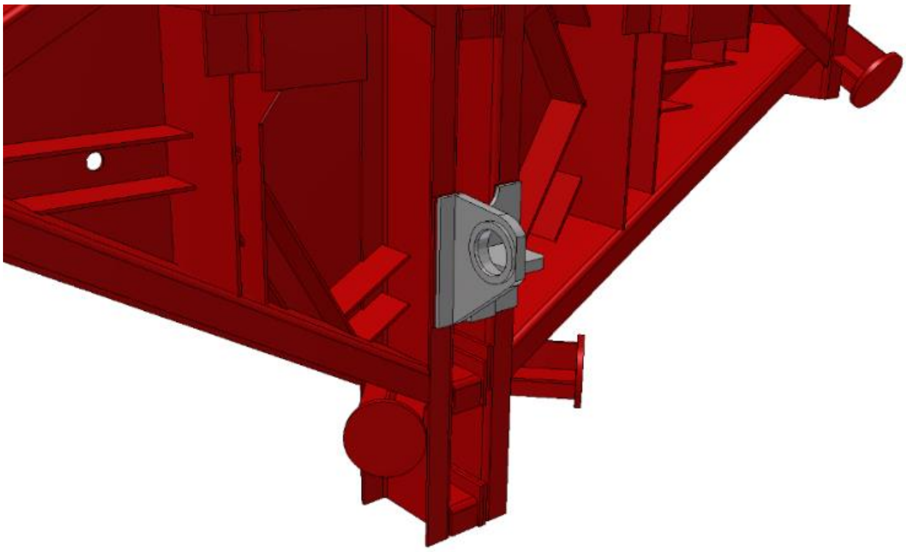


Figure 4-12: Elevation stow pin bush.

Finally, a group of shields made of perforated steel sheets are located on the upper two sides of the hexagon providing snow and ice protection to the M1 supports when the telescope is in its parking position. The sides are naturally sloped to ease snow and ice evacuation.

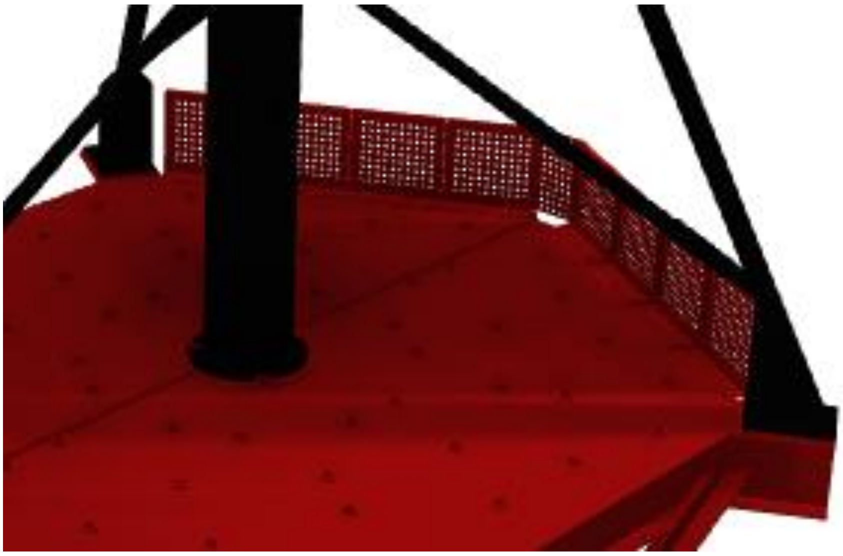


Figure 4-13: M1 Shields

4.2.2. M1 Dish, updated design

Following the actions of the SST DVER, the M1 Dish underwent a second round of optimisation (also called M1 Dish option1).

The aim of this work was to improve the structural performance of the M1 Dish (in terms of stiffness to mass ratio) and to improve the availability of the structural shapes used in the manufacturing.

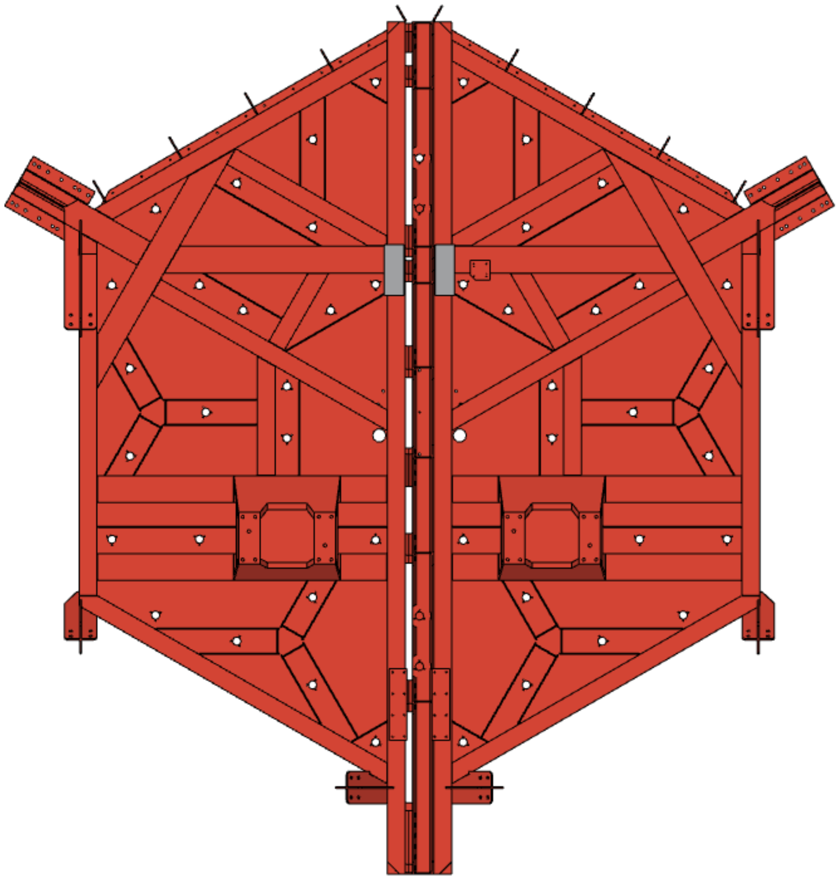


Figure 4-14: M1 Dish, improved structural design.

As reported in [RD1-3], the layout of the structural beams backing up the flat plate has been completely reviewed based on a structural optimization process (in fact it includes topology optimization and topography optimization for the structural beams). The interface to the Elevation bearings has been redesigned from scratch to provide greatly improved stiffness to the M1 dish with the help of topology optimization.

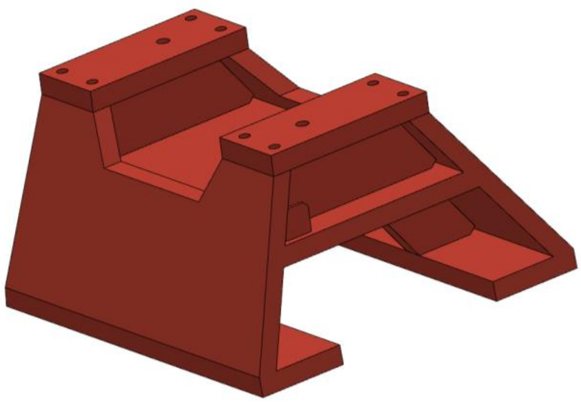


Figure 4-15: Elevation bearings interface

Moreover, the used of press-bent structural profiles has been eliminated, and the updated design used only hot-rolled standard structural shapes, such as IPE and UPE beams.

All this work has been performed while maintaining unchanged all interfaces towards the rest of the SST-MEC; thus, the updated design has been implemented in the SST baseline "plug-and-play".

Structural analysis has been performed comparing the two M1 designs with local models of the Dish alone with boundary conditions representative of the rest of the telescope.

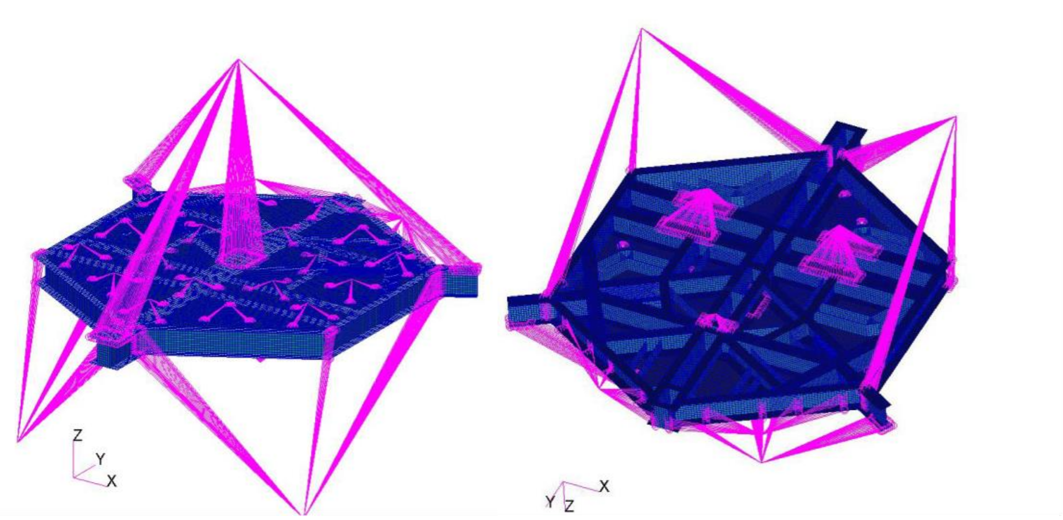


Figure 4-16: Local model of the M1 dish, updated design

Results of this analysis show a reduction of displacements and stresses due to self-weight:

Table 4-1: Gravity-induced displacements and stresses in the Dish structure - comparison between designs

Elevation angle	**Design**	**Displacements [µm]**	**Max Von Mises stress [MPa]**
0	Baseline	11.7	11.9
	Updated	22.6	2.8
90	Baseline	42.9	7.0
	Updated	23.3	3.8

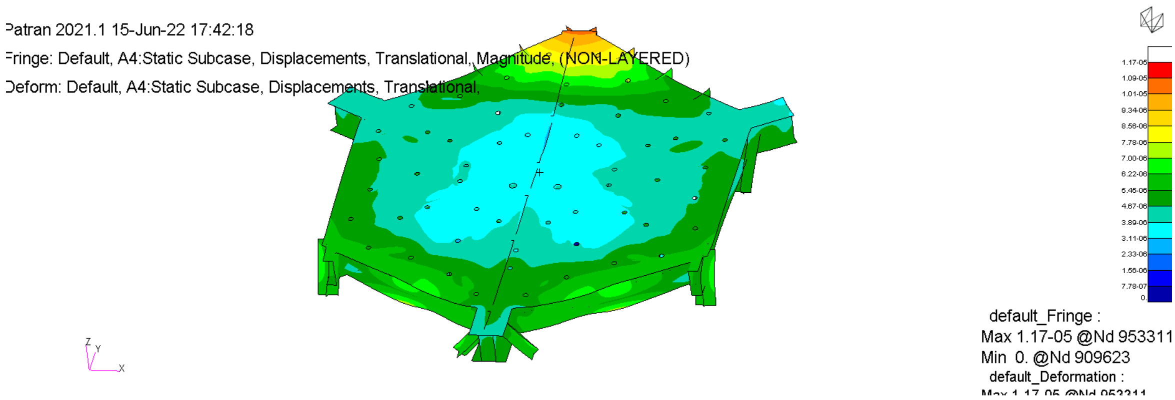


Figure 4-17: FEA of the M1 dish baseline design, 0deg Elevation

The modal behaviour has also been improved compared to the baseline:

	f baseline (Hz)	f updated (Hz)
1	57,4	93,4
2	81,1	98,4
3	100,4	129,2
4	113,0	131,6
5	121,4	133,5

Figure 3-19: M1 Dish baseline vs updated design modal frequencies comparison

In addition to this, the mass of Dish has been lowered by about 5%:

Option	Mass (kg)
Baseline	3 004
Updated	2 859

Figure 4-18: M1 Dish baseline vs updated design mass comparison

Analysis of the M1 Dish updated design have been implemented in the global telescope model [RD4].

4.2.3. Counterweights

The Counterweights supporting beams have been reviewed with respect to ASTRI-Horn, to construct them with a single plane angle instead of double angle flanges. This eases the manufacturing process and improves at the same time the operations during the installation phases. The principle of installation of the masses remains unchanged with some aligning pins that are made to ease installation. Threaded rods allow to install fine balancing masses.

Figure 4-19: Counterweights

4.2.4. Mast and Central Tube

As outlined in the previous sections, the mast is provided with three pipes support systems spread at 120 degrees to each other. The real reason to this design choice is to provide a much simpler M2 BUS and a better stability of its interface. The top ring guarantees to have a single stiff structure that improves repeatability during M2 BUS removal and/or installation. In this way, alignment is also easier. Finally, the top ring also provides some sort of baffle for the M2 even if its main function has been described earlier.

Figure 4-20: Mast and Central Tube

4.2.5. M2 Support Structure

The structure designed to host the support suitable for M2 is simplified with respect to that of ASTRI-Horn, with a triangular layout, which tries to avoid as much as possible complication during manufacturing.

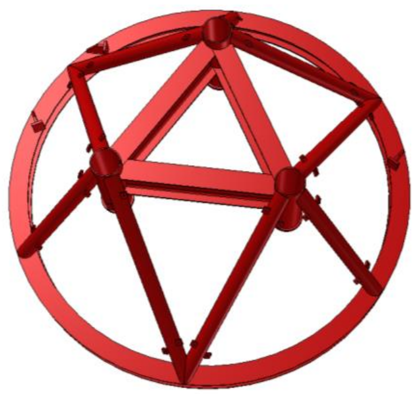


Figure 3-23: M2 Backup structure

Basically, there is a M2 support structure ring, which mates with OSS upper structure top ring and an upper triangle, which is designed to support the M2 actuators. Some structural pipes are positioned to grant the best load distribution configuration from the mast to the actuators' interfaces.

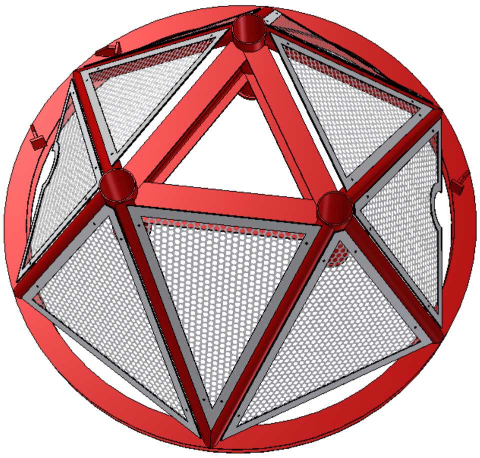


Figure 4-21: M2 Shields

To protect the M2 actuators and load-spreaders from wind and snow some shields made of perforated aluminum sheets are provided.

4.2.6. Camera chiller interface

The telescope foundations shall also host the Camera chiller interfaces. It is deemed best to have the chiller positioned on the foundation and not onboard of the telescope, so not to be constrained to a precise interface and allowed volume for the entire lifetime of the observatory.

The chiller shall be positioned on top of a small precast, or cast-in-place, concrete slab, adjacent to the telescope slab, in the closest position possible.

To determine the Camera chiller position, the telescope sweep volume has been obtained from the CAD model, as a Boolean union of the 0deg and 90deg elevation angles, as shown in the next image:

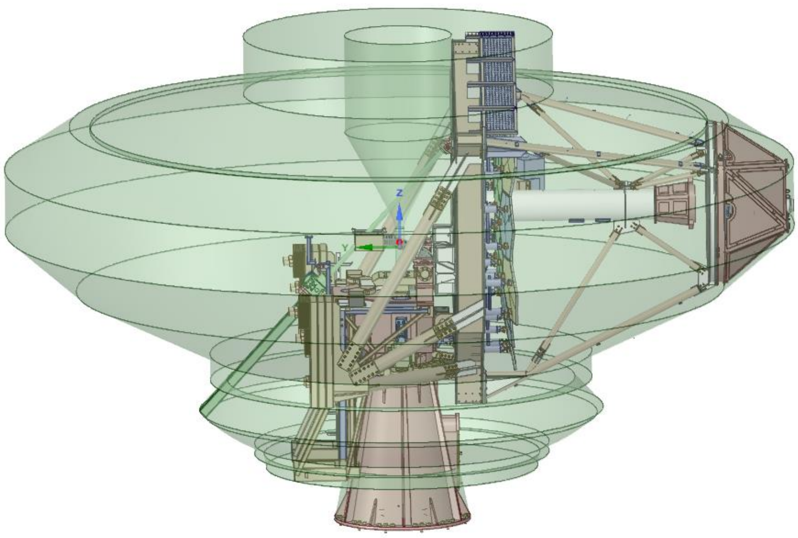


Figure 4-22: SST telescope sweep volume

It has then been hypothesized to allow a 1000x1500 mm footprint and 1500 mm height as an envelope for the Chiller, as shown in the next images:

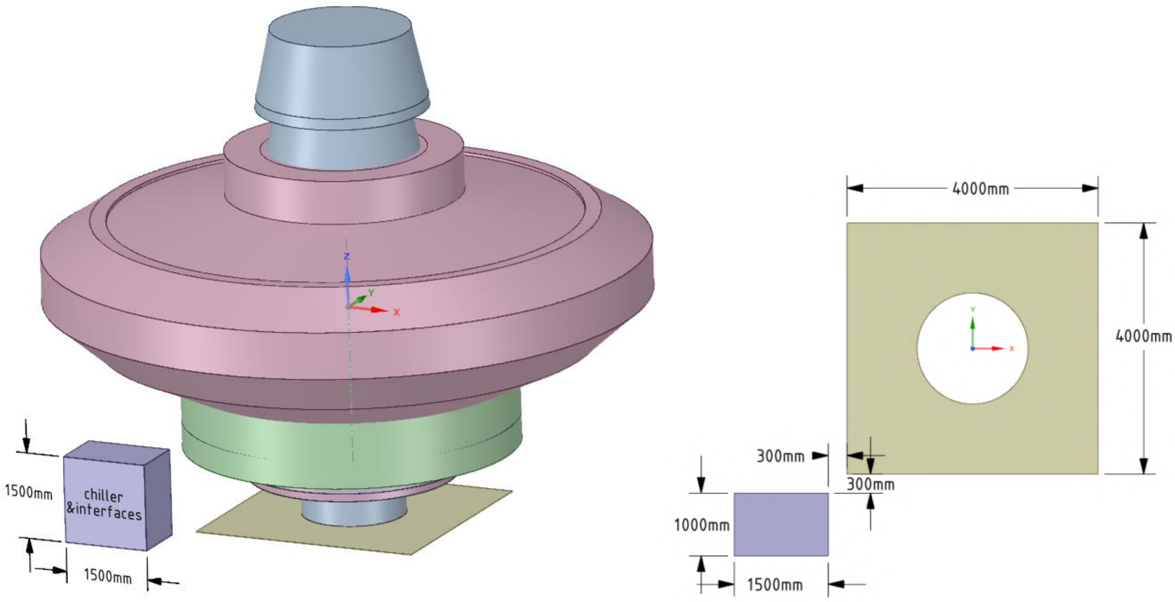


Figure 4-23: Camera chiller allowed volume and footprint.

In this way, the chiller is in the closest position possible to the telescope, while maintaining about 300 mm clearance from the closest telescope part.

5. SST-MEC mechanisms design description

The description of the mechanisms present in the SST Telescope is subdivided following the product tree. Having that in mind, the description will outline Mount Assembly (3110-000) including all sub-systems and Optical support structure (3120-000).

5.1. Mount Assembly

Mount assembly represents that part of the Telescope which hosts all motion and safety systems.

The following picture provides the locations and the volumes occupied by all sub-systems.

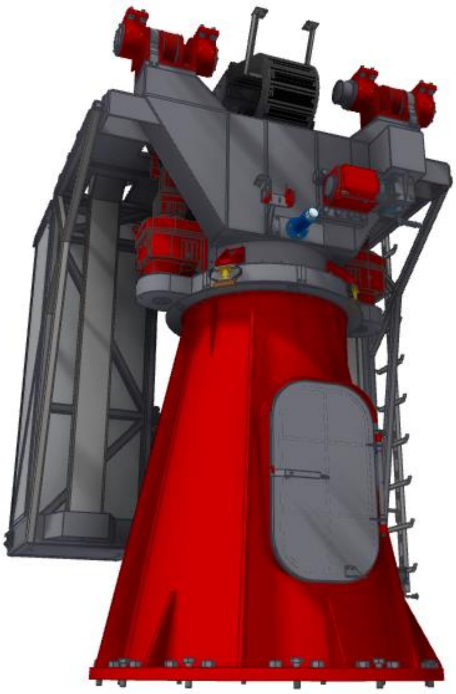


Figure 5-1: fully populated Mount subassembly

Pictures highlight that the fork hosts the largest number of subsystems to optimize the cables length and routing. The Base hosts only the Azimuth encoder and the witnesses necessary for the Azimuth switches to minimize the number of cables going through the cable wraps, whether in Azimuth or Elevation.

