ASTRI Mini-Array
Telescope Design Report

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DOCUMENT HISTORY		
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1 Introduction

The **ASTRI** (Astrofisica con Specchi a Tecnologia Replicante Italiana) **Mini-Array** is an INAF project aimed consisting of nine identical dual-mirrors Cherenkov gamma-ray telescopes that will be installed at the site of the Teide Observatory in Tenerife (Spain) to study astronomical sources emitting at very high-energy in the TeV spectral band.

Besides the gamma-ray scientific program, the ASTRI Mini-Array will perform optical intensity interferometric observations of bright stars.

1.1 Purpose

This document defines the architecture of the single ASTRI Telescope, including implementation details, and the subsystem decomposition.

1.2 Scope

This document contains a full description of the ASTRI Telescope Architecture, including the lessons learnt during construction, assembly, integration and operation of ASTRI-Horn at the INAF Astronomical Station of Serra La Nave on Mount Etna.

1.3 Definitions and Conventions

1.3.1 Abbreviations and acronyms

The following abbreviations and acronyms are used in this document:

AIT	Assembly Integration and Testing
AIV	Assembly Integration and Verification
ASIC	Application Specific Integrated Circuits
ASTRI	Astrofisica con Specchi a Tecnologia Replicante Italiana
AR	Camera Acceptance Review
ATRR	Acceptance Test Readiness Review
BEE	Back End Electronics
CDR	Critical Design Review
CFI	Customer Furnished Item
CITIROC	Cherenkov Image Telescope Integrated Read Out Chip
COTS	Commercial Off The Shelf
DAQ	Data Acquisition
EMC	Electro Magnetic Compatibility
FEE	Front End Electronics
FEM	Finite Element Analysis
FPGA	Field Programmable Gate Array
FMECA	Failure Mode Effects and Criticality Analysis
HW	Hardware

IAC	Instituto de Astrofísica de Canarias
IIM	Intensity Interferometry Module
INAF	Istituto Nazionale di Astrofisica
IPC	Industrial Computer
ITW	Integration Time Window
KOM	Kick Off Meeting
LLI	Long Lead Item
MIUR	Ministero dell’Istruzione, dell’Università e della Ricerca
MSA	Mechanical Structure Assembly
OPC-UA	Open Platform Communications Unified Architecture
PA	Product Assurance
PBS	Product Breakdown Structure
PCB	Printed Circuit Board
PDM	Photon Detection Module
PDR	Preliminary Design Review
PR	Cameras Production Review
OPC-UA	Open Platform Communications - Unified Architecture
QA	Quality Assurance
QR	Qualification Review
QTRR	Qualification Test Readiness Review
RAM	Reliability, Availability and Maintainability
RR	Camera Requirements Review
SCADA	Supervisory Control And Data Acquisition system
SE	System Engineering
SiPM	Silicon Photo-Multiplier
SLN	Serra La Nave
SMM	Structural Mathematical Model
SOW	Statement of Work
SU	Safety Unit
SW	Software
TCS	Telescope Control Software
TE	Test Equipment
TMM	Thermal Mathematical Model
UPS	Uninterruptible Power Supply

VCD	Verification Control Document
VDB	Voltage Distribution Box
VHE	Very High Energy
WR	White Rabbit

1.3.2 Definitions

SCADA (Supervisory Control and Data Acquisition): The software system controlling all the operations carried out at the ASTRI Mini-Array site at Teide. SCADA is the central control system which interfaces and communicates with all systems (e.g. Telescopes, Environmental Monitoring system, etc.) installed at the ASTRI Mini-Array site.

Telescope: A system composed of an Instrument (Cherenkov Camera and Intensity interferometry Unit) and Telescope Structure that is used to collect sky images due to astronomical objects or Cherenkov light from Air Showers.

Telescope Optical axis: In an ideal telescope the optical axis (a telescope without mechanical defects, misalignments, etc.), is the axis perpendicular to the centre of curvature of the telescope focal plane.

Telescope Pointing: the selection of the two mechanical angles (for the ASTRI Telescope azimuth, *Az* and elevation, *El*) that bring the telescope optical axis into alignment with a specified celestial target direction specified in Right Ascension (R.A) and Declination (Dec).

Telescope Tracking: is the continuous rotation of the telescope around the azimuth and elevation axes needed to compensate the apparent motion of the celestial objects caused by the rotation of the Earth. Tracking is performed in blind mode, without the aid of any guiding system (e.g. a CCD camera monitoring the celestial target and providing feedback). It is a special sequence of pointing positions based on a pre-calculated tracking trajectory.

2 Related Documents

2.1 Applicable Documents

[AD1]	ASTRI Quality Plan	ASTRI-INAF-PLA-3000-001
[AD2]	ASTRI Mini Array Environmental Conditions:	ASTRI-INAF-SPE-2000-002
[AD3]	ASTRI Mini Array Product Breakdown Structure	ASTRI-INAF-DES-2000-001
[AD4]	ASTRI Mini Array Optical design description	ASTRI-INAF-DES-7200-001

2.2 Reference Documents

[RD1]	ASTRI-Horn “Heritage” Telescope Control System	ASTRI-INAF-REP-9100-001
[RD2]	ASTRI Mini Array Top Level architecture	ASTRI-INAF-DES-2100-001

3 Overview of the ASTRI Mini Array

The ASTRI mini-array consists of a set of 9 wide-field Cherenkov telescopes of the 4 meters class that will be installed at the Observatorio del Teide in Tenerife (Spain). The ASTRI mini-array will be operated by INAF in collaboration with IAC on the basis of a hosting agreement. The ASTRI acronym stands for “Astrofisica con Specchi a Tecnologia Replicante Italiana” (“Astrophysics with Italian Replication Technology based for Mirrors”), making a direct reference to the method invented by INAF for the production of the low-cost mirrors for Cherenkov Telescopes in ground based gamma ray astronomy.