5.1.1. Azimuth encoder

The azimuth encoder is an optical Sin-Cos incremental encoder with absolute reference marks. The encoder thus requires an initialization process before being able to work.

The Azimuth encoder includes two main sub-systems: the steel scale tape and a group of scanning heads. In this case, scanning heads are 4 and are displaced along a circle at 90° one from the others. The tape slot is machined in the Azimuth bearing and the scanning heads are installed in proper supports, which grant a complete adjustability along all 3 axes.

Under the reliability of reading point of view, the large scanning field for this type of Heidenhain encoders additionally reduces sensitivity to contamination. In many cases this can prevent encoder failure. Even if the contamination from printer's ink, PCB dust, water or oil is up to 3 mm in diameter, the encoders continue to provide high-quality signals.

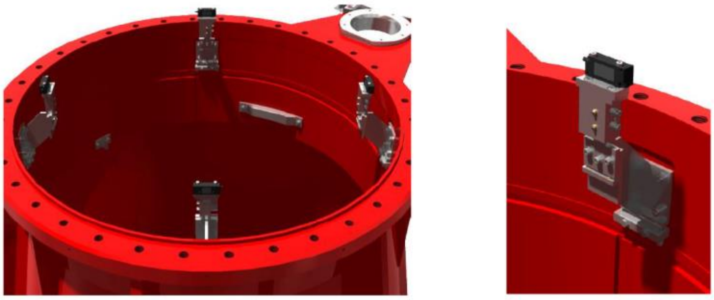


Figure 5-2: Azimuth encoder scanning heads installation and support detail

A trade-off analysis has been performed to evaluate the possibility of replacing this encoder with an absolute single-turn, such as the one depicted in the following picture:

Figure 5-3: Alternative absolute single-turn encoders

Such encoders are only available with integral bearing or on a steel drum. The implementation of those kind, which insists on a diameter smaller than the one of the telescope azimuth bearings, would make human access to the telescope base much harder.

Moreover, they would require an additional precisely interface plate connected to the upper ring of the azimuth bearing. However, realistic manufacturing error of such plate (eccentricity of the encoder interface) would introduce an important measuring error, this being the formula of the angular error given by mechanical eccentricity:

$$\Delta\varphi = \pm 412 \cdot \frac{e}{D}$$

$\Delta\varphi$ = Measurement error in ″ (angular seconds)
e = Eccentricity of the scale drum to the bearing in µm (1/2 radial runout)
D = Mean graduation diameter in mm
M = Center of graduation
φ = "True" angle
φ' = Scanned angle

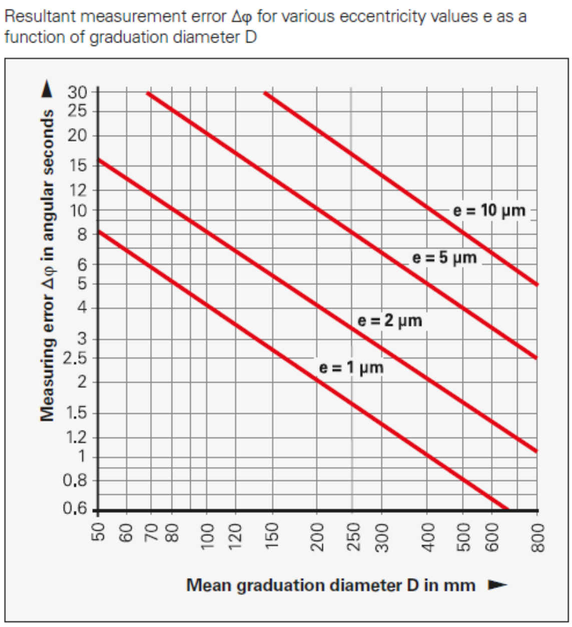


Figure 5-4: Encoder error due to mounting shaft eccentricity

5.1.1.1. Azimuth encoder calculation

The scanning heads number comes out from the error budget carried out by Heidenhain, which considers the geometry of the system, the run-out of the Azimuth bearing and other aspects, which are intrinsic of this application such as mounting errors etc.

A first trade-off study has been carried out by Heidenhain between configuration with 2 and 4 scanning heads. The configuration with 2 scanning heads seemed to be insufficient to guarantee the requested accuracy for the application.

The Error budget has been provided by Heidenhain for the configuration with 4 scanning heads and the results are outlined in the following figure:

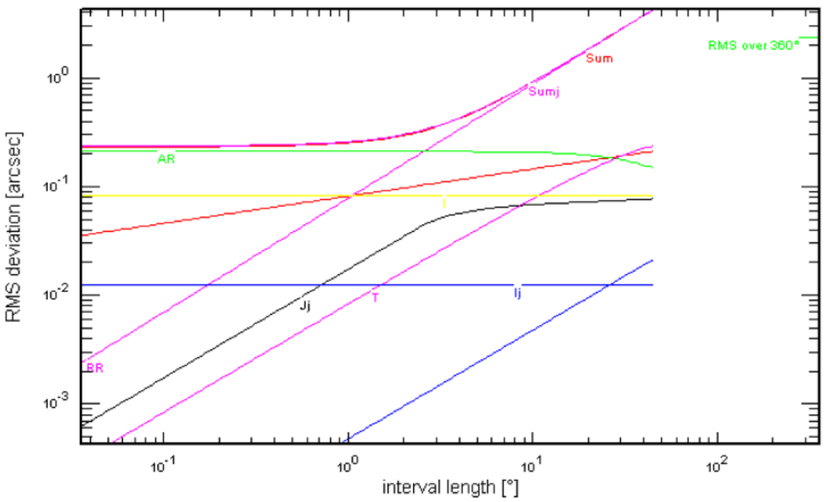


Figure 5-5: Accuracy without online interpolation error compensation

As reported on this graph the system RMS accuracy over 360° (marked in green) is equal to about 2.3 to 2.4 arcsec. It improves to 1 arcsec in a stroke of about 10°. The tape slot diameter foreseen for this application is 713.24mm.

5.1.2. Azimuth bearing

Azimuth bearing mounted on ASTRI Mini-Array Telescopes is a custom slewing bearing made by Rollix De Fontaine based on a standard one. The elements, which permit the rotation, are crossed cylindrical rollers. This choice was made in order to satisfy the stiffness requests by the telescope.

A section view of the azimuth bearing is shown in the following image:

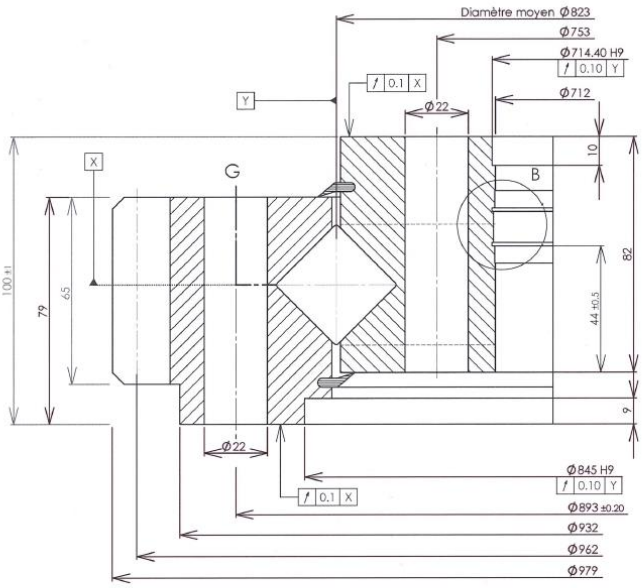


Figure 5-6: Section view of the azimuth slewing ring (copyright by Rollix)

The outer face of the ring fixed on the Azimuth base upper flange is provided with a rack to permit Azimuth axis rotation by means of two pinions driven by the Azimuth drives.

The inner face, the one fixed on the Azimuth fork lower flange is provided with a proper slot to allow the encoder tape installation.

The encoder tape groove shall be precisely machined according to the manufacturer specification:

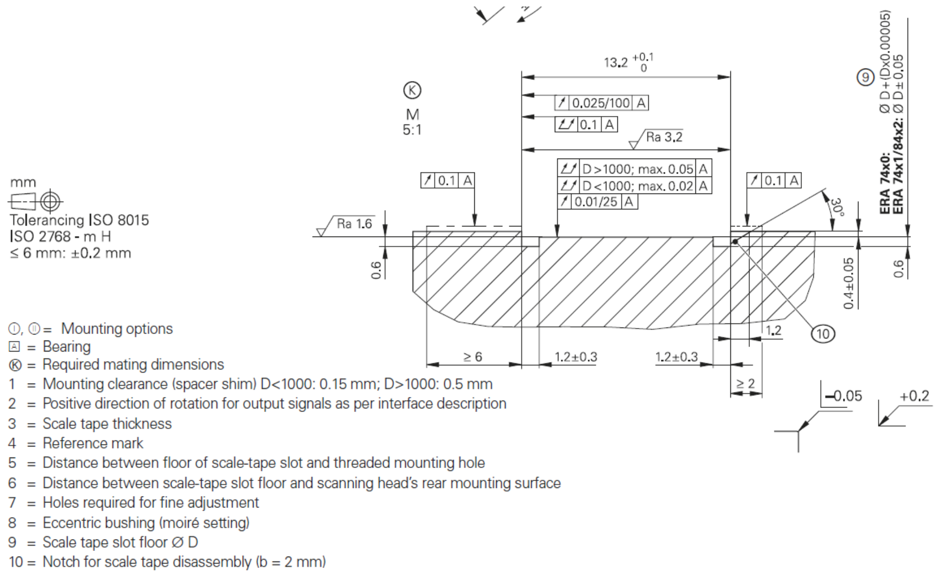


Figure 5-7: Specification for the machining of the azimuth tape encoder groove

The current choice of azimuth bearing is quite cost-effective, being based on a customization of a COTS product.

5.1.3. Azimuth cable chain

Cables coming from the fixed part of the telescope and going to the azimuth rotating part, are organized into a 3D cable chain, which aim is only to keep the cables neatly organized, and to simplify the procedure of laying a new cable o replacing and existing one. The chain is laid out in a hook shape.

5.1.4. Elevation axis bearings

The minor changes performed on this item provided only the details necessary for maintainability, assembly, and feasibility. This sub-assembly includes two couples of conical preloaded bearings. The size of the bearings is big compared to the loads involved for this application. Moreover, these bearings are used in the Elevation actuator hinges to improve availability and reduce at the same time the number of different COTS used in the telescope.

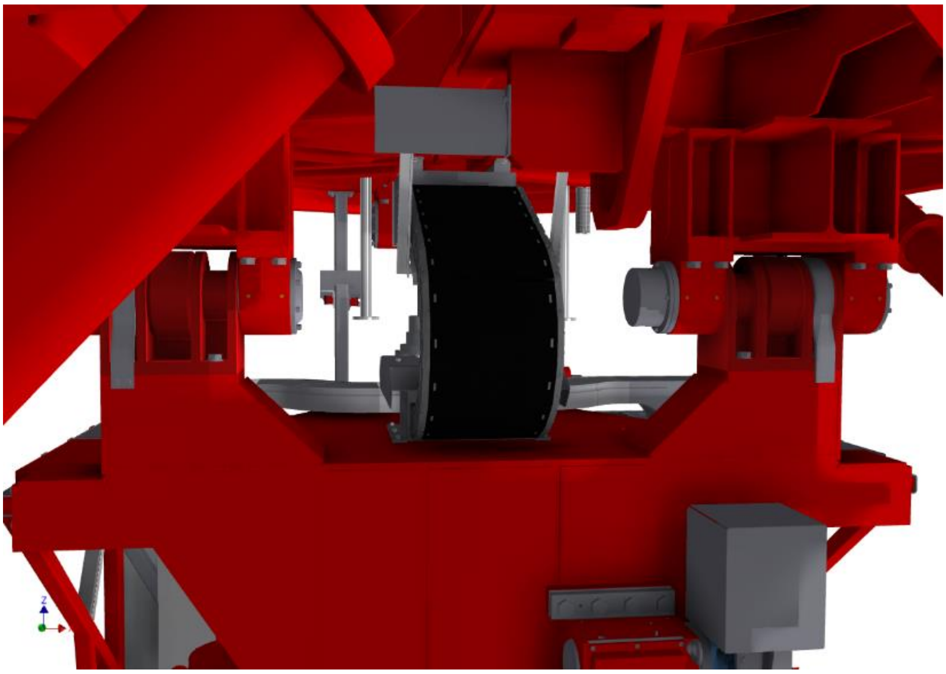


Figure 5-8: Elevation bearings

5.1.5. Azimuth drive

The Azimuth axis motion is granted by two gearbox motor units located at 180° one from the other. Moreover, there is a differential torque between them to provide a preload to guarantee precision during motion in all operational conditions.

Figure 5-9: Azimuth motors group

The Azimuth motor group consists of a gearbox and a motor equipped with brake (braking torque equal to 5Nm).

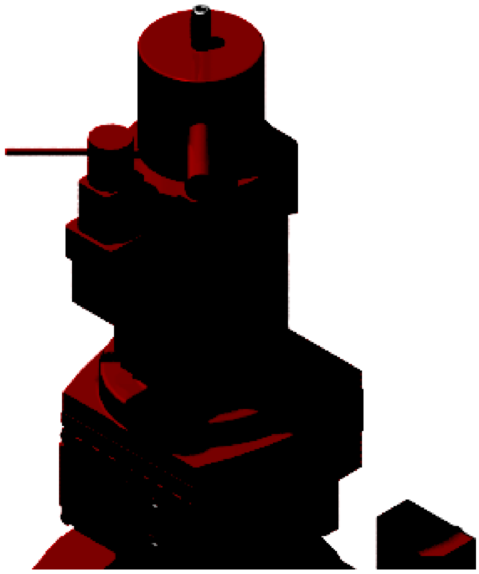


Figure 5-10: Detail of Azimuth motor brake, hand release, and emergency shaft

5.1.6. Elevation drive

The motion around the Elevation axis is possible with a preloaded ball screw jack driven by a brushless motor. The ball screw jack is a high efficiency mechanism, with a mechanical efficiency of about 80%, needed to reduce stick-slip problems.

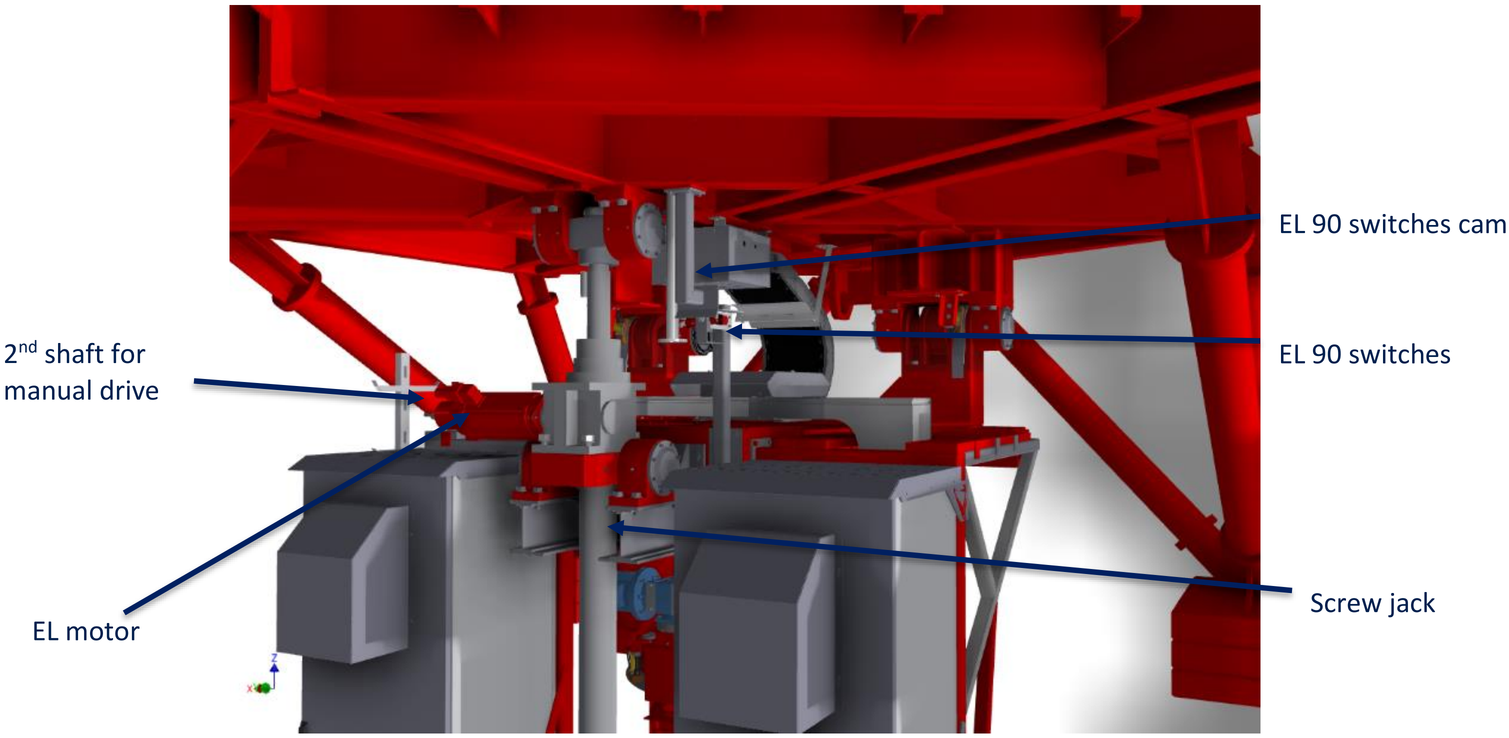


Figure 5-11: Elevation drive

The preloaded ball screw jack is fixed by means of hinges one located on the top of the ball screw and the other installed on the ball screw jack body. This allows to provide motion of the M1 dish and thus, all Optical support structure. The ball screw is fully deployed with Elevation angles close to horizon and completely retracted when Elevation angles are close to zenith position. To protect the ball screw from weather agents when it is deployed, a bellow is provided; since the screw is passing through the jack, a protection tube hosts it when the ball screw is fully retracted.

The size of the ball screw is 80x10 mm (nominal diameter x pitch).

The servomotor is equipped with brake to provide safe operation and no damages for people and hardware. The brake stops any motion, but it can be released and the 2° emergency shaft, permits to move the ball screw jack manually with the aid of a portable electrical drill.

An unbalance is introduced in the elevation assembly of about 4000 Nm, so eliminates backlashes in the reduction gearbox. Due to this unbalance and to the high efficiency of the jack, the brake on the elevation motor is needed for safety reasons.

Figure 4-1 show the system as implemented in the ASTRI Mini-Array Telescopes.

Figure 5-12: The ASTRI Mini-Array Telescope Elevation mechanism.

The study of the system geometry permitted to observe the behaviour of the ball screw speed in function of Elevation angle. This study result is outlined here below:

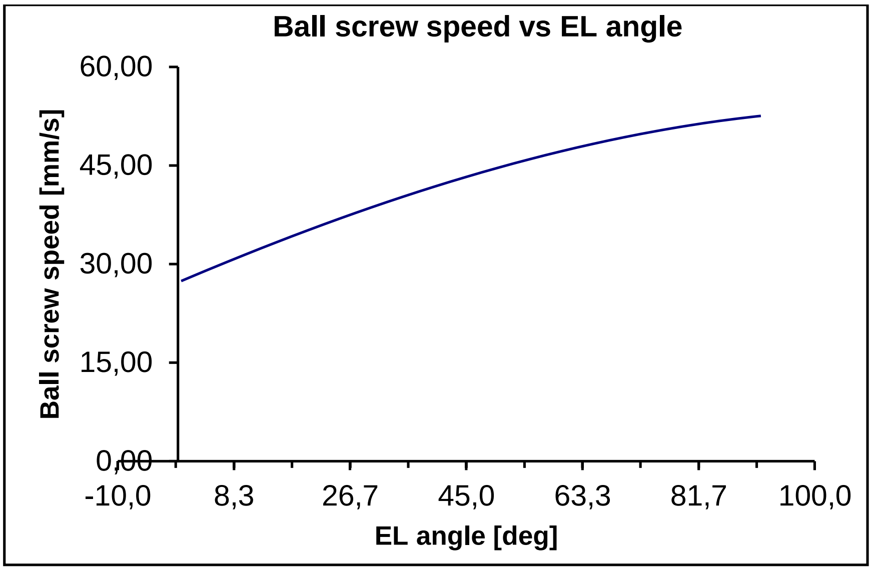


Figure 5-13: Elevation ball screw speed [mm/s] as a function of the Elevation angle [deg]

5.1.7. Elevation encoder

The design has been adapted in function of the encoder shape. The encoder is an Heidenhain RCN2580 as per INAF request. The accuracy of this item is 2.5arcsec within a range of temperature of 0°C to 50°C. Since the encoder is covered, its functioning for the ASTRI Horn prototype was accepted despite the imposed environmental conditions foresee an operational temperature range of -10°C to 40°C. The Encoder is normally working under all environmental condition of the ASTRI-Horn site (Serra La Nave, on the Etna Volcano Mount) since 2014.

The encoder is in the inner side of the EL bearing unit in order to be easier to be accessed from the central platform on top of the fork structure. The central platform on top of the fork can be accessed by means of the ladder shown in Figure 3-8 of this document.

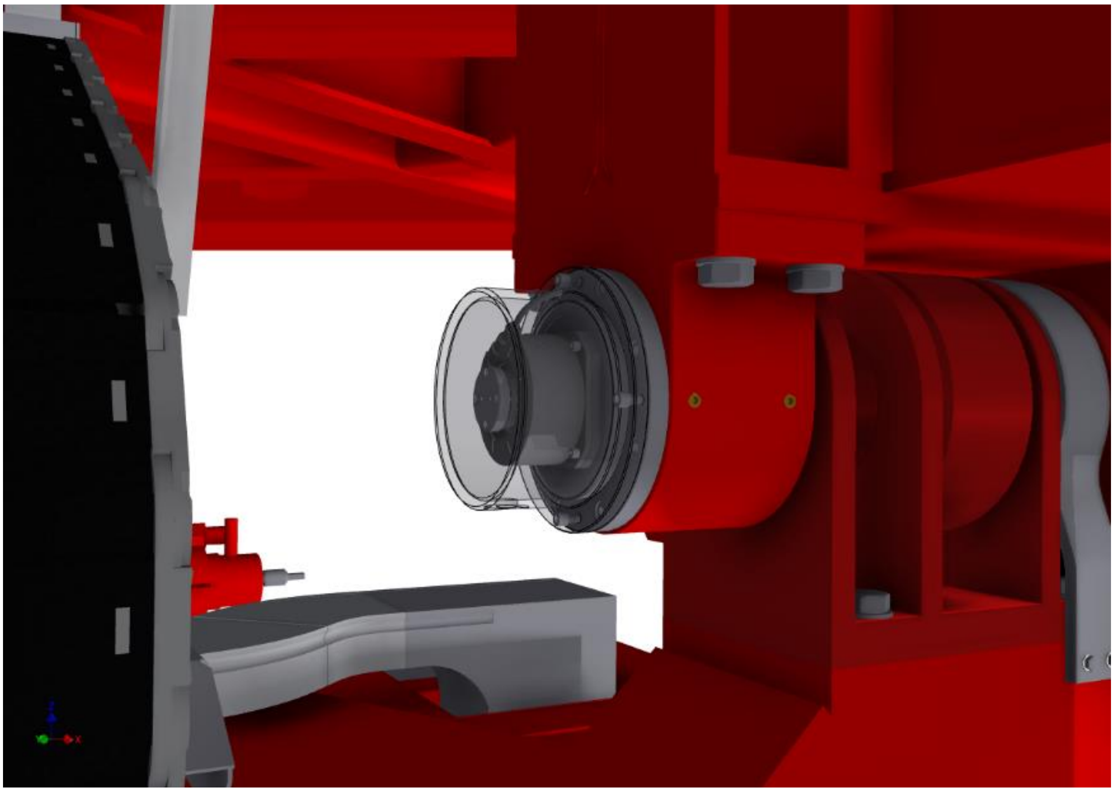


Figure 5-14: Elevation encoder installation detail

5.1.8. Azimuth switches

The Azimuth switches are in a proper bracket which offers interface for 7 switches. In detail the type of switches is listed here below:

- 2 inductive proximity switches located at Azimuth angle ±260° in order to provide a deceleration when telescope is in "proximity" of the Azimuth motion bounds. The speed of Azimuth axis when these switches are engaged is reduced to 1°/s. That is essential to guarantee safety operations for hardware (Azimuth cable wrap) in the range of angles close to the outer limits of Azimuth axis motion.
- 2 directional safety limit switches located at Azimuth angle ±270°, which do not allow the drive to continue motion to angle wider than 270°. The motion in the opposite direction is still allowed. These switches are part of the interlock chain (Functional Safety STO Signal to the Motor Drive).
- 2 power-off safety limit switches located at Azimuth angle ±272.5°, which cut off drives power to preserve hardware from damages. Without these cautions the Azimuth cable wrap could suffer damages for excessive twisting. These switches are part of the interlock chain.
- 2 limit switches Roller Yoke (the redundancy is necessary for safety reasons) with witness located at raw Telescope Az 0° (West direction), which have the function to allow a rotation of more than 360°. This switch has the function of deactivate the positive or negative angle limit switches in order to by-pass and ignore their engagement. In particular, when this switch is in "positive" position (positive Azimuth angles) the switches necessary for lower

bound (-260°, -270° and -272.5°) are deactivated; when it is "negative" position (negative Azimuth angles) the switches necessary for upper bound (+260°, +270° and +272.5°) are deactivated.

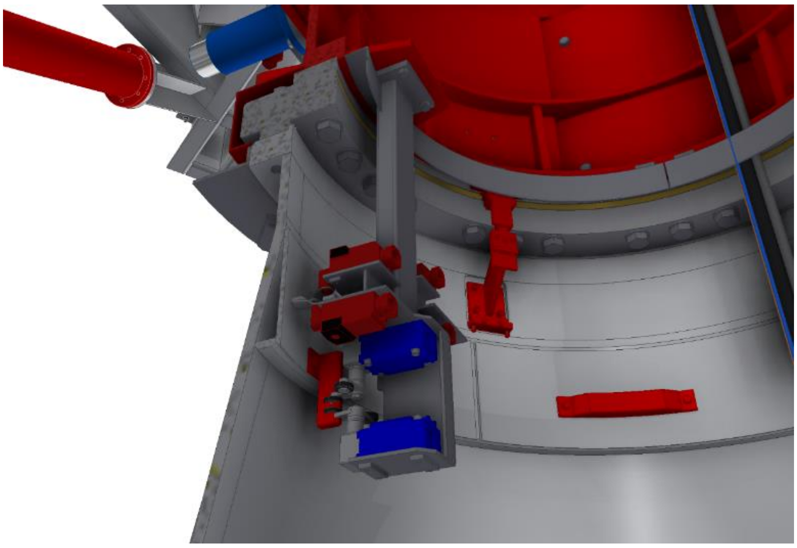


Figure 5-15: Azimuth switches

5.1.9. Elevation switches

The Elevation switches are in a proper blade support, which offers interface for 6 switches. In detail the type of switches is listed here below:

• **Two inductive proximity switches (PROX)** located respectively at Elevation angle +91° and +0.5° to provide a deceleration when telescope is in "proximity" of the Elevation motion bounds. The speed of Elevation axis when these switches are engaged is reduced to 1°/s. That is essential to guarantee safety operations for hardware and thus, to avoid unwanted dynamic loads for the optical elements in the range of angles close to the outer limits of Elevation axis motion.

• **Two directional limit switches (DIR)** located respectively at Elevation angle +91.25°and -0.1°, which do not allow the drive to continue motion to angle wider respectively over +91° and 0°. The motion in the opposite direction is still allowed. The switch at 0° will be adjusted to allow stow pin insertion without being engaged. That, to avoid unwanted behaviour with motion to reach correctly stow pin position.

• **Two power-off limit switches (EM)** located respectively at Elevation angle +91.5° and -0.35°, which cut off drives power to preserve hardware from damages. If the motion continues over -1° Elevation bumper start to be engaged.

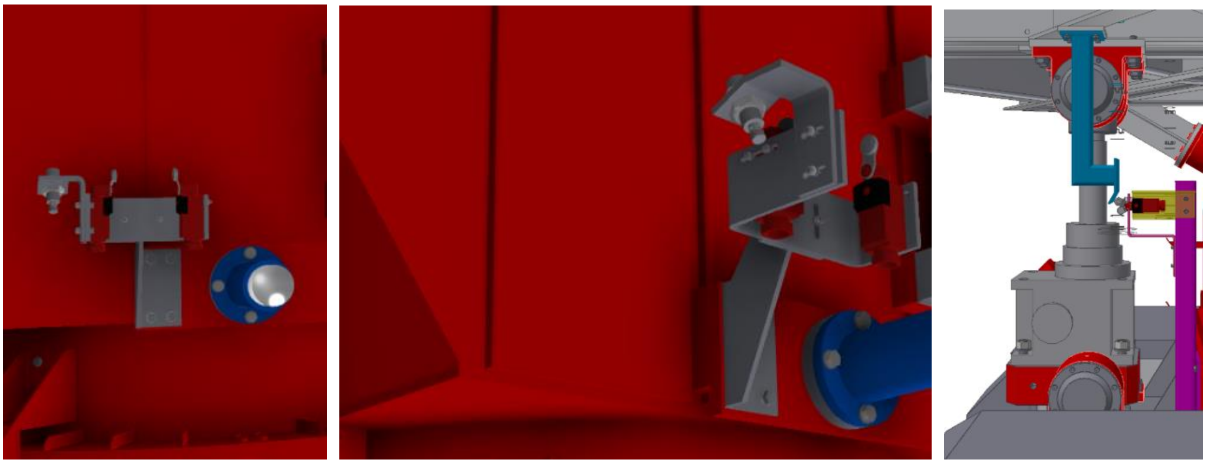


Figure 5-16: Elevation switches

Here below is reported a summary of the Elevation limit switches plus the stow and bumper positions:

Table 5-1: Elevation switches positions

	BMP END	BMP ENG	EM 00	DIR 00	STOW	PROX 00	RANGE	PROX 90	DIR 90	EM 90
Angle	-0.8	-0.4	-0.35	-0.1	0	0.5		91	91.25	91.5
Speed (°/s)		0	0.1	0.1	0.1	0.1	2	0.1	0.1	
Acceler. (°/s^2)				0	0	-8	1	-8	0	
Interlock			Yes	Yes					Yes	Yes

5.1.10. Elevation cable wrap

Cable ways from Azimuth fork and Optical support structure is allowed using a unique, central Elevation cable wrap. This cable wrap is standard IGUS R4.56.30.150, which grants protection for the cables as well as the correct guide from Azimuth fork till M1 dish. Its motion is provided passively following Elevation axis one. Spare is reserved for the Cherenkov Camera cooling hoses.

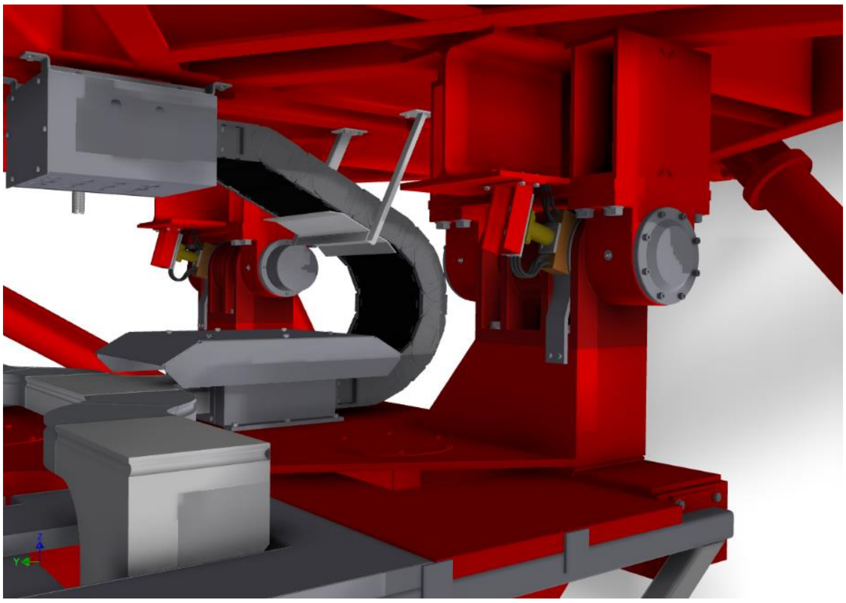


Figure 5-17: Elevation Cable Wrap

5.1.11. Azimuth Stow Pin

The Azimuth stow pin guarantees no motion for Azimuth axis and it is very similar to the concept of the Elevation stow pin. The loads for this unit (shear load of about 95kN), is lower than the Elevation one (see following paragraph); for this reason, the concept has been kept to speed up production of parts.

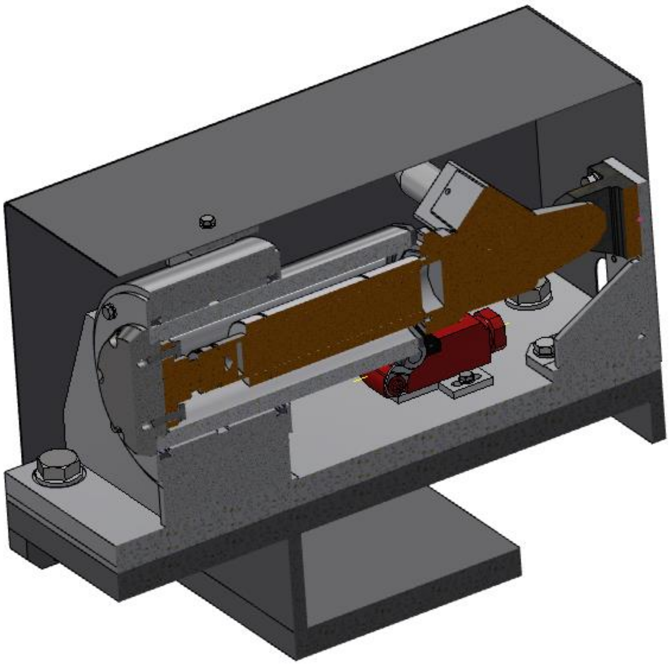


Figure 5-18: section view of azimuth stow pin

The Azimuth stow pin features 4 switches, which give status stow pin fully deployed, not deployed, and proximity (which has the function to slow Azimuth axis motion). The fourth switch is indicating the correct alignment (in combination with the encoder position) between the pin and the bush.

The calculation for Elevation Stow Pin is applicable also to Azimuth one. Since loads are heavier in Elevation case, the calculations have been performed just for the elevation one.

Three azimuth parking positions of the telescope are foreseen. In fact, the azimuth stow pin can be inserted into three separate bushings displaced at 60deg in azimuth between each other, as shown in the next image:

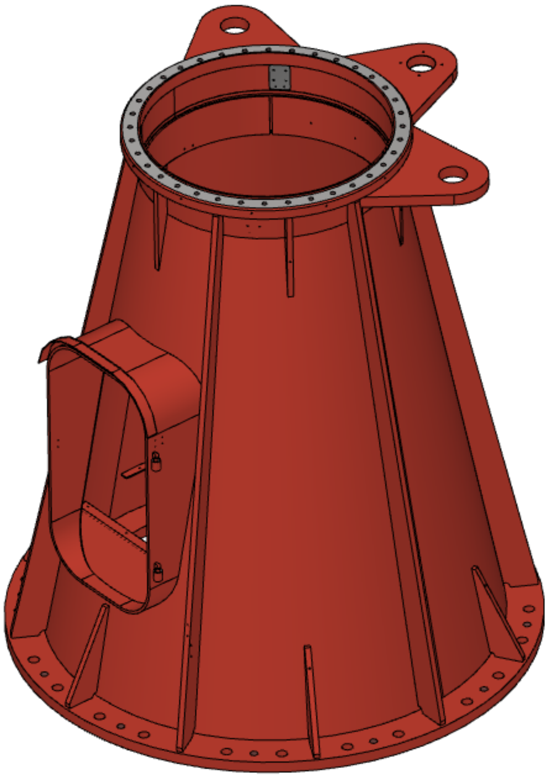


Figure 5-19: Azimuth stow pins bushings.

In this way, better sun protection during the day can be achieved, also for maintenance purposes.

5.1.12. Elevation Stow Pin

The Elevation stow pin guarantees no motion during maintenance and Telescope parking position. The position is only one, precisely at Elevation angles 3.5°. It must be mentioned that parking position is the same of the maintenance position.

The Elevation stow pin features 4 switches, which give status stow pin fully deployed, not deployed, proximity to engage (which has the function to slow Elevation axis motion). The fourth switch is indicating the correct alignment (in combination with the encoder position) between the pin and the bush.

5.1.13. Elevation Bumper

The Elevation axis design imposed a certain unbalance to provide no backlash during operation. The unbalance introduces a torque which would bring the Optical support structure to move spontaneously from zenith to horizon position. For this reason, a safety issue rise. In case the Elevation actuator (mechanical jack), for whatever reason, is not able to stop the rotation of the Optical support structure from zenith to horizon there must be a safety device able to stop without damages this undesired motion. This device is a bumper system composed by a shock absorber as per the following figure:

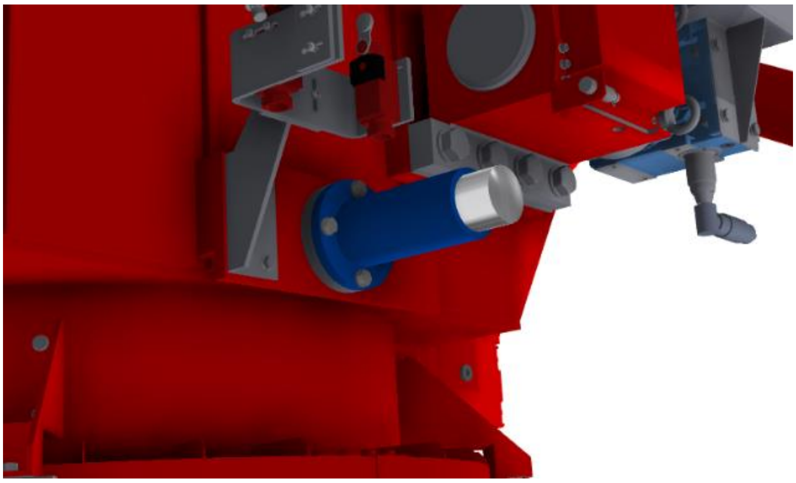


Figure 5-20: Elevation Bumper

Please note that there are no bumpers in azimuth, as the ±270deg azimuth functional range is not limited by cable torsion. Azimuth cables have been tested to be able to withstand a torsion of several full turns. Bumpers in azimuth have thus been judged as an unnecessary component.

5.1.14. Automatic Lubrication System

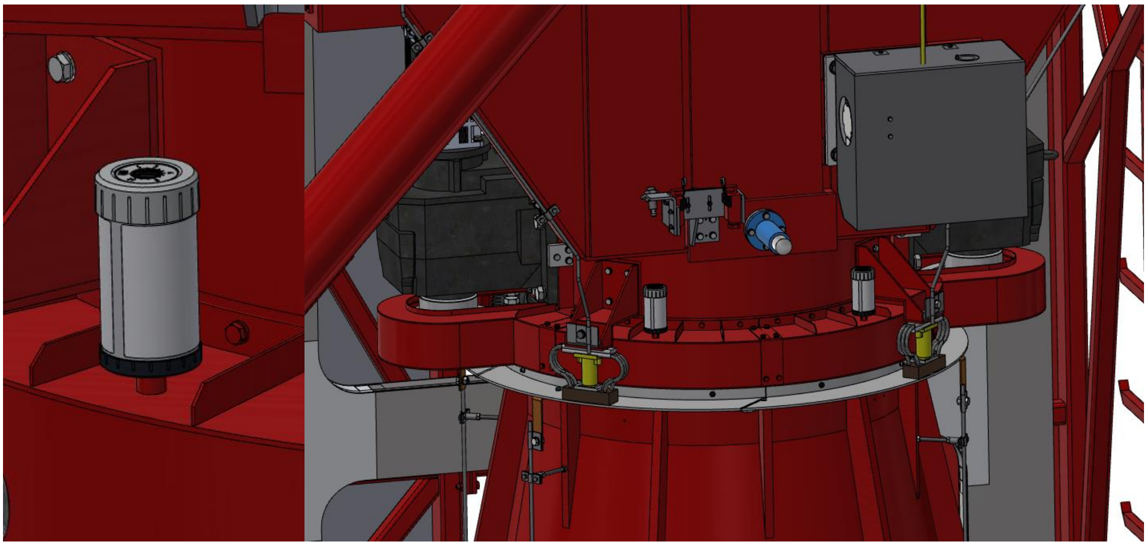


Figure 5-21: Azimuth bearing with automatic lubrication cartridges.

Lubrication of gears, bearings, and in general of all transmission elements of the telescope is the most common maintenance operation that must be performed.

The main items that must be lubricated every 3 to 6 months are:

- Azimuth bearing gear and azimuth pinions.
- Elevation bearings.
- Elevation screw jack supports bearings.
- Elevation screw jack.
- Azimuth bearing.

In the frame of an array of several telescopes to be maintained, it is introduced an automatic lubrification system onboard of each telescope.

The simplest of such systems is completely passive and require no electrical power, as it uses a gas-loaded cartridges. Based on a setting screw, the gas expands and pushes out all the grease contained in cartridge in the selected time frame (6 months, 1 year).

This simple system is shown in the image for the azimuth external gear.

Anyway, it will be worthwhile to study more complicated but even more automatized lubrication system, based on a centralized grease storage, a pump and a series of pipes distributing the grease to all required items.

Figure 5-22: Example of centralized lubrication unit

5.2. Optical Support Structure

The so-called Optical Support Structure represents that assembly of the Telescope, which hosts the support of the optics.

The following picture provides the locations of the sub-systems.

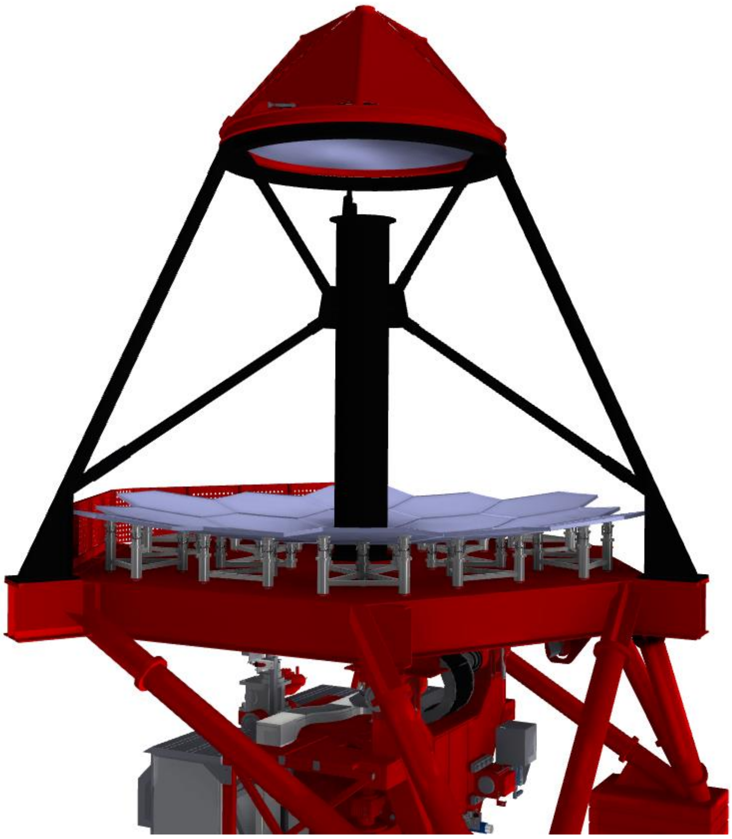


Figure 5-23: Populated Optical Support Structure

Pictures highlight the M1 Dish, the M2 Support and all the subsystems. The central tube only hosts the Cherenkov camera necessary for the observations.

5.2.1. M1 Segment Support Assembly

The M1 segment assembly layout is based on a radial Coordinate system. In this way it was possible to design only three types of units: the inner, the intermediate and the outer ones. These units are repeated six time with an “hexagonal symmetry”.

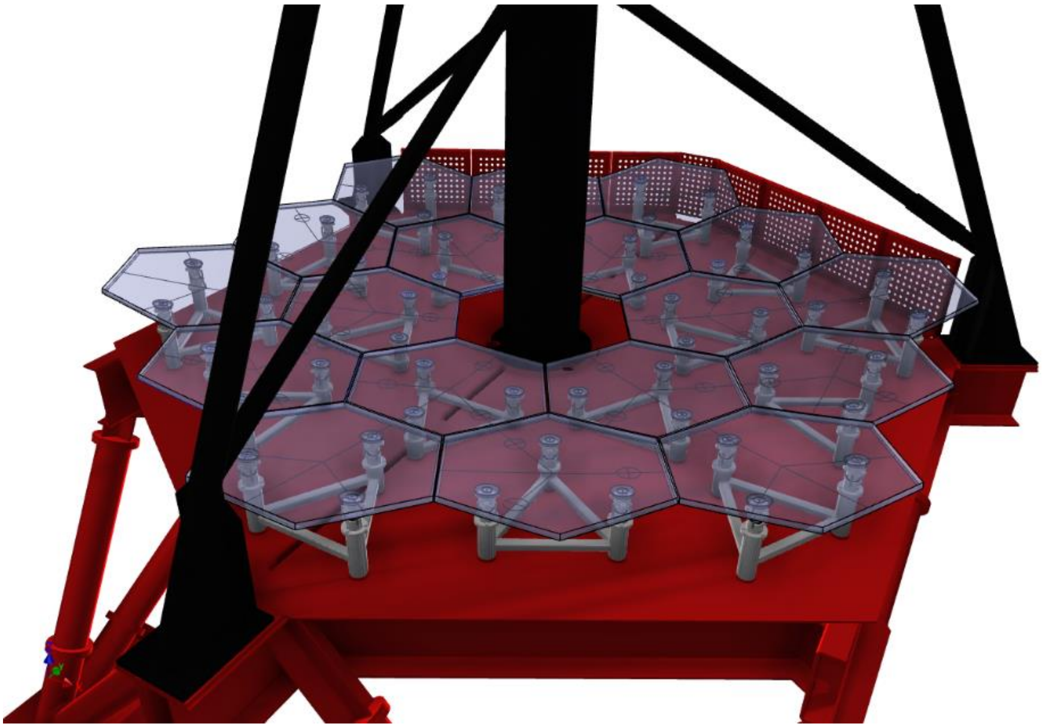


Figure 5-24: M1 segments support assembly with transparent M1

Each segment is provided with three passive actuators preloaded by means of springs with a stroke of ±7.5mm and fixed in their positions with tapered locking devices which works with friction.

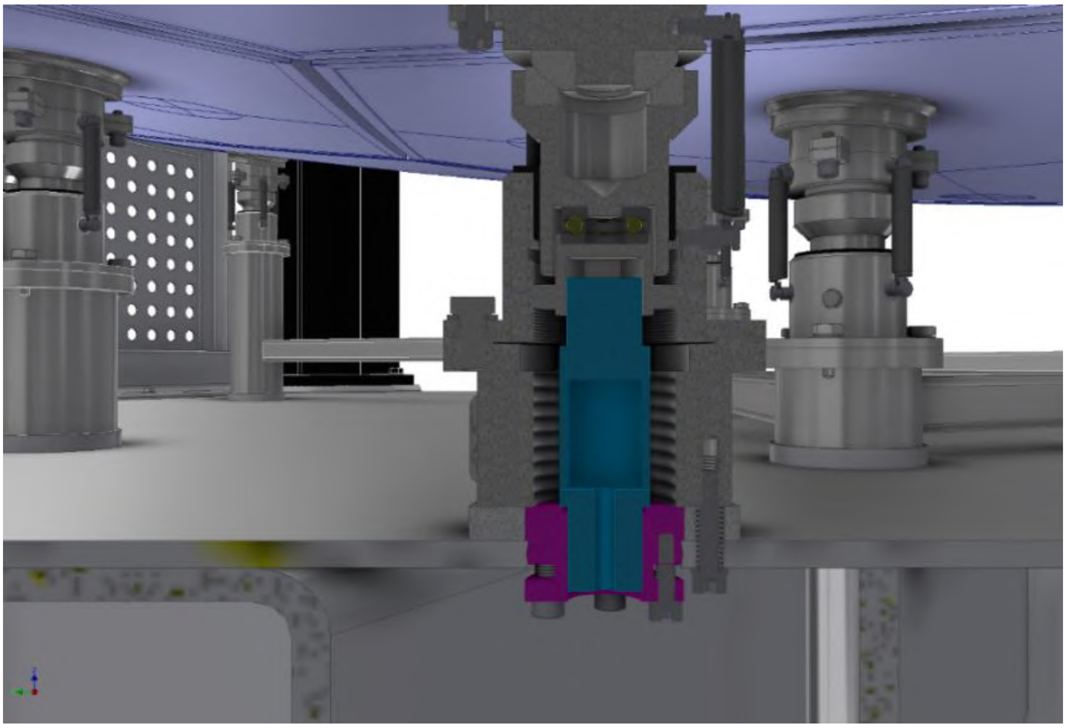


Figure 5-25: M1 segment support actuator with locking device

The handling is possible by removing for each actuator, the locking device the fixing screws and installing, the sliding bush and the relative pipe. It is essential to do these operations on a single actuator per time to avoid damages. For this reason, there will be a sign on the bottom of the M1 cell in correspondence with each segment indicating:

"remove locking device and install the sliding system before removing the remaining locking devices of the actuators belonging to the same segment – remover el acoplamiento e instalar el sistema de deslizamiento antes de remover los acoplamientos restantes que pertenecen a los actuadores del mismo segmento".

When the sliding devices are installed on all three actuators, the segment can be slid out to permit the mirror removal.

Mirror can be detached from the actuators removing three fixing screws per pad. An eyebolt will be sufficient to lift the mirror segment up; springs will remain in their places.

It must be considered that a cherry picker is sufficient for the mirror segment removal as the operators can hold them by virtue of its light weight.

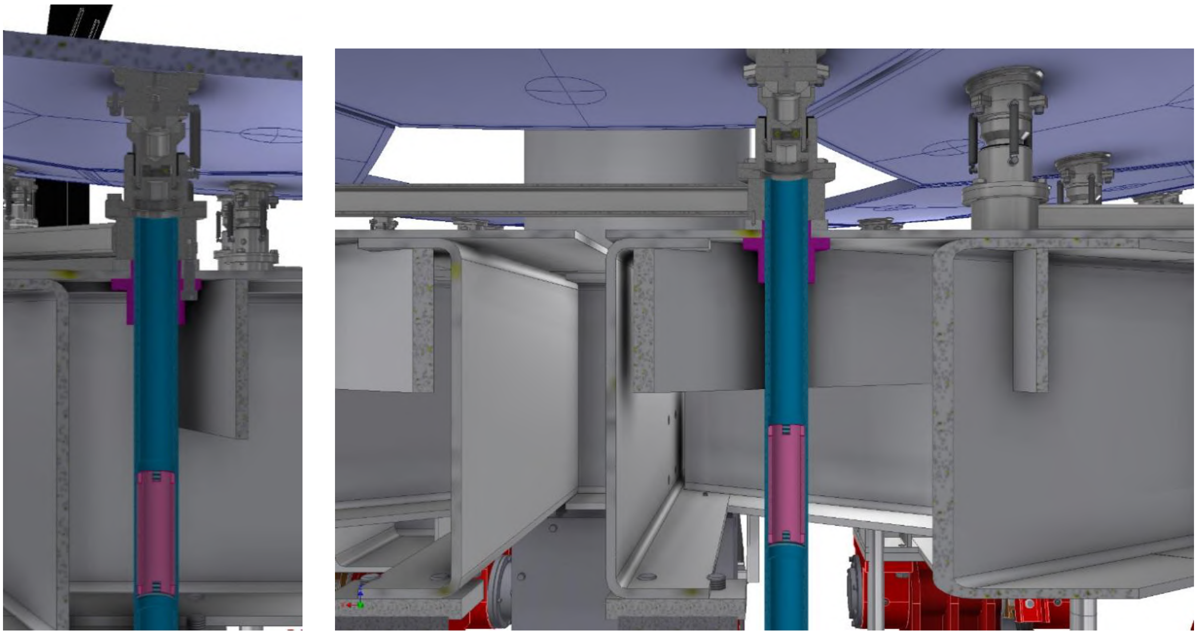


Figure 5-26: M1 segment sliding tool

5.2.2. M2 Support

M2 is supported by a system, which includes an active tripod system, which allows M2 precise positioning along Z axis and tip-tilt (rotation around X and Y axes), and a lateral support, which grants safety support and safe load transmission. Tripods consist in three loadspreaders provided with 3 flexures each to transmit axial loads only.

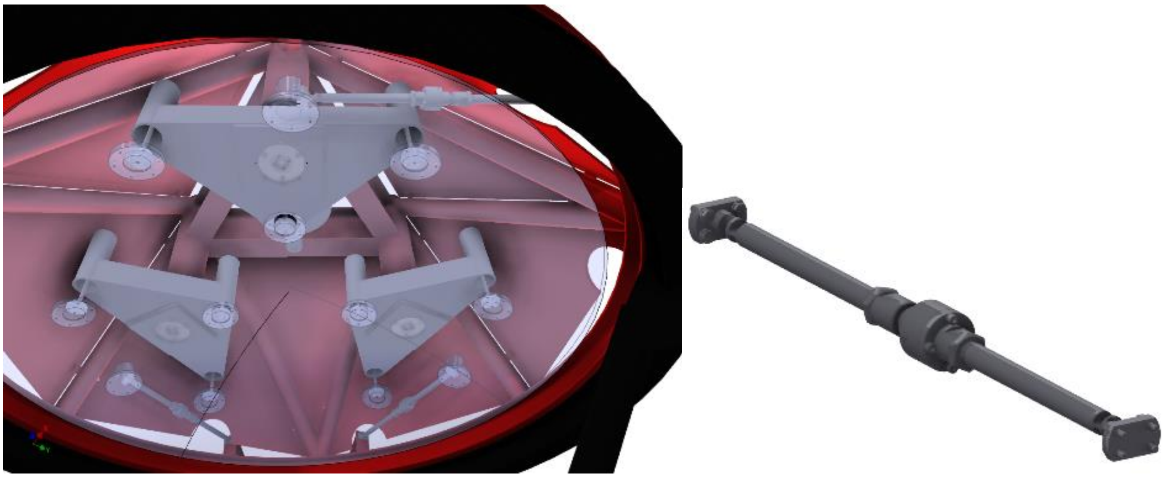


Figure 5-27: M2 support (left); Lateral fix point (right)

The motion is possible with a motor and a ratio gear, which permits the actuators to move with an axial stroke of ±7.5mm. Each driving unit is equipped with an absolute encoder and two electrical limit switches to have full feedback of position and safety of motion. The joint between the flexures structure and the actuator consists in a double-tilting system, which grants the M2 to be tilted and displaced along the optical axis without constraints.

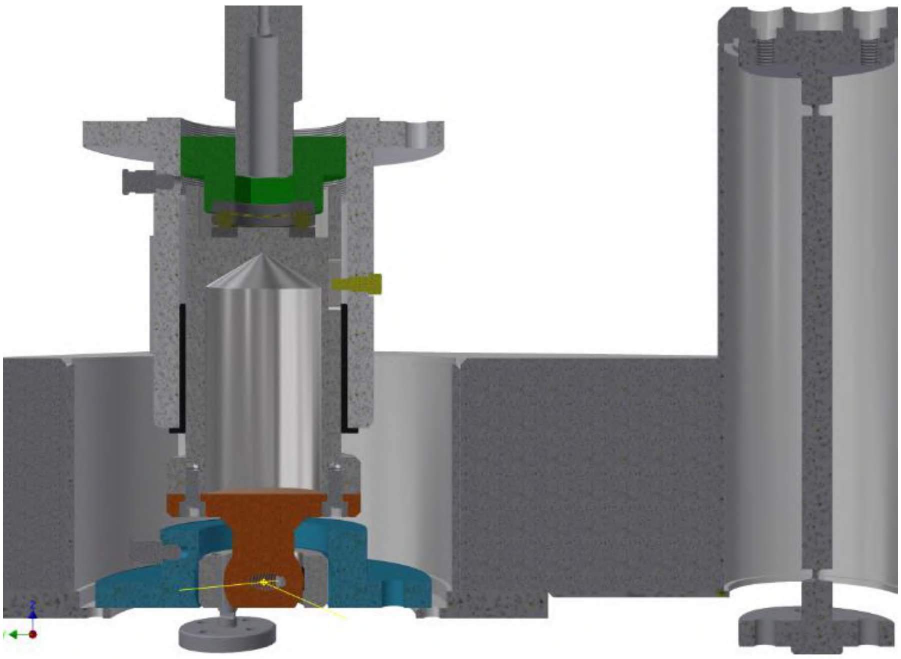


Figure 5-28: Section of M2 actuator and Loadspreader flexure

Maintenance or replacement of the lateral fixed points can be done when the telescope is in its parking position by means of threaded rods, which support temporarily the mirror loads during substitution.

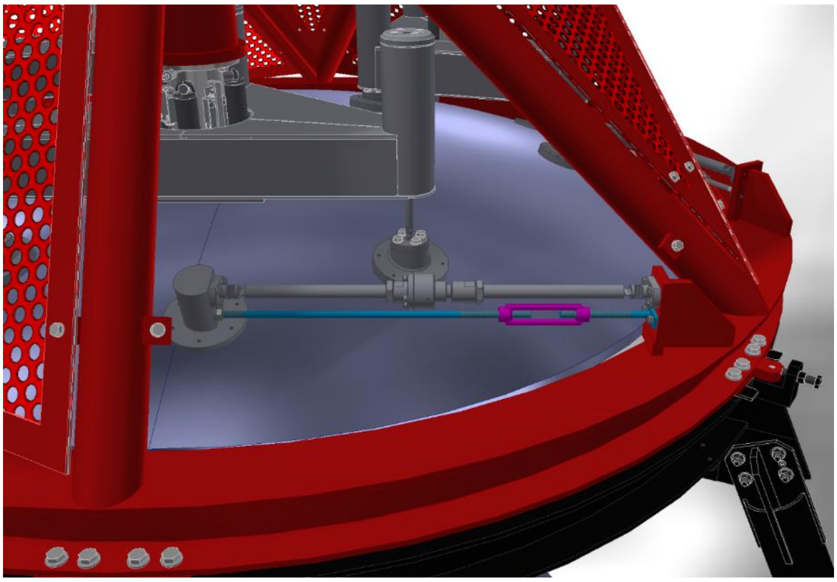


Figure 5-29: Maintenance threaded rod for lateral fixed point

M2 removal can be done only removing the M2 support.

The lateral device must be able to bear till a maximum load of 2900N and then for safety reason must interrupt load transmission. The load foreseen for this application is 1010N. To grant this performance a mechanical fuse is introduced with these characteristics.

A pin with diameter of 2mm will be used with a gap between the two arm elements of 0.1mm. This allows a stiffness loss of only 0.34% with respect to a continuous rod. This pin will fail with a load within the range of 1306N and 1850N, which fulfils the requirements.

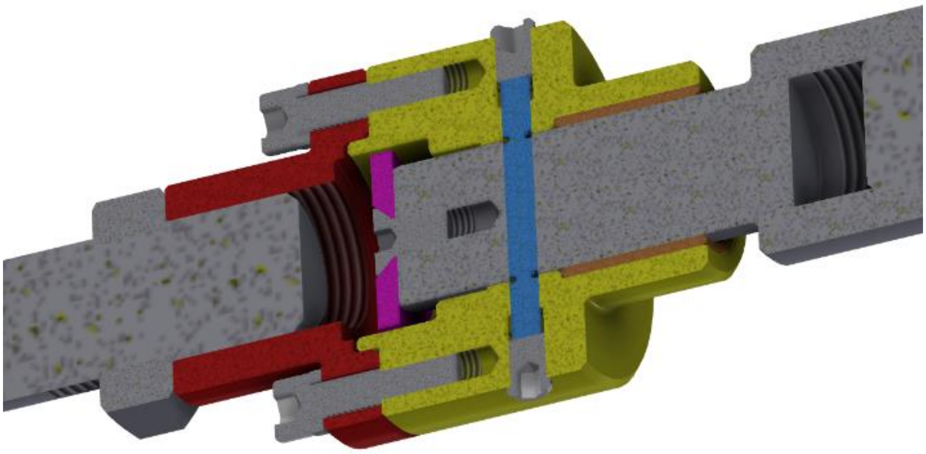


Figure 5-30: Section of lateral fixed point with mechanical fuse

5.2.3. M1-M2 Alignment

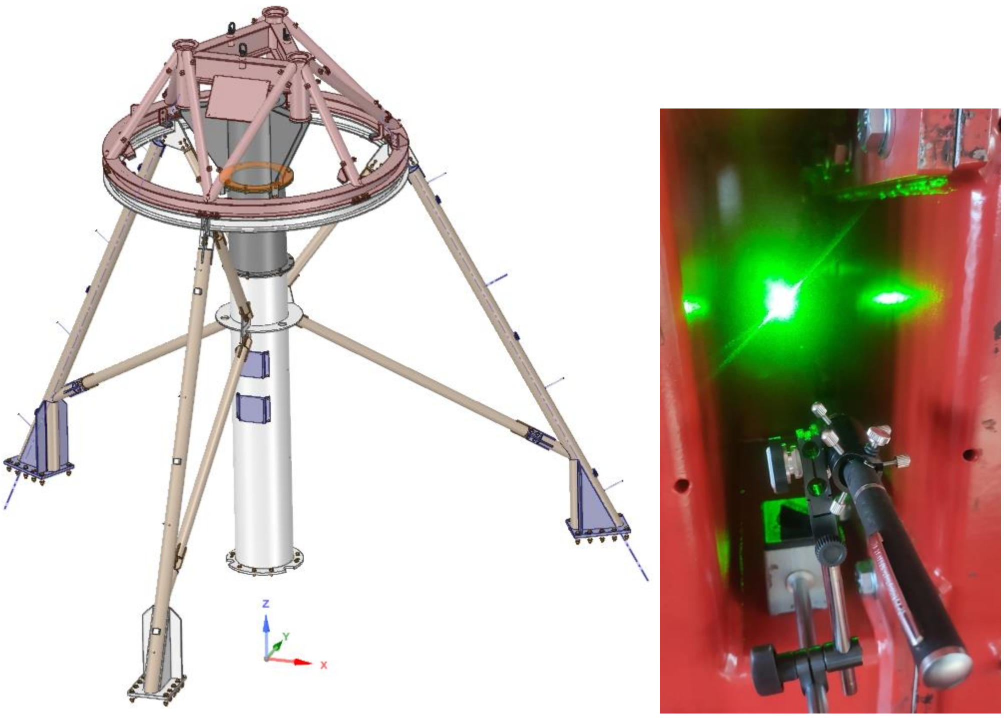


Figure 5-31: Configuration of the Upper Optical Support Structure for M1-M2 alignment (left); laser pointer behind M1 dish (right)

One of the factory procedures required during the integration of the telescope, is the mechanical alignment of the M2 cell with the optical axis of the telescope.

In the baseline procedure, a laser pointer is inserted behind the M1 Dish, in a small hole. A laser target is placed on the Camera interface, and then the laser pointer is aligned with the target.

After that the Camera target is removed, and the M2 mounting template (a reversed cone shape space) mounted on the telescope, along with the M2 cell on top.

The M2 cell features another laser target on the PMC interface. With a bronze sliding disc (highlighted in the image) the M2 cell is displaced in-plane until the laser spot exits from the M2 target.

After this alignment has been achieved, holes for pins are drilled in the M2 cell, and the mounting template is removed.

This procedure is quite complicated and is heavily affected by the stability over time of the laser pointer. Moreover, the alignment error is the sum of the diameter of the laser spot (2 mm) and the diameter of the target holes (2 mm), therefore 4 mm.

The proposed improvement is to rely only on machined interfaces to align the M2 cell with respect to the M1, producing a M2 mounting template that does not have a sliding disc.

The resulting alignment error is expected to be in the order of 1-2 mm, much less than what is achieved with the laser.

5.2.4. M1 Calibration System

While the M2 actuators are permanently mounted onboard of the M2 Support, in the SST baseline the M1 calibration actuators are not permanently mounted on the telescope, but consist in a set of 54 units that are shared among a certain number of telescope (in case of the ASTRI mini-array, one set is shared among nine telescopes), which are mounted only once every 1-2 years to optimize the PSF of the telescope.

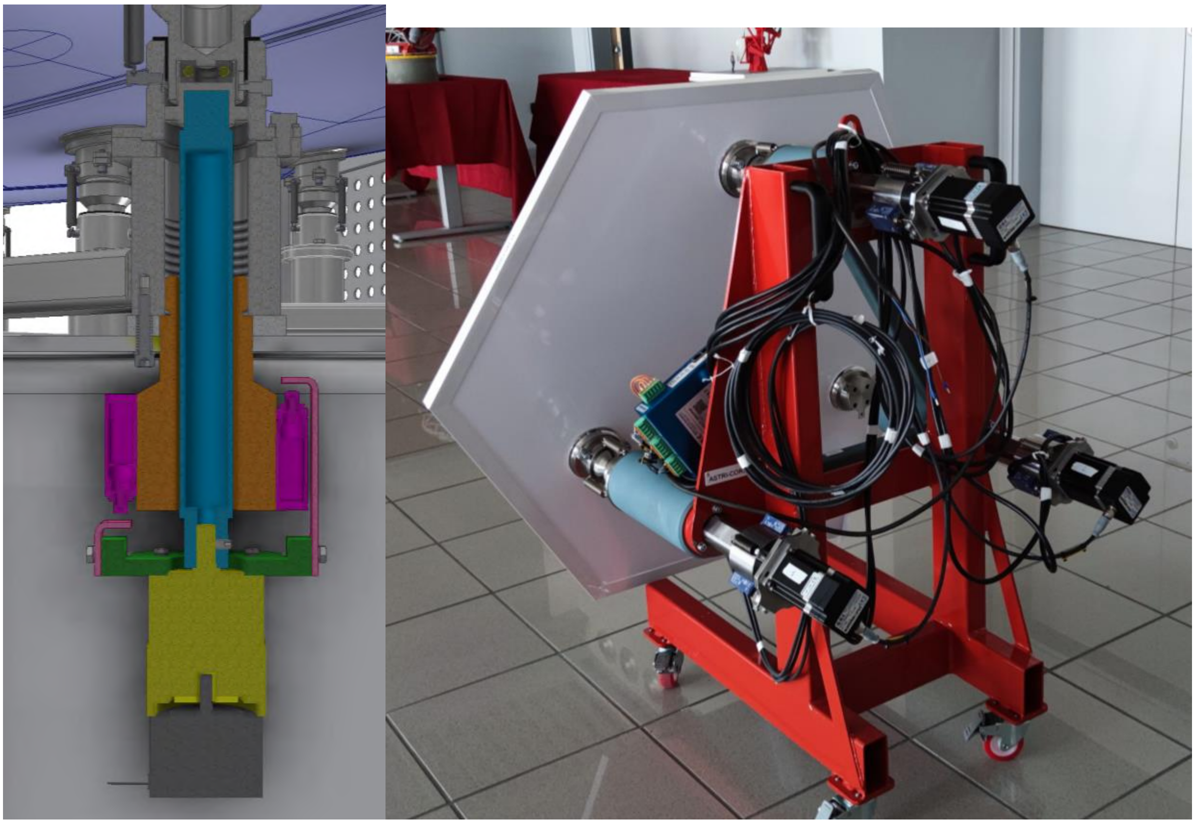


Figure 5-32: Section view of an actuator mounted on the telescope; M1 actuators mounted on a test bench

The M1 calibration actuators are inserted into the backside of the M1 dish and connected with a hex-key coupling to the passive M1 actuators that are onboard of the M1 supports. The mounting is achieved simply by turning the whole actuator into threaded holes accessible from the backside of the Dish.

They feature a stepper motor with a planetary reduction gearbox that acts on a shaft, which in turn rotates the fine-pitch screw placed inside the passive actuators, which translated the rotary motion of the motor into linear motion of the actuator.

Limit switches are present to provide the mechanical limits of the M1 calibration actuators motion.

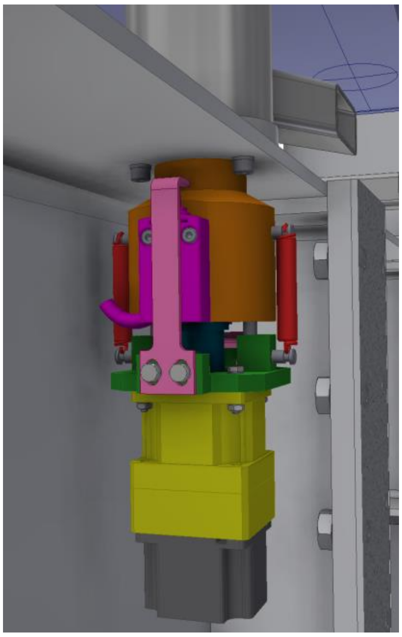
 

Figure 5-33: Calibration actuator mounted on the M1 Dish; set of actuators for a telescope

A control cabinet needs to be installed as well to power and control the 54 actuators. This cabinet, called Calibration Cabinet, houses the AC-DC converters to supplies power to the motors and the motor controllers. It is installed on the side of the Lower Power Cabinet.

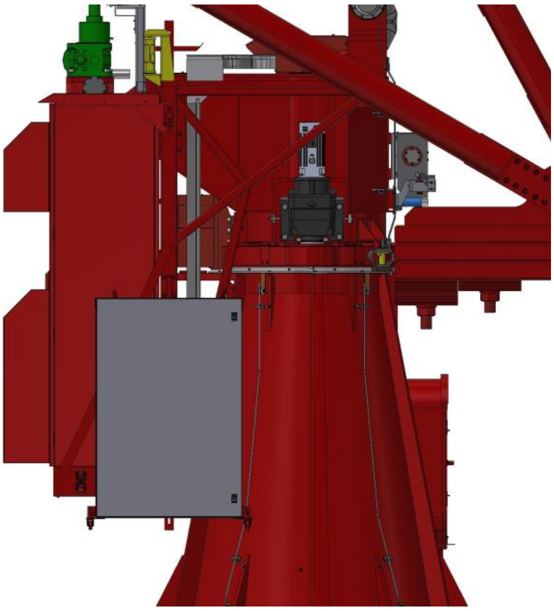
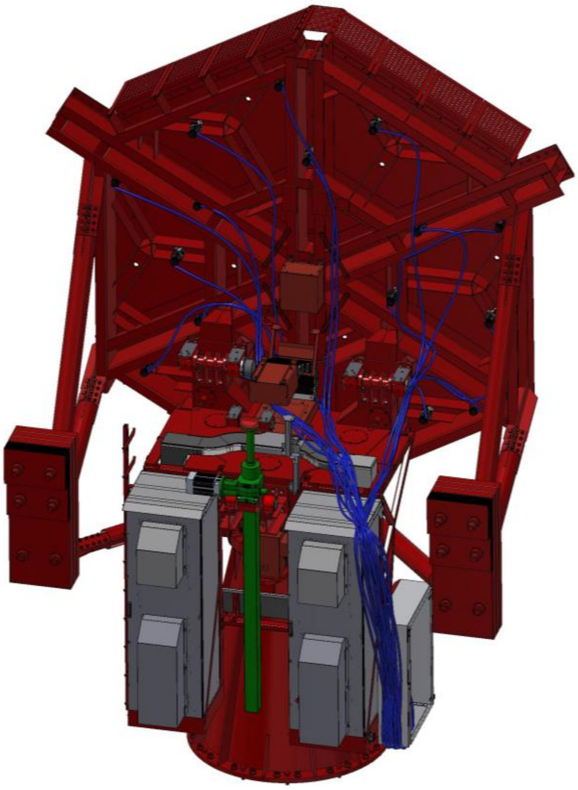
 

Figure 5-34: Calibration cabinet (left); M1 actuators cable routing (right)

Cables are bundled into one bundle of cables for each M1 segment (so 18 bundles in total) and exit the Calibration Cabinet from one of the sides, by means of panel connectors. So, being connectorized at both ends, the installation of cables on the telescope is made easier.

The temporary fixing of the M1 calibration cables on the telescope structure is achieved by means of a series of magnets, one each meter of length.

On the rear side of the Low Power Cabinet, power and Ethernet plugs are available for the Calibration cabinet. The Ethernet plug goes into a “hot-plug” board inside the telescope Control cabinet , allowing hot start of the Calibration System into the Telescope Control Unit (PLC).

The design of the M1 calibration actuator coming from the ASTRI Mini-Array can be improved by adopting motors with integrated controllers. In this way it is eliminated the need of having a Calibration Cabinet. The power supply to the motors can come from an electric box located on the backside of the M1 Dish, while the EtherCAT fieldbus connects all the devices in a daisy chain. The first item in the EtherCAT chain can be connected to an Ethernet plug on such electrical box. The limit switches can be brought to the digital inputs of the controller onboard of the motors.

The alignment procedure of M1 segments is described in the Optical Design Report [RD5].

6. Electrical design

6.1. Electrical design assumption

The Telescope receives power from an external double interface with the following characteristics:

- a 3P+N+PE, 400Vac, 50Hz Power Line

The design of the Telescope power network has been done assuming that the three phase short-circuit current at telescope interface point is equal to 10 kA; the phase-neutral and phase-ground short circuit current have been assumed as 60% of the three phase one (i.e. 6kA).

The relevant earthing system is TN-S (i.e., PE and N are separate conductors that are connected to the ground only near the power source).

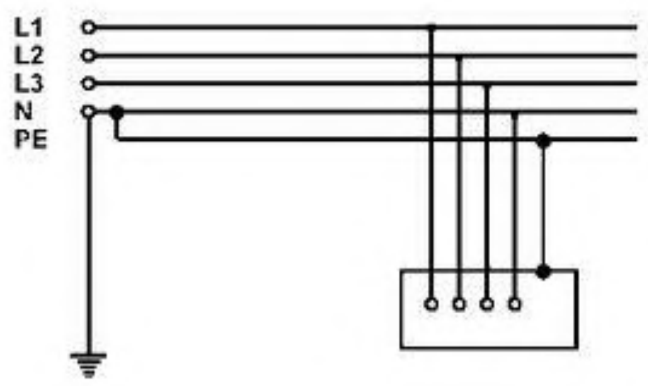


Figure 6-1: TN-S representative scheme

6.2. Electrical safety

The design of the electrical distribution grid respects, for each feeder:

1. the protection against overload;
2. the protection against short-circuits;
3. the protection against indirect contacts.

It follows the description of the methods used in the designing of the network.

6.2.1. Protection against overload

For the protection against overload, the Standard IEC 60364-4-43 that specifies the coordination between live conductors and overload protective devices has been respected.

All protective devices have been chosen in the respect of the two following conditions:

$$I_b \leq I_n \leq I_z$$

$$I_2 \leq 1.45 \cdot I_z$$

Where:

- I_b is the current for which the circuit is dimensioned;
- I_z is the continuous current carrying capacity of the cable;

- I_n is the rated current of the protective device; for adjustable protective releases, the rated current In is the set current;
- I_2 is the current ensuring effective operation in the conventional time of the protective device.

According to the first condition, to correctly choose the protective devices, it is necessary to check that the circuit-breaker has a rated (or set) current that is:

- higher than the load current, to prevent unwanted tripping;
- lower than the current carrying capacity of the cable, to prevent cable overload.

The verification of the second condition is not necessary in the case of circuit-breakers because the I2 is 1.3 x In for industrial use circuit-breakers (complying with IEC 60947-2) and I2 = 1.45 x In for circuit-breakers complying with IEC 60898 (for household and similar installations). Therefore, for circuit-breakers, if In ≤ Iz, the formula I2 ≤ 1.45 Iz will also be verified.

When the protective device is a fuse, it is essential to check the second condition because the standard IEC 60269-2-1 states that a 1.6 x In current must automatically melt the fuse. In this case, the formula becomes 1.6 x In ≤ 1.45 x Iz or:

$$I_b \leq I_n \leq 0.9 I_z$$

6.2.2. Protection against short circuit

Circuit breakers and fuses are dimensioned with a breaking capacity higher than the maximum short-circuit current in the point of installation.

The chosen cables are protected against short-circuit since, for every feeder, it is verified that the specific let-through energy of the relevant protective device (I^2t) is lower or equal to the withstood energy of the cable itself (k^2S^2):

$$I^2 t \leq k^2 S^2$$

Where:

- I_2t is the specific let-through energy of the protective device which can be read on the curves supplied by the manufacturer;
- S is the cable cross section [mm^2];
- k is a factor (based on IEC 60364-4-43 and IEC 60364-5-54) that depends on the cable insulating and on the conducting material.

The formula must be verified along the whole length of the cable. Due to the shape of the specific let-through energy curve of a circuit breaker, it is generally sufficient to verify the formula only for the maximum and minimum short-circuit current that may affect the cable. The maximum value is normally the value of the three-phase short-circuit current at the beginning of the line, while the minimum one is the value of the phase to neutral or phase to earth short-circuit current at the end of the cable.

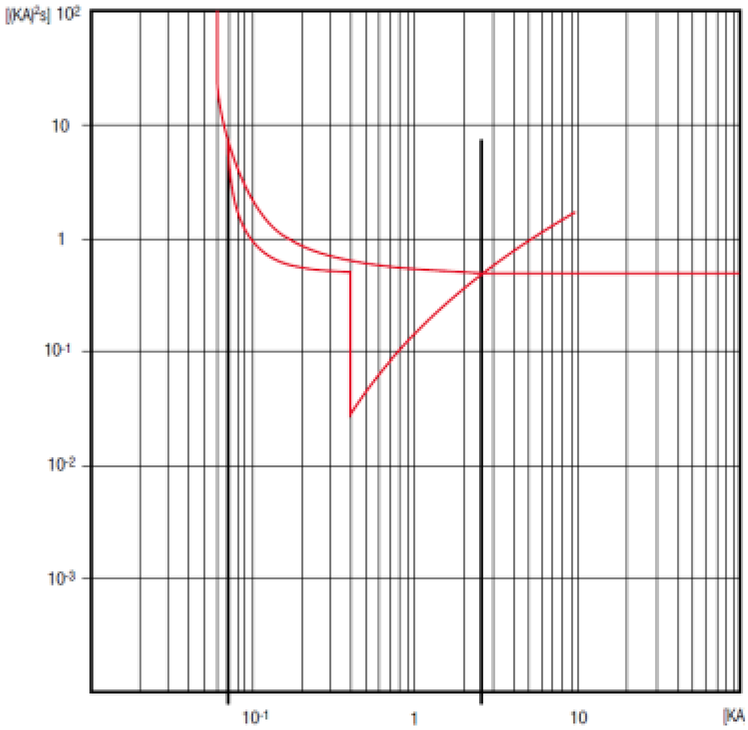


Figure 6-2: Typical protection against short-circuit verification

6.2.3. Protection against indirect contacts

A contact is indirect when a part of the human body touches an exposed conductive part, usually not live, but with voltage presence due to a failure or wear of the insulating materials.

The protection against indirect contacts in the power distribution network has been assured with the following measures:

a. automatic disconnection of the supply within the appropriate times. In our case, that is a TN-S system, a protective device shall automatically disconnect the supply to the circuit so that the touch voltage on the exposed conductive part does not persist for a time sufficient to cause a risk of harmful physiological effect for human beings.

b. residual current devices where the previous condition is not satisfied or where specifically requested by design specifications.

Regarding the point "a", an earth fault in a TN system involves the circuit represented hereunder:

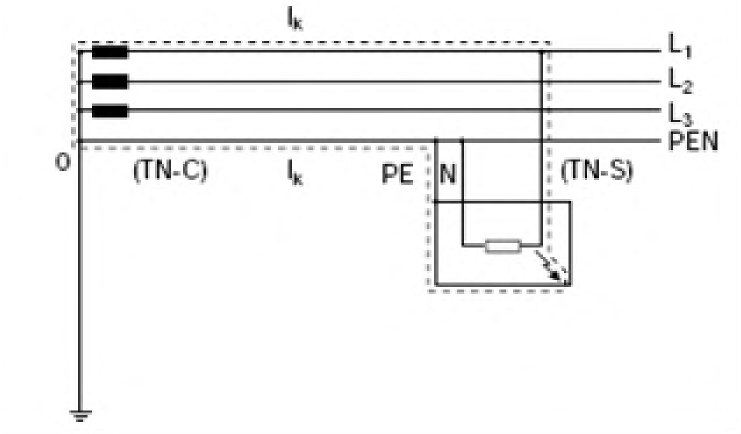


Figure 6-3: TN-S (or TN-C) earth fault

The fault loop does not affect the earthing system and is basically formed by the connection in series of the phase conductor and of the protective conductor (PE).

To provide a protection with automatic disconnection of the circuit, according to IEC 60364-4 prescriptions, the following condition shall be fulfilled:

$$Z_s \cdot I_a \leq U_0$$

Where:

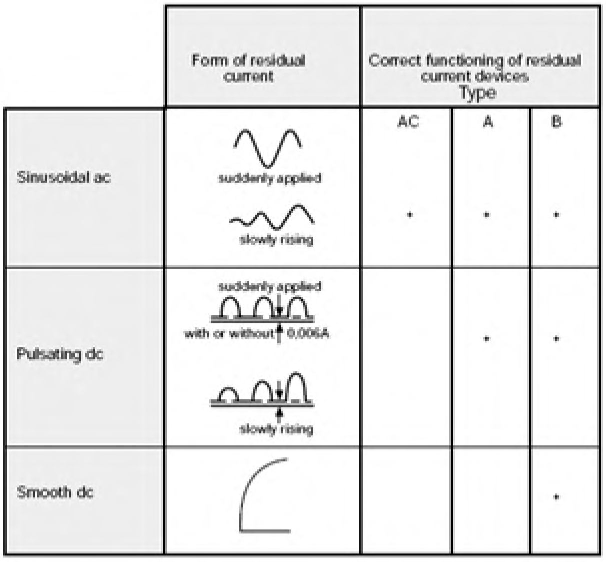
- Z_s, is the impedance of the fault loop comprising the source, the live conductor up to the point of the fault and the protective conductor between the point of the fault and the source [Ω];
- U_o, is the nominal ac r.m.s. voltage to earth [V];
- I_a, is the disconnection current [A] of the protective device within the times stated in the next table as a function of the rated voltage U0 for final circuits with currents not exceeding 32 A, or within 5 s for distribution and final circuits with current exceeding 32A.

	$50V<U_0\leq120V$ s		$120V<U_0\leq230V$ s		$230V<U_0\leq400V$ s		$U_0>400V$ s	
System	a.c.	d.c.	a.c.	d.c.	a.c.	d.c.	a.c.	d.c.
TN	0.8	Note 1	0.4	5	0.2	0.4	0.1	0.1

NOTE 1 Disconnection may be required for reasons other than protection against electric shock.

Figure 6-4: Maximum disconnecting times for TN system

The protection devices making part of the Telescope distribution system respect this safety condition. Where not satisfied or where imposed by the standard (e.g., for the sockets in outdoor application), a residual current device has been added. It has been chosen the type AC or A residual current device whose meaning it is reported in the following table.



	Form of residual current	Correct functioning of residual current devices Type		
		AC	A	B
Sinusoidal ac	suddenly applied slowly rising	•	•	•
Pulsating dc	suddenly applied with or without 0,006A slowly rising		•	•
Smooth dc				•

Figure 6-5: Residual current device types

6.2.4. Protection against direct contact

A direct contact occurs when a part of the human body touches a part of the plant, usually live (bare conductors, terminals, etc.).

The adopted measures of protection against direct contact are:

- insulation of live parts with an insulating material which can only be removed by destruction (e.g., cable insulation);
- barriers or enclosures: all live parts are inside enclosures or behind barriers providing at least the degree of protection IPXXB or IP2X; for horizontal surfaces the degree of protection is at least IPXXD or IP4X.

6.2.5. Protective devices and cables dimensioning

The choice of all the protective devices and the relevant cables has been performed to obtain the best compromise between the over-current discrimination of the upstream and downstream protective devices and the conductors cross-section optimization, according to the absorbed current of each load.

For what concern the choice of the protective devices the following (conservative) assumptions have been done:

- Operating temperature equals to the maximum admissible temperature inside the cabinet (40°C);
- Derating factor, considering the type of installation and the proximity of other electrical devices which reduce the heat dissipation capacity, K = 0.76.

It has to be taken into account that the dielectric properties and the electrical operating ranges of the equipment are affected by the reduction in air density (reduced cooling, reduced insulation capacity, etc.) with reference to the altitude of installation (2150m a.s.l.). In the same way, the air density conditions the thermal exchange dynamics.

Anyway, most electrical/electronic equipment is suitable up to 2000 m. a.s.l and undergoes to a derating factor equal to 1% for each 100 meters over the 2000 m a.s.l.

Also, the problems caused by UV radiation (minimal) and ozone concentration must be taken into consideration.

For the ASTRI Mini-Array all have been derated according to manufacturer prescriptions.

For the ASTRI Mini-Array the entrance of the power cabinets +Telescope Power Cabinet (Normal Power Supply) has been equipped with one switch fuse. This device guarantees the protection of the downstream circuits against over-currents together with the disconnection function, ensuring the total de-energization for service or maintenance of the electrical circuits.

For the ASTRI Mini-Array at each entrance of the cabinet +Telescope Control Cabinet (Normal Power Supply and UPS Supply) it is foreseen a load disconnector which guarantees the possibility to open the circuit also when energized while the over-current protection is provided by the circuit-breaker installed upstream.

A lockout-tag out disconnector in the telescope power interface box must be installed, inside in the telescope base, to guarantee a sure “padlock” against inadvertent Telescope movements in case of personnel presence.

For the ASTRI Mini-Array all the other circuit breakers and protective devices have been chosen according to the power absorption of the relevant loads also in compliance with the verifications mentioned in the previous paragraphs.

As general preference, where applicable, Miniature Circuit Breakers (MCBs) with time-current characteristic “K” have been adopted in the ASTRI Mini-Array. This characteristic presents the following advantages:

- no nuisance tripping in the case of functional peak currents up to 10 x In (depending on the series);
- protection to damageable elements in the overcurrent range (thanks to its highly sensitive thermostatic bimetal trip).
- high protection to cables and lines.

The dimensioning of cables has been done respecting the following points:

- continuous current carrying capacity of the cable correlated to the load current and to the upstream protection device.
- maximum allowed voltage drop set at 4%.
- general 20-30% oversizing for installation methods.
- insulation voltage 300/500 V or 0,6/1 kV where applicable and necessary.

Fire retardant and UV radiation resistant cables installed for any purpose and application (power, control, telecommunication, data, signal, etc.) have been adopted in the ASTRI Mini-Array. The same properties are exhibited by any cable routing means (e.g. ducts) made of non-metallic materials.

The Neutral and Protective Earth (PE) conductors have the same section of the relevant phase conductor.

Shielded cables for power and communication purposes must be used. The shielded cables, where possible, will be bonded at each end with 360° iris connection, avoiding “pig tail” connection. Whenever possible, power and signal wires will be routed separately avoiding ground loops; where routed together, the minimum insulation voltage of the cables shall not be lower than the maximum nominal voltage of the circuits involved.

6.2.6. Safety ground

Starting from the safety ground connections (PE), a TN-S system has been considered. For this kind of connection each device on "field" does have its own PE conductor connected to the PE bar of the relevant cabinet. The two PE bars of the cabinets +Telescope Power Cabinet (TPC) and +Telescope Control Cabinet (TCC) are at the same earth potential thanks to the presence of the PE conductors connecting the cabinets themselves (additionally, since the telescope is almost completely metallic, an highly improved equipotential bonding between all the metallic devices and parts of the telescope is guaranteed).

From the PE bar of cabinets, the connections proceed down till the equipotential bar inside the base where also the PE (referred to the site ground potential) coming from the star-center of the power transformer is connected.

6.2.7. Functional grounding

The functional grounds of equipment (namely chassis, analog, digital, shields, PE and equipotential grounds) can use the single point grounding if the frequencies inside or between equipment are relatively low.

In case of high frequencies, the best configuration will be the multipoint grounding where all the above-mentioned grounds are connected to an equipotential plane which is connected at the end to the ground earth.

Inside the cabinets the different grounds are, as much as possible, divided in different copper bars and then connected in a tree fashion to the main bars.

6.3. Electrical cabinets design

The design of the electrical cabinets follows the requirements and the constraints imposed by AD1.

The Telescope will mount two thermally controlled cabinets where all the necessary electrical and electronic components will be installed.

The first one is called Telescope Power Cabinet (TPC) and consists of:

- the major drive electronics (AZ and EL main axis);
- the high-power supply distribution.

The second one is called Telescope Control Cabinet (TCC) and consists of:

- all the electronic hardware in charge to control and monitor the telescope.
- the hardware in charge to power some specific equipment and the servo minor drives (M2 Active mirrors);
- the hardware in charge of the data/timing/communication.

The two cabinets have a protection level IP65 (IP54 installing the fans and their external covers) and they are especially suitable for outdoor application; in particular the main characteristics, which allow the cabinets to withstand in outdoor environments, are:

- presence of a sloping roof, to avoid water and snow accumulation.

- Monoblock rigid body.
- high mechanical endurance.
- high protection level (guaranteed over time, especially for the sealing, even in case of low environmental temperature and UV radiation presence).

6.3.1. Thermal design of cabinets

To thermally control the cabinets a system consisting in heating resistors (installed inside the cabinets) and fans (mounted on cabinets frontal door) is foreseen.

Starting from the heat dissipation of each single component installed inside the cabinets, the dimensioning of the cabinet resistors and fans has been performed to maintain the internal temperature inside the range 0°C - +35°C for every environmental condition (as reported in the paragraph 3.1). The control (switch on-off) command is given by dedicated thermostats inside the cabinets.

For the components for which the heat dissipation data was not available, a very conservative heat dissipation equals to 30% of the relevant power absorption has been considered.

Heating resistors dimensioning

For the heating resistors dimensioning two methods have been followed:

a. use of a software developed by Stego company (https://www.stego.it/home/);

b. calculation of the heat needed to increase the cabinet temperature to allow the correct operation of the equipment and devices installed inside it.

The starting hypothesis used for these two methods are:

i. external environmental temperature: -5°C;

ii. temperature inside the cabinet: +1°C;

iii. ground-mounted cabinet.

iv. forced convection air external to the cabinet.

v. natural convection air inside the cabinet.

vi. no heat dissipation of the equipment inside the cabinet (most conservative case).

To be highlighted that, the internal temperature (point ii) has been fixed at +1°C to consider the thermostat accuracy of +/-1°C; in this way we are sure that, in any climatic condition, the minimum temperature inside the cabinet does not go under 0°C.

For what concern the point (iii), we considered a higher number of cabinet surfaces which transfer heat to the external environment.

For the method (b.) the following heat flows have been computed:

- Convective heat transfer between inside and outside of the cabinet → the used formula is:

$$Q_{tras} = K \cdot S \cdot \Delta T$$

where:

K is the heat transfer convection coefficient [W/m^{2}K], S is the surface involved in the heat transfer [m^2],

ΔT is the temperature difference between inside and outside [K].

From the calculation it results Q_{tras} = 84 W

- Radiative Heat transfer between cabinet surface and sky → the used formula is:

$$Q_{sky} = S \bullet \varepsilon \bullet \sigma \bullet (T^4_{sup} - T^4_{sky})$$

where:

S is the surface involved in the heat transfer [m^2],

ε is the emissivity factor,

σ is the Stefan-Boltzmann constant [W/m^2K^4],

T_{sup} is the surface external temperature of the cabinet [K],

T_{sky} is the sky temperature [K].

Calculating T_{sky} with Walton algorithm (-23.3°C) and the surface temperature of the cabinet (-5.9°C), it results Q_{sky} = 77 W.

Therefore, the heating resistors, to be installed inside the cabinet, must produce at least 84 + 77 = 161 W of heat.

This calculation is compatible with the results obtained by the software (point a)); in this case it results a needed power of 322 W.

Therefore, considering the worst case obtained with the two methods, 2 heating resistors (200 W + 200 W) for each cabinet will be installed. The resistors are equipped with PTC-type heating elements which stabilize the surface temperature (for example at +75°C for an ambient temperature of -5°C), avoiding potentially dangerous situation due to overheating.

Furthermore, inside the cabinets, to constantly monitor the internal temperature and eventually warn in time the operator about any anomalous situation, some temperature sensors connected to the telescope control system, are installed.

Finally, it must be underlined that also an air humidity control is implemented inside the cabinet; in particular, to avoid problem of condensation, the use of a dedicated heating resistor (200W), commanded by one hygrostat has been foreseen.

This hygrostat will be set to 60% (relative humidity), therefore the heating resistor will be switched on in case this value would be exceeded to decrease the relative humidity value.

<u>Fans dimensioning</u>

For the fans dimensioning two methods have been followed:

a) use of a software developed by Stego company;

b) calculation of the external air flow rate needed to keep low the temperature inside the cabinet for the correct operation of the equipment.

The starting hypothesis used for these two methods are:

i. external environmental temperature: +25°C;

ii. temperature inside the cabinet: +39°C;

iii. ground-mounted cabinet;

iv. forced convection air external to the cabinet;

v. natural convection air inside the cabinet;

vi. maximum heat dissipation of the equipment inside the cabinet (1595 W for +HPC and 715 W for +LPC).

To be highlighted that, the internal temperature (point ii) has been fixed at +39°C to consider the thermostat accuracy of +/-1°C; in this way we are sure that, in any climatic condition, the maximum temperature inside the cabinet does not go over +40°C.

For the method b), since the heat transfer with the external environmental, causes a thermal load reduction inside the cabinet, this was not considered in the calculation (conservative assumption).

Additionally, during the day, the solar radiation contribution has been considered; to do this the method described in the standard UNI EN ISO 13970 has been adopted. This method considers the solar flux as the product of three factors:

- I, monthly mean solar radiation for vertical surfaces (from UNI10349);
- Also, sun capture area;
- F, shading reduction factor.

For the solar radiation, it has been considered 1200 W/m2 as the standard value for maximum solar heat flux, with the cabinet surfaces exposed to east/west and north (direction of contemporaneous maximum solar radiation) and a solar absorbance of 0,2 (steel light green colour);

- 240 W/m2 for the surfaces exposed to east/west and north

It has been considered that two sides of the cabinet are exposed to the solar radiation, one completely (F=1, A=1.2 m2) and the other one partially (F=0.5, A=1.4 m2).

The sun capture area has been calculated with the formula:

$U = 1/ (1/\alpha_i + s/\lambda + 1/\alpha_e)$

where:

- α_i = 3 W/m2K (natural convection, 2150m altitude)
- α_e= 15 W/m2K
- $s_{cabinet}$ = 3mm
- λ_{steel} = 54 W/mK

The maximum contribution of the solar radiation to the heat generation is 27 W.

Now, considering the global thermal loads Q to be dissipated by the cabinets (sum of the heat dissipated by the internal equipment and the solar radiation contribution), the air flow rate has been determined by the formula:

$m = Q / (cp \ \Delta T)$

where:

- cp is the air specific heat [J/KgK],
- ΔT is the temperature difference between inside and outside [°C].

Note: An air density of 0,90 kg/m^3 (at 2150m, @25°C) has been considered.

The computed air flow rates are:

- m(+HPC) = 460 m^3/h;
- m(+LPC) = 210 m^3/h;

For what concern the software results (point a)) the following air flow rates have been obtained:

- m(+HPC) = 480 m^3/h;
- m(+LPC) = 215 m^3/h.

Therefore, considering the worst case obtained with the two methods, the following fans have been chosen:

- TPC: RITTAL fan with 900 m^3/h nominal (the real flow rate becomes 820 m^3/h with filters both in the fan and in the two grilles foreseen);
- TCC: RITTAL fan with 550 m^3/h nominal (the real flow rate becomes 440m3/h with filters both in the fan and in the grille foreseen).

Finally, it has to be underlined that the use of RITTAL solution (fan + filter + external cover) guarantees a level of protection IP 56 which is suitable for outdoor application (and compatible with the protection level of the cabinet, i.e. IP 65); in this case the global protection level becomes IP55.

6.4. Cabling

In this section of the document a general description of the electrical installations (cabling and routing) on the SST Telescope is presented. For any specific and detailed information refer to the drawings listed in the applicable documents.

From the Telescope Interface Infrastructure (Interface Point) the power and communication incoming lines enter the telescope from the base, pass through the azimuth cable drape up to the two electrical cabinets installed on the fork of the Telescope. From here the routing of the cables to the final loads on board of the telescope are described in the following paragraphs.

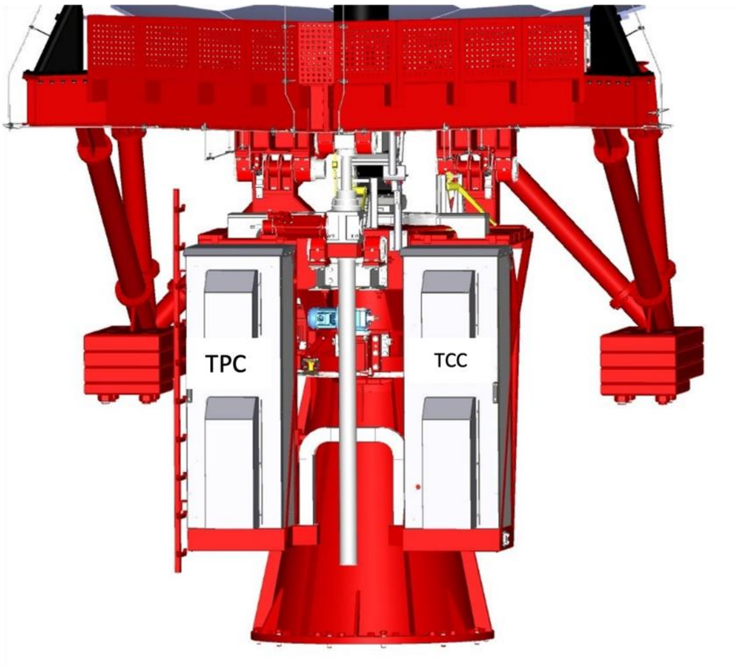


Figure 6-6: Electrical cabinets

6.4.1. Base cabling

As previously described the Telescope has four electrical interfaces incoming from the infrastructure that are:

- 400 V (3P+N, 50 Hz) for Normal power;
- 230 V (P+N, 50 Hz) for UPS power;
- fiber optic for control, safety, timing and data;
- Ethernet connection for diagnostic in local mode.

These cables are then routed through the AZ cable drape, considering that an appropriate spare length must be left, in order to allow the cables to follow the movement of the axis in all its rotational range without damages.

To avoid potential damages due to the cables weight, appropriate strain relief systems have been foreseen (i.e., clamp clips system mounted on DIN rail base and other common off the shelf solutions).

Figure 6-7: Applicative example of a clamp clips system

In the telescope base (fixed part) are present the following devices/equipment:

- AZ encoder heads;
- Base door limit switch.

6.4.2. AZ Fork cabling

At the top interface of the AZ cable drape there is a box (named "AZ fork cable box"), which is the interface with the cable ducts system. This one allows the cables distribution towards the cabinets (+TPC and +TCC) and towards the EL cable wraps.

Furthermore, the cables, which shall be interfaced with the various devices/equipment installed on this area, exit from these cable ducts by means of dedicated cable glands.

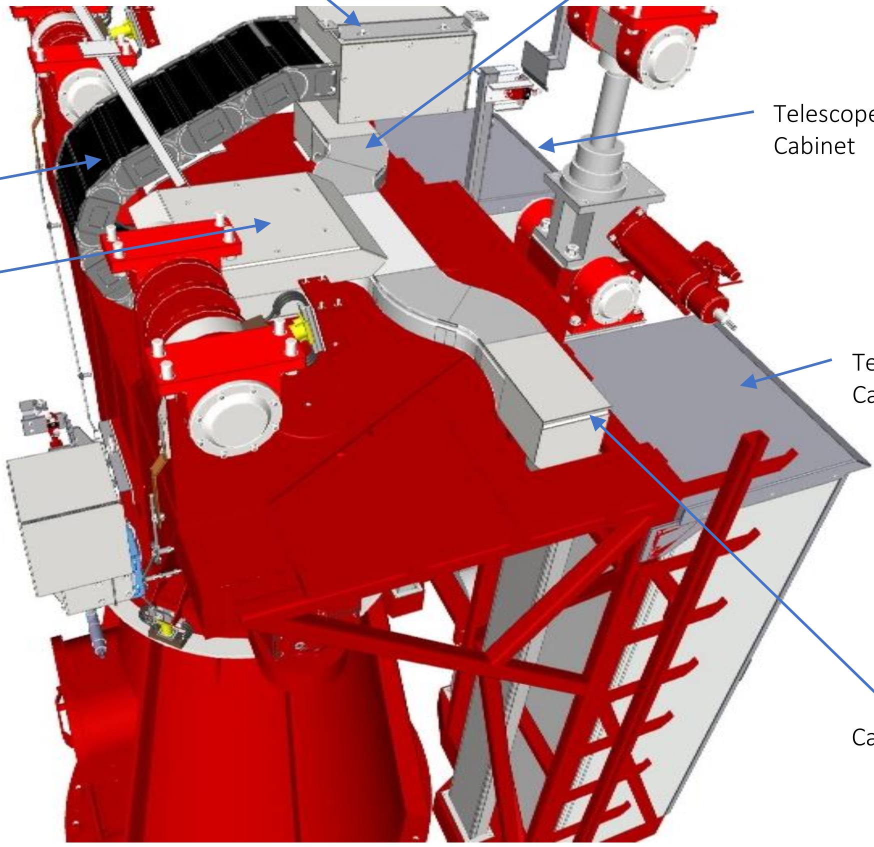


Figure 6-8: Cable ducts system (in grey, with cabinets)

In the telescope fork (moving part) are present the following devices/equipment:

- EL encoder (the relevant cables exit from the EL cable wrap);
- AZ and EL rotational limit switches;
- AZ and EL rotational motors;
- AZ and EL stow pins;
- Base light.

6.5. Mast and M2 support

From the EL cable wrap, by means of opportune cable conduits (external to the masts), the cables are distributed along the mast path.

The central masts are used to distribute the cables towards the Cherenkov Camera and all its relevant equipment.

Another set of cable conduits continues along the masts, till reaching the equipment foreseen in the M2 area.

In this area, there are:

- M2 actuators (with the relevant M2 box used as electrical interface and disconnection point);
- M2 actuators encoders;

- PMC equipment.

Figure 6-9: M2 Junction Box

6.6. Telescope automation and safety

According to the technical literature for automation of machinery, a system can be normally divided in three base functions (i.e., subsystems):

- Input;
- Logic;
- Output.

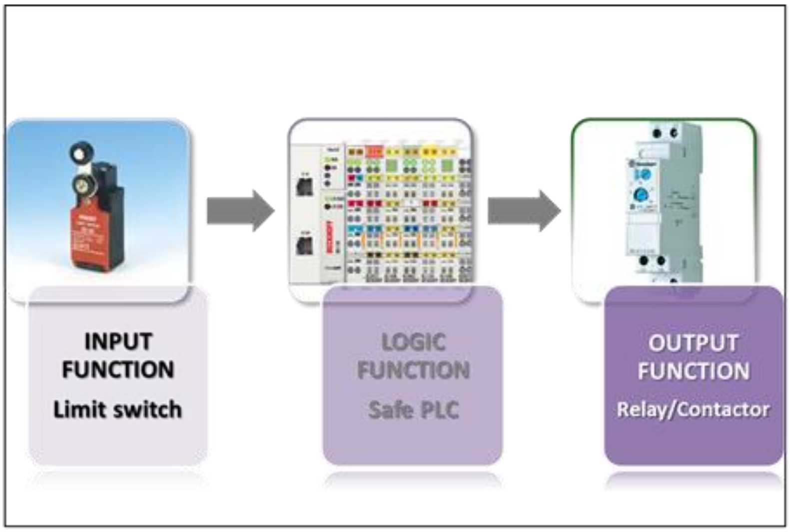


Figure 510: Functions of a safety system

- 31 inputs:

o AZYO, AZYOA → DIF Limit “Fork arm witness” (electro-mechanical switches): it gives the information if the rotation in AZ is CW or CCW.

o AZLCW0, AZLCCW0 → DI: AZ Pre-limit CW and CCW (inductive switches): when triggered, the system limits the speed to a tracking speed;

o AZLCW1, AZLCCW1 → DI: AZ Operational limit CW and CCW (electro-mechanical switches): when triggered, they block the movement to the same direction; only movements in the opposite direction are allowed;

o AZLCW2, AZLCCW2 → DIF: AZ Emergency limit CW and CCW (electro-mechanical switches): when triggered, the axis is blocked (STO function activated by the Safe PLC);

o ELPLOW, ELPHIGH → DI: EL Pre-limit “Low” and “High” (inductive switches): when triggered, the system limits the speed to a tracking speed;

o ELOLOW, ELOHIGH → DI: EL Operational limit “Low” and “High” (electro-mechanical switches): when triggered, they block the movement to the same direction; only movements in the opposite direction are allowed;

o ELELOW, ELEHIGH → DIF: EL Emergency limit “Low” and “High” (electro-mechanical switches): when triggered, the axis is blocked (STO function activated by the Safe PLC).

o AZSTOPRE → DI: Pre-limit for AZ stow pin (inductive switch): when triggered, the system limits the speed to a tracking speed. The trigger of this pre-limit is considered only if the “Stow procedure” is called, otherwise the pre-limit status is ignored by the system and produces no action;

o AZSTOIN, AZSTOEX → Position limit switches for AZ stow pin (electro-mechanical switches): when triggered, it means that the Stow pin is completely (respectively) inserted or retracted. Only in case the pin shaft is completely retracted the axis can be moved.

o ELSTOPRE → Pre-limit for EL stow pin (inductive switch): when triggered, the system limits the speed to a tracking speed. The trigger of this pre-limit is considered only if the “Stow procedure” is called, otherwise the pre-limit status is ignored by the system and produces no action;

o ELSTOIN, ELSTOEX → Position limit switches for EL stow pin (electro-mechanical switches): when triggered, it means that the Stow pin is completely (respectively) inserted or retracted. Only in case the pin shaft is completely retracted the axis can be moved;

o CABINETS DOOR → Limit switches for cabinet door monitoring (electro-mechanical switches): they are triggered in normal condition (cabinet door closed). When a cabinet door is open (+LPC or +HPC) the movement of the telescope axes are inhibited unless a software override command is run by the operator (for maintenance or test purposes).

o EMERGENCY STOPS → Red mushroom buttons manually engaged by the operator in case of emergency; when triggered, the movements of the telescope axes are inhibited. Three emergency push buttons are foreseen:

- In front of the +LPC door (for local operations, especially in case of maintenance or test)
- In the control room (for remote interventions)
- In the pendant station (directly connected to the telescope control system by mean of a dedicated plug next to the electrical cabinets).

o STOW BUTTON → The stow button is located on the pendant station (hand paddle). It's function is for a local operator to be able to locally park the telescope from any position with an automatic procedure.

o BASE DOOR → Limit switch for base door monitoring (electro-mechanical switch); when the base door is open (opening angle shall be higher than 5°) the movements of the telescope axes are inhibited;

o Cabinets MAIN DISCONNECTORS → Auxiliary contacts of the main disconnectors inside the electrical cabinets; these contacts give the information about the intervention (in case of fault or manual operation) of the Telescope main disconnectors;

o STO DRIVE FEEDBACK → Safety contact of the main drive system (AZ and EL), which trips when the motors have been safely blocked by the STO function calling from the Safe PLC (STO condition).

To be noted that, where applicable, the switches do have a positive action, that is they do have a contact structure which ensures the opening of even a welded NC contact. They are commonly indicated by this symbol: 

• 1 safe PLC:

One Beckhoff TwinSAFE PLC plus some other modules used for all fail-safe inputs and outputs. In case an emergency condition is detected (at the inputs) the TwinSAFE PLC brings its outputs to "0" and, thanks to some electromechanical relays, a safe stop (STO function) to the drive system is commanded.

Safe Torque Off according to IEC 61800-5-2 via disconnection of the safety-related 24 V supply.

If the STO function is activated, the frequency inverter no longer supplies power to the motor for generating torque. This safety function corresponds to a non-controlled stop according to EN 60204-1, stop category 0.

The safety-relevant 24 V power supply must be switched off by a suitable external safety controller or a suitable external safety relay.

The following figure applies to safe torque off STO:

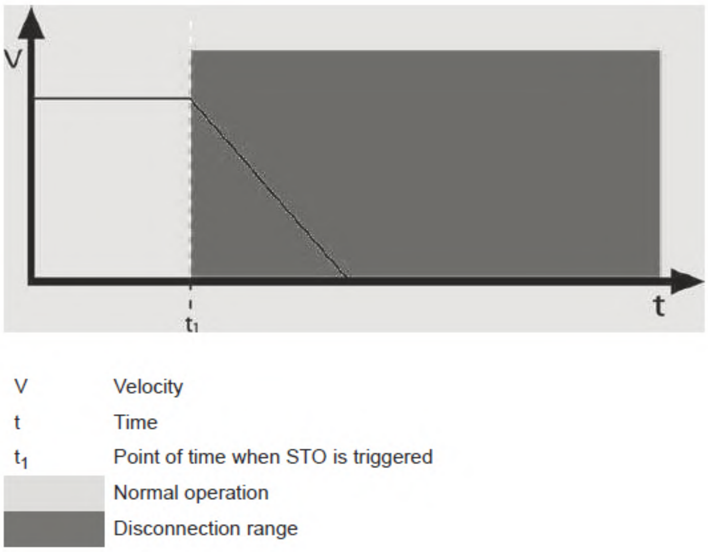


Figure 6-10: STO safety function

In order to perform this function, the procedure is the following:

- Recommendation: X10:1 and X10:x are disconnected at the same time, e. g. in case of an emergency stop.
- The 24 V safety input X7 is disconnected.
- The motor coasts to a halt, if no brake is activated.

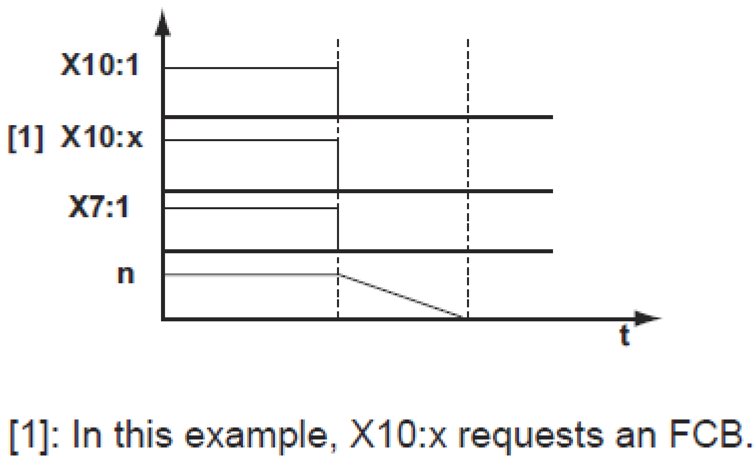


Figure 6-11: STO function – drive inputs status

- 2 outputs:

To implement the STO function above described it is necessary to use:

- safety output for commanding the STO function (i.e. the safe condition for which the motor cannot generate torque anymore): this is performed by two redundant time relays which act on the drive safety input X7:1.

6.7. Interface with the CTA-S site

The interface with the Electrical Power of the CTA South site is given in [AD2].

The power lines arrive to the telescope from a cable duct housed inside the foundation to the center of it, exiting inside the telescope Base.

A dedicated Box is present within the telescope base to interface the telescope with the site E-power distribution. Here the main circuit breaker is present, which connects and disconnects the telescope from the grid. On the outside of the box a power changeover switch is present to operate manually the circuit breaker.

On the outside of the telescope Base, it is also present a power socket to attach the 10-15kVA portable generator, which can power the whole telescope in case of emergency.

The communication connection point to the telescope array is also performed in another box within the telescope Base, containing a fiber optic and an Ethernet patch panel.

7. Telescope Protection System

7.1. Lightning Protection System

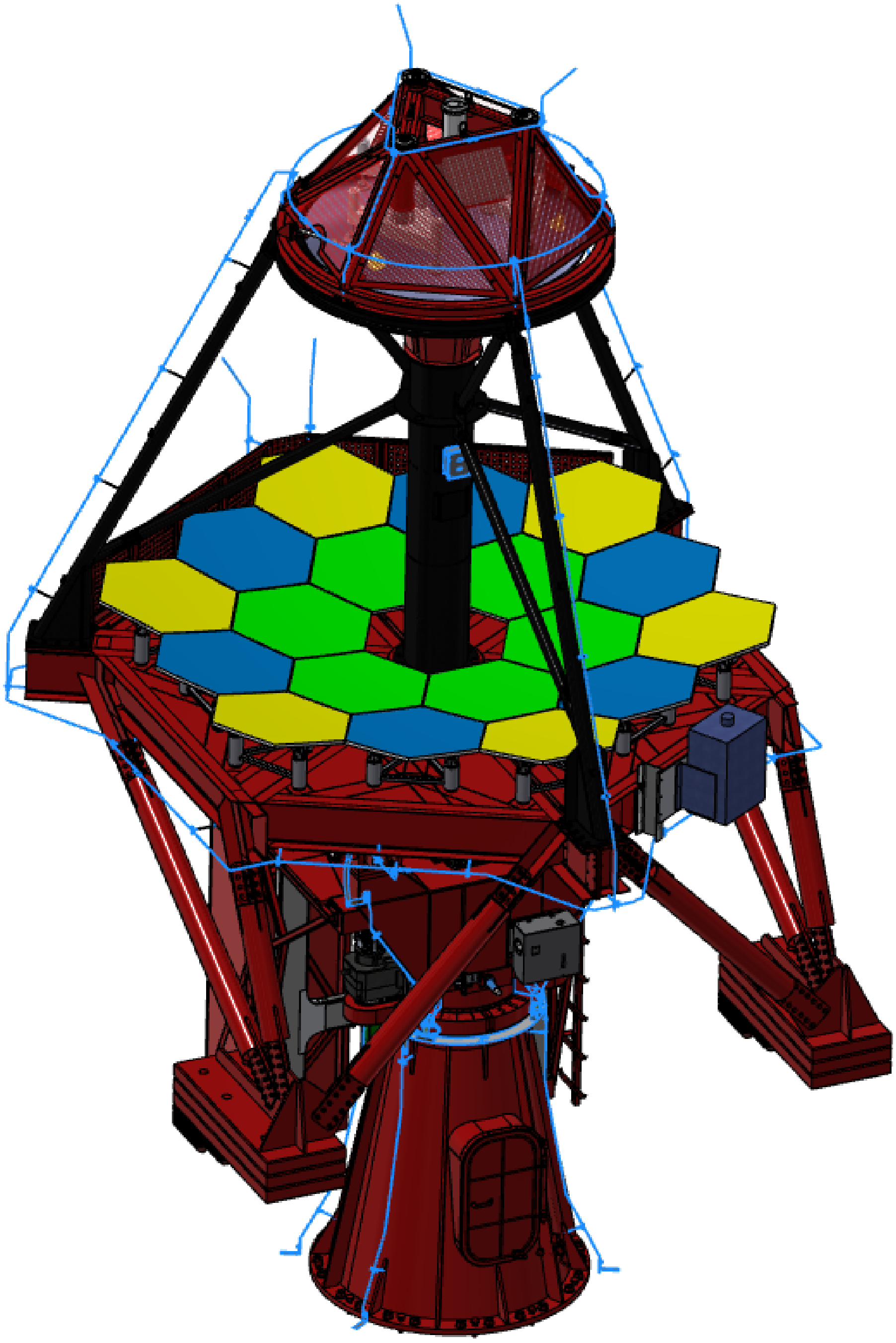


Figure 7-1: CAD model of ASTRI telescope, with LPS routing highlighted

7.1.1. Basis of LPS design

The design of the ASTRI telescope Lightning Protection System has been based on the internationally recognized standards released by the International Electrotechnical Commission (IEC), namely the IEC 62305 series, as listed in the next section.

7.1.1.1. Applicable standards

The regulations that have been applied to the design of the ASTRI LPS are the following:

- IEC 62305-1:2010 Protection against lightning. Part 1: General principles
- IEC 62305-2:2010 Protection against lightning. Part 2: Risk management
- IEC 62305-3:2010 Protection against lightning. Part 3: Physical damage to structures and life hazard
- IEC 62305-4:2010 Protection against lightning. Part 4: Electrical and electronic systems within structures

Contents of the IEC 62305 series are represented in the following graph, taken from IEC 62305-1:

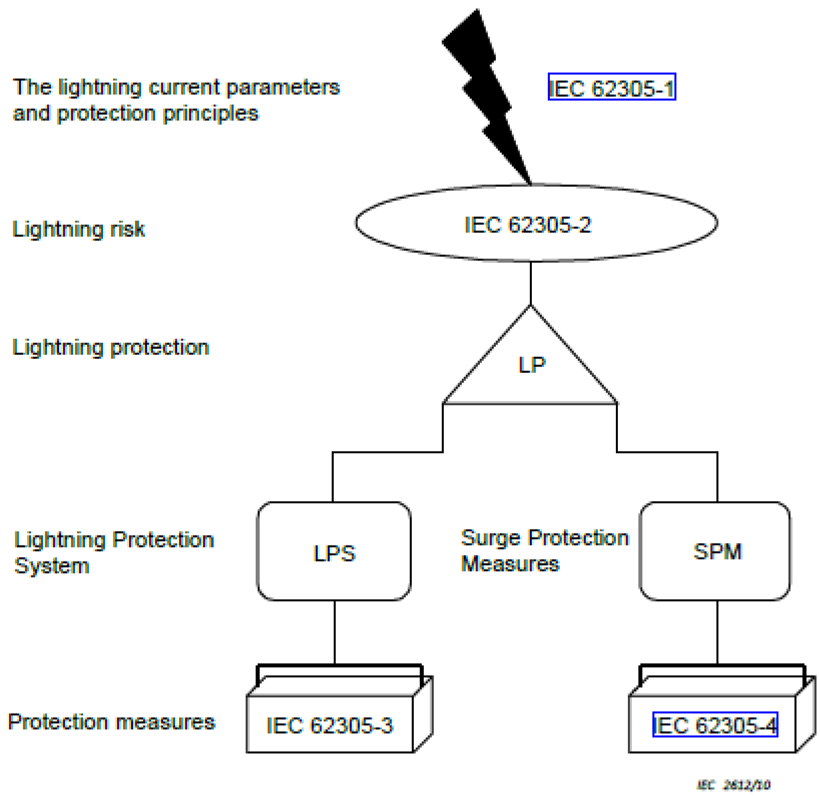


Figure 7-2: Connection Between the various parts of IEC62305.

7.1.2. Damage due to lightning

The damage that can be induced on structural and mechanical components by a lightning event (LEMP) is mainly constituted by the unbearable temperature rise caused by Joule heating effect. This can cause local “fusion welding” making the component useless. The most common example is a ball bearing with balls welded to the raceways due to the high local current density.

On the other hand, the damage that can be induced on electrical and electronical devices regards cable short-circuiting and burning of internal components.

A LEMP is characterized by a very high current spike for a very short duration, thus with a limited amount of released energy.

In the current design, steel air terminations feature a diameter larger than 4 mm to prevent hot spots. The minimum cross-sectional area of conductors and of bridging elements between movable parts is 50 mm2 so to give a low resistance path to the ground and to sustain a high peak current with low current density.

While the LEMP is discharging itself through the path identified by the conductors, a high short-term electromagnetic field is generated, leading to an induced surge current on cabling of electrical and electronical devices, which then damages (burns) the device interfaces. Surge protection devices are applied to protect this kind of equipment. For equipment that is not suitable for surge protection devices, equipotential connections are applied on the housing or casing.

7.1.3. Lightning protection levels

For the purposes of IEC 62305 and of the correct dimensioning of the LPS, four lightning protection levels (LPL) I to IV are introduced. For each LPL, a set of maximum and minimum lightning current parameters is fixed.

The LPL is usually selected because of a risk assessment, which is based on the estimated or measured annual frequencies of LEMPs, and on the consequences and type of losses due to lightning damage.

Since this risk assessment has not been performed for the case of the ASTRI Mini-Array, the highest protection level (I) has been assumed in the design.

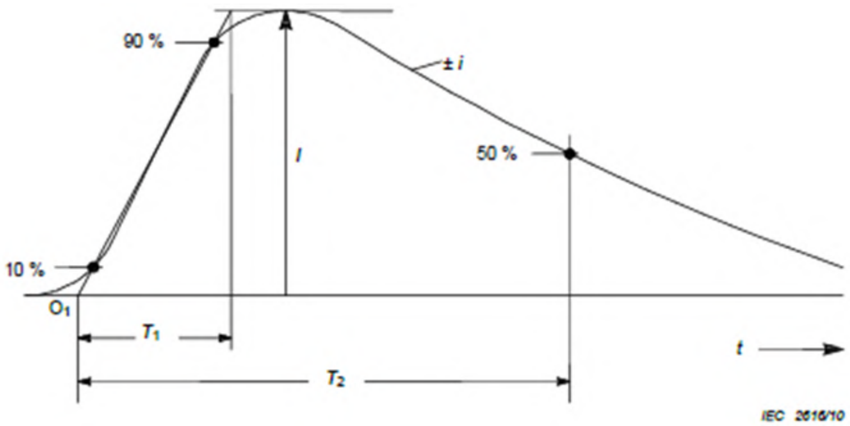
The parameters for the design of the SST telescope LPS in terms of peak current, charge, and durations, which are based on the selected LPL (I) and on the type of LEMP, are reported in the following table:

Current parameters		Symbol	Unit	LPL			
				I	II	III	IV
First positive short stroke	Peak current	I	kA	200	150	100	
	Charge	Q_{SHORT}	C	100	75	50	
	Specific energy	W/R	MJ/Ω	10	5,6	2,5	
	Time parameters	T_1/T_2	µs/µs	10 / 350			
First negative short stroke [a]	Peak current	I	kA	100	75	50	
	Average steepness	di/dt	kA/µs	100	75	50	
	Time parameters	T_1/T_2	µs/µs	1 / 200			
Subsequent short stroke	Peak current	I	kA	50	37,5	25	
	Average steepness	di/dt	kA/µs	200	150	100	
	Time parameters	T_1/T_2	µs/µs	0,25 / 100			
Long stroke	Charge	Q_{LONG}	C	200	150	100	
	Time parameter	T_{LONG}	s	0,5			
Flash	Charge	Q_{FLASH}	C	300	225	150	

[a] First negative stroke concerns only calculations and not testing.

Figure 7-3: Maximum Values of lightening parameters according to LPL.

Shorts strokes are defined by a duration less than 2 ms, whereas long strokes are defined by a duration longer than 2 ms. Positive/negative refers to the polarity of the stroke. Time parameters are identified as per the following figure:



Key

O_1 virtual origin

I peak current

T_1 front time

T_2 time to half value (typically T_2 < 2 ms)

Figure 7-4: Definitions of impulse current parameters according to IEC 62475.

The most important design parameter for the correct sizing of the LPS is the Peak current value of the first positive short stroke, which for LPL I corresponds to 200 kA. The maximum values of lightning current parameters related to LPL I are expected to be exceeded with a probability lesser than 1%, so they are almost deterministic.

This parameter is used to design lightning protection components (e.g., cross-section of conductors, thickness of metal sheets, current capability of SPDs, separation distance against dangerous sparking).

In addition, the minimum value of lightning current amplitude is used to derive the rolling sphere radius, so to define the lightning protection zone LPZ 0B, i.e., the area that cannot be reached by a direct strike. The rolling sphere radius is in turn used to define the positioning of the air-termination system. Such values for the different LPL are given in the following table:

Table 4 – Minimum values of lightning parameters and related rolling sphere radius corresponding to LPL

Interception criteria			LPL			
	Symbol	Unit	I	II	III	IV
Minimum peak current	*I*	kA	3	5	10	16
Rolling sphere radius	*r*	m	20	30	45	60

7.1.4. Lightning Protection Zones

Lightning protection zones are defined in IEC 62305-1 based on the implemented protection measures:

- LPZ 0A zone where the threat is due to the direct lightning flash and the full lightning electromagnetic field. The internal systems may be subjected to full or partial lightning surge current;
- LPZ 0B zone protected against direct lightning flashes but where the threat is the full lightning electromagnetic field. The internal systems may be subjected to partial lightning surge currents;
- LPZ 1 zone where the surge current is limited by current sharing and by isolating interfaces and/or SPDs at the boundary. Spatial shielding may attenuate the lightning electromagnetic field;
- LPZ 2, ..., n zone where the surge current may be further limited by current sharing and by isolating interfaces and/or additional SPDs at the boundary. Additional spatial shielding may be used to further attenuate the lightning electromagnetic field.

The higher the number of the protection zone, the lower the EM environment parameters. Threats to which components inside each LPZ are exposed are identified in the following table:

LPZ	Exposure Threats		
	Direct strike	Lightning Current or Induced Current	Electromagnetic Field
LPZ 0_A	Y	Full	Full
LPZ 0_B	N	Partial	Full
LPZ 1	N	Limited	Partial

LPZ	Exposure Threats		
LPZ 2	N	Reduced below LPZ 1	Reduced below LPZ 1

The following drawing identifies the LPZ of SST telescope:

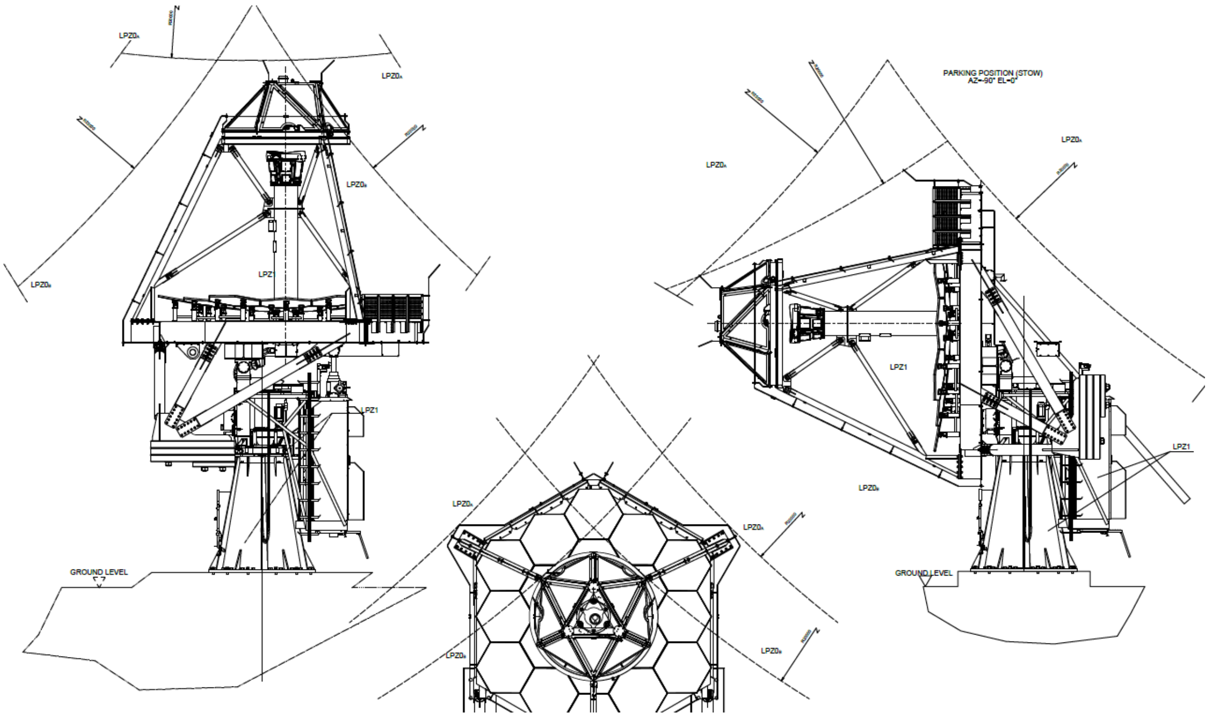


Figure 6-4: SST LPZ

7.1.5. External Lightning Protection System

An overview of the external LPS of SST telescope is given in the following figure:

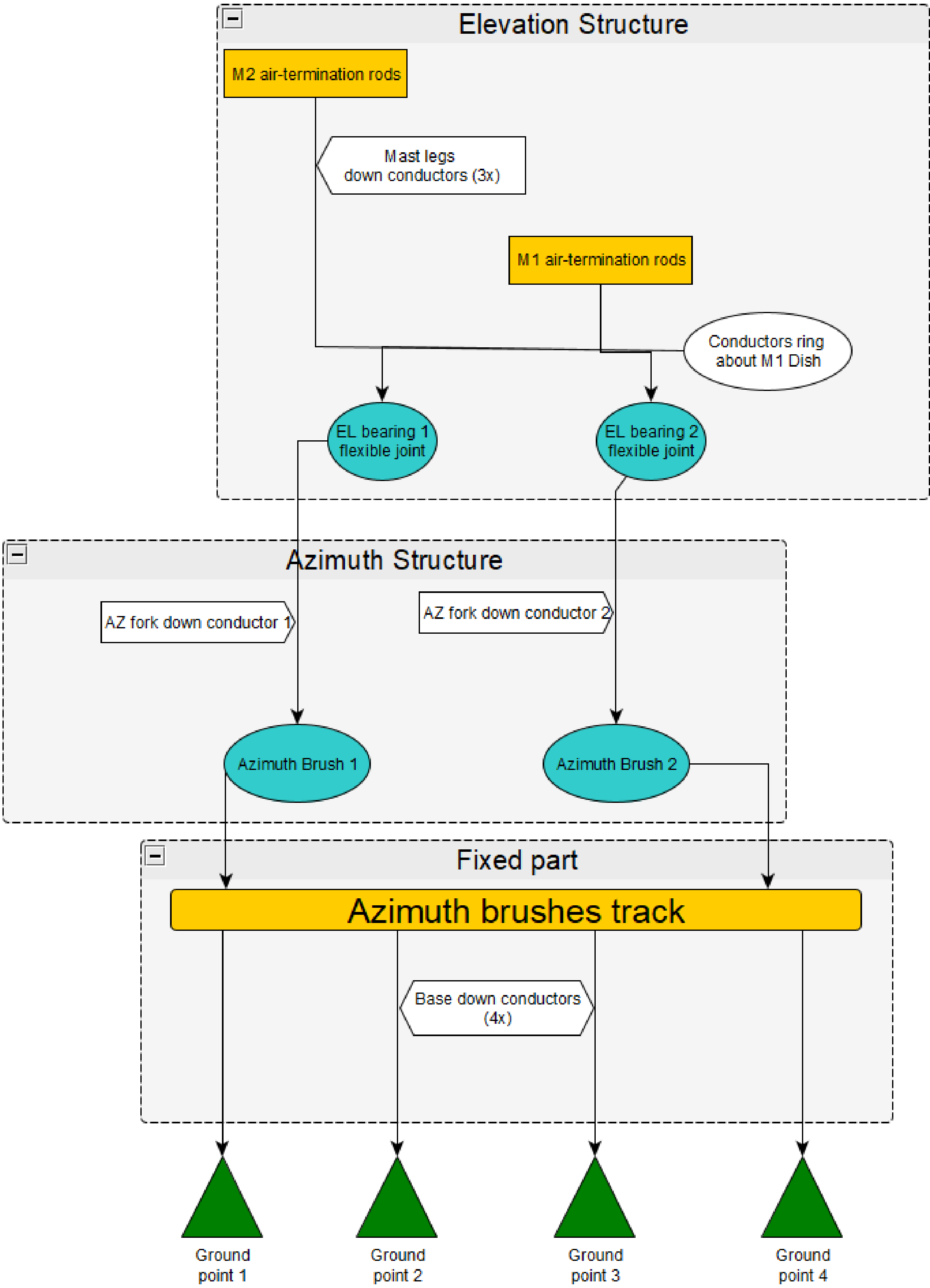


Figure 7-5: Diagram of SST external LPS

Each part of the system is then described in the next sections.

7.1.5.1. Air-termination System

The air-termination system is composed by rods located on the top of the M2 support structure and on the upper side of the M1 Dish (considering the telescope in the parking position).

The location of the air-termination system has been determined by means of the rolling spheres drawing, considering spheres of 20 m radius.

Three air-termination rods are located on the top of the M2 support structure, which is the highest point of the telescope when pointing at zenith. The rods are made of stainless steel and feature a diameter of 8 mm and length of about 500 mm. They are shown in the following figure:

Figure 7-6: M2 Support structure air-termination rods

In addition, two air-termination rods are located on the top of the M1 Dish, which is the highest point of the telescope when pointing at horizon. The rods are made of stainless steel and feature a diameter of 8 mm and length of about 500 mm. They are shown in the following figure:

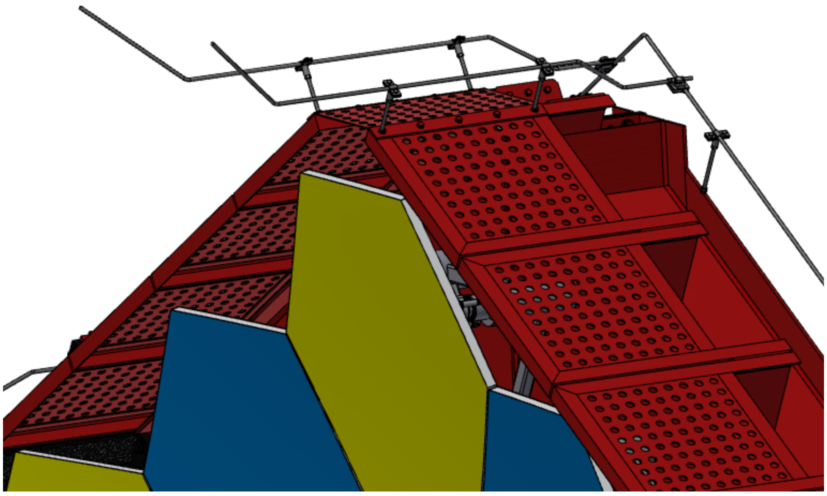


Figure 7-7: M1 Dish air-termination rods

7.1.6. Down-conductor system

An external down-conductor system envelops the whole telescope structure to form a direct, low-resistance path to grounding points.

All down-conductors are stainless steel solid round wire of 8 mm diameter, so with a cross-sectional area of 50 mm2. This is in accordance with IEC 62305-3 for material and minimum section of down-conductors:

Table 7 – Material, configuration and minimum cross-sectional area of air-termination conductors, air-termination rods, earth lead-in rods[e] and down-conductors[a]

Material	Configuration	Cross-sectional area mm^2
Copper, Tin plated copper	Solid tape	50
	Solid round[b]	50
	Stranded[b]	50
	Solid round[c]	176
Aluminium	Solid tape	70
	Solid round	50
	Stranded	50
Aluminium alloy	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round[c]	176
Copper coated aluminium alloy	Solid round	50
Hot dipped galvanized steel	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round[c]	176
Copper coated steel	Solid round	50
	Solid tape	50
Stainless steel	~~Solid tape[d]~~	~~50~~
	~~Solid round~~	~~50~~
	Stranded	70
	Solid round[c]	176
Copper clad steel	Solid round c	176

NOTE In France stranded conductors cannot be used as down-conductors.

[a] Mechanical and electrical characteristics, as well as corrosion resistance properties, shall meet the requirements of IEC 62561 (all parts).

[b] 50 mm^2 (8 mm diameter) may be reduced to 28 mm^2 (6mm diameter) in certain applications where mechanical strength is not an essential requirement. Consideration should in this case, be given to reducing the spacing between the fasteners.

[c] Applicable for air-termination rods and earth lead-in rods. For air-termination rods where mechanical stress such as wind loading is not critical, a 9,5 mm diameter, 1 m long rod may be used.

[d] If thermal and mechanical considerations are important then these values should be increased to 75 mm^2.

[e] If the earth lead-in rod is partially installed in soil it has to fulfill the requirements of Table 8.

[f] If an insulating down-conductor fulfils the requirements of IEC TS 62561-8, the cross-sectional area can be reduced to the tested cross section area.

7.1.6.1. Elevation structure

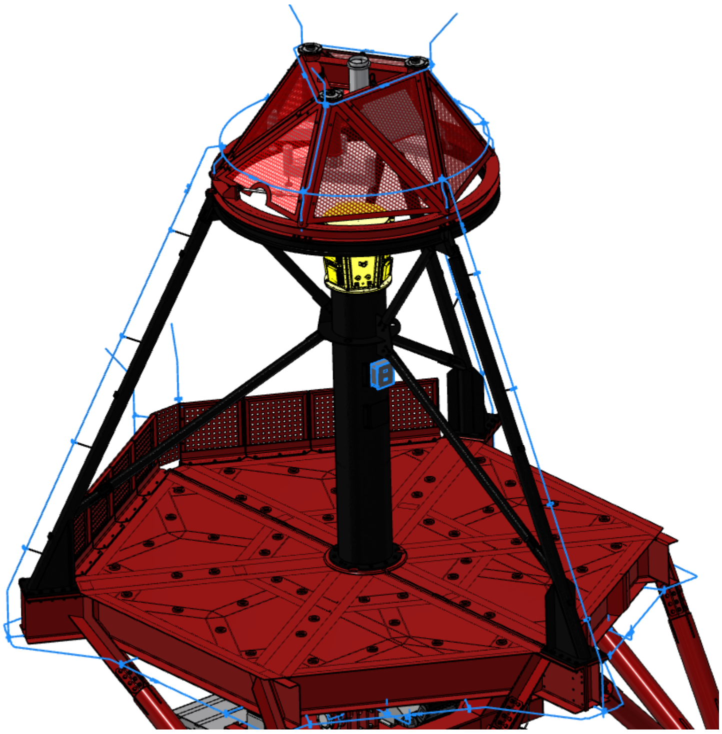


Figure 7-8: Elevation structure down conductors highlighted.

The down-conductor system of the Elevation structures makes first a ring about the M2 Support Structure, then descends along the three Mast legs, and forms again a ring about the M1 Dish.

Down-conductors reach then the location of the two elevation bearings. At those point, a flexible joint that accommodates the 0-90deg Elevation rotation is present.

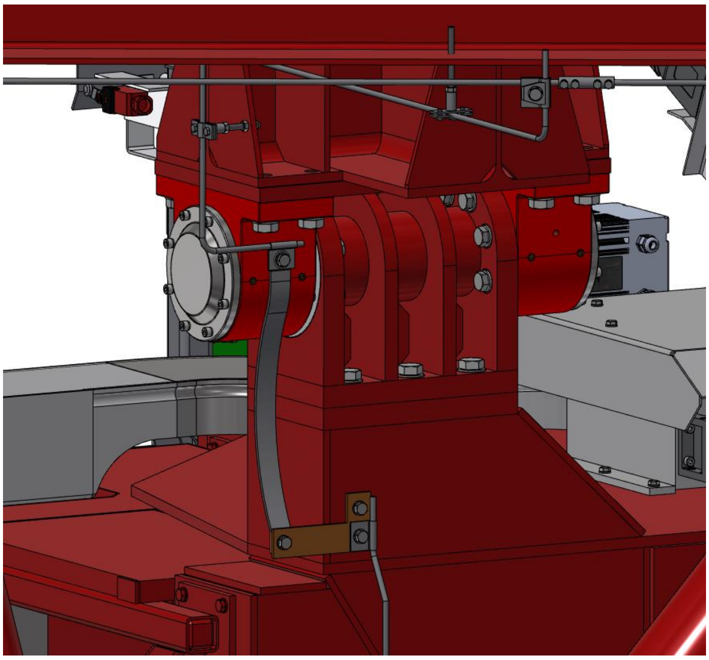


Figure 7-9: Flexible Elevation bearings joint

This is composed by an insulated copper braided tape featuring 75 mm2 cross-sectional area.

Figure 7-10: Insulated copper braided tape (right); example without insulation (left)

7.1.6.2. Azimuth structure

From the two elevation bearings two down-conductors reach respectively the two azimuth brushes, shown in the following picture:

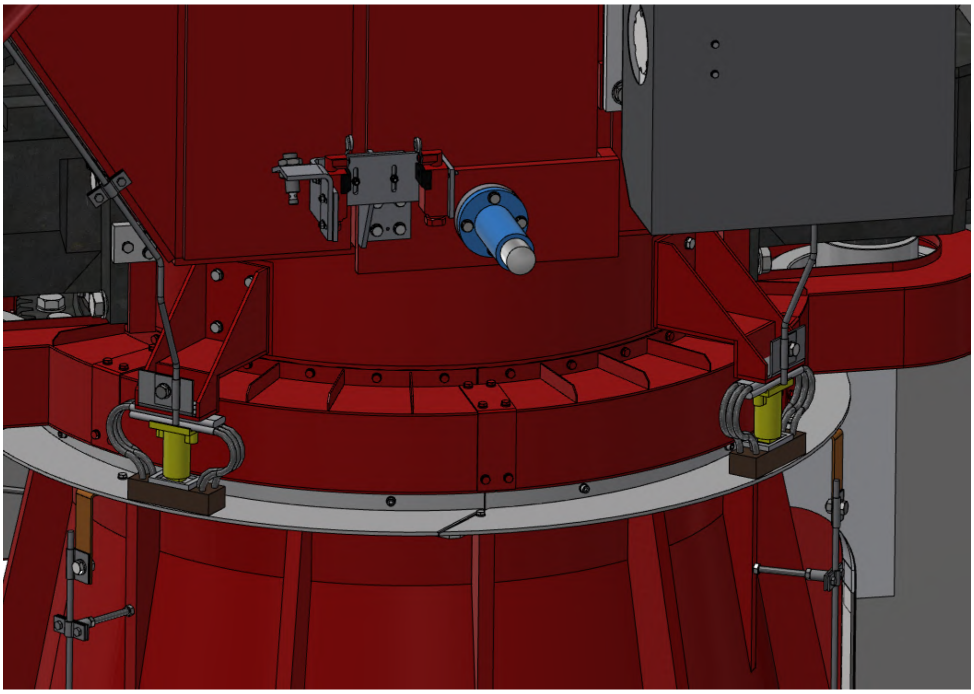


Figure 7-11: Azimuth brushes and track

Brushes are composed of a metal-graphite compound pad, which is pushed against a steel track by the force of a pre-compressed spring. In this way continuous rotation about the azimuth axis is allowed while assuring electrical conductivity.

To the bottom surface of the brushes track, in four equally spaced points, down conductors are connected, which transmit the strike along the telescope Base to four grounding points, as shown in the next images.

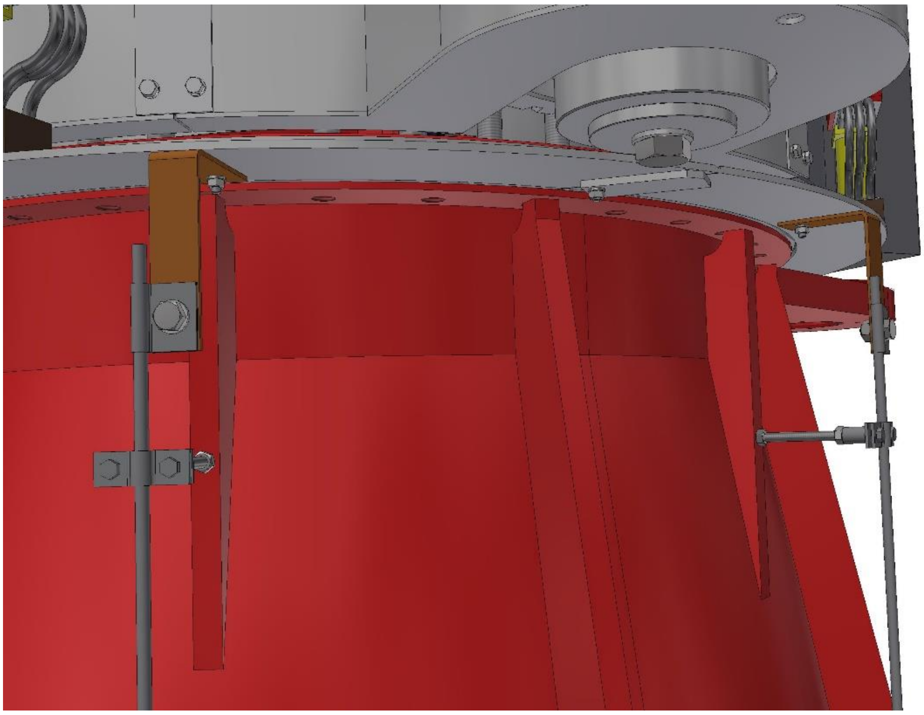


Figure 7-12: Base down conductors connected to the azimuth brushes track

Figure 7-13: Base down conductors

In the images of the 3D model, base down-conductors are connected to anchor bolts, whereas they will be connected to ground rods, which are separate from anchor bolts.

7.2. Surge Protection Devices

The SPDs have been chosen considering the requirements listed in [AD1] and the various withstand levels of the equipment installed in the Telescope.

As general rule, the internal systems are protected if:

- their impulse withstand voltage Uw is greater than or equal to the voltage protection level Up of the SPD plus a margin necessary to take into account the voltage drop of the connecting conductors;
- they are energy coordinated with the upstream SPD.

It has to be underlined that for devices (like the Camera and PMC) there is not any information about their withstand voltage; therefore a conservative design has been done, foreseeing SPDs next to the devices themselves, for all the lines (power and signal) connected to them. It has been foreseen the following:

Located inside "Base SPD junction boxes":

- SPDs (phases + neutral) as surge arrestors for the incoming power lines;
- SPD for the cable of the emergency stop push button inside the control room;

Located inside +HPC:

- SPD for overvoltage suppression on the main power lines.

Located inside "Camera SPD junction boxes":

- SPDs for 24Vdc lines for Camera and Camera Thermal Control;
- SPDs for Ethernet lines for Camera;

Located inside "M2 junction box":

- SPDs for 24Vdc and 5Vdc lines for PMC;
- SPDs for Ethernet lines for PMC.

All the SPDs are coordinated among them.

Note: Although the above-described design represents the best and the most conservative possible choice, the lack of information about some devices anyway introduce a minimum level of uncertainty regarding the protection of the devices themselves that necessarily must be accepted at the current stage.

End of the document