INAF started the ASTRI project in 2010 and, in this context, the end-to-end prototype ASTRI-Horn Cherenkov telescope, based on the innovative dual-mirror Schwarzschild-Couder aplanatic configuration and small plate-scale has been developed and installed at the INAF “M.C. Fracastoro” observing station in Serra La Nave (Mount Etna, Sicily). With this telescope a number of technologies and innovative sub-systems were utilised and tested, including the cold glass replication technology, the hot forming method for the production of the secondary mirrors, a Cherenkov camera prototype based on small pixel size SiPM sensors and an innovative read-out approach, the use of proper control software, ICT systems and data analysis pipelines and archive. Major results achieved include the first proof ever done of the optical behaviour of a Schwarzschild-Couder system and the first detection of the Crab in gamma-rays at energies larger than 3 TeV with a dual mirror system.

The ASTRI mini-array observations will operate in the 1 TeV - 100 TeV band an energy band potentially very interesting for new scientific discoveries. In this respect, compared to currently operating IACT systems (HESS, VERITAS and MAGIC), the ASTRI mini-array would extend the sensitivity up to 100 TeV and beyond, an almost never-explored energy range by IACTs. Moreover, it will benefit from a much larger field of view (a few degrees in diameter), which will allow us to simultaneously monitor a few close-by sources during the same pointing. The combination of the sensitivity extended to 100 TeV and of the homogeneous performance across the FOV will allow us to study e.g. emission from extended sources such as SNRs and PWNs at $E > 10$ TeV, and to investigate the presence of spectral cut-offs. The energy threshold about 1 TeV will naturally lead to focusing the schedule on a few well defined, deeply exposed, science driven targets.

The ASTRI mini-array will operate when the present IACT experiments, observing in a lower but partly overlapping energy range, will still be active, allowing direct comparison of scientific data (spectra, light-curves, integral fluxes). Also, fruitful synergies with the water Cherenkov HAWC and LHAAZO experiments (both operating in the northern hemisphere), surveying a very large stripe of the northern sky, with pointed observations are also clearly foreseen. In summary, the ASTRI mini-array will allow us to carry out seminal studies on both Galactic and extragalactic sources, tackling frontier issues at the intersection of the fields of astrophysics, cosmology, particle physics and fundamental physics.

Furthermore, the ASTRI Mini-Array (MA) will be equipped with an instrument that will allow stellar intensity interferometry, previously developed by Hambury-Brown, on brilliant stars in the visible band with very long baselines (hundreds of meters), allowing in principle to obtain angular resolutions as good as 50 micro-arcsec.

From the point of view of the definition of the operation model the ASTRI Mini-Array several objectives and constraints were taken into account to reduce costs and manpower. In particular, during (night) normal/science operations of the ASTRI MA, no persons are foreseen at the Teide Observatory, and the MA will be controlled remotely from the main Control Room located at the IAC La laguna Facility. Occasionally, only 2 to 3 persons will be present on site during daytime, for maintenance operations.

A brief overview of the ASTRI Mini-Array system components and functions is reported in the following section.

3.1 ASTRI Mini-Array Decomposition

The following figure shows the subsystems composing the ASTRI Mini-Array system.

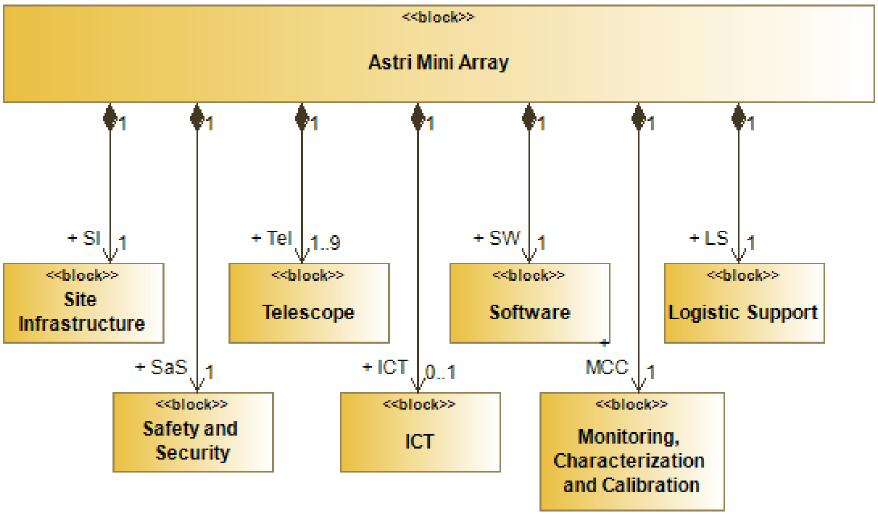

Figure 1. ASTRI Mini-Array system decomposition

3.1.1 ASTRI Mini-Array subsystems description

Here, we give a brief description of the subsystems. The single Telescope subsystem will be described in detail in the rest of this document.

3.1.1.1 Site Infrastructure

The ASTRI Mini-Array Site infrastructure is composed of all those parts needed to make the observational site suitable to host the telescopes of the ASTRI Mini-Array. It includes:

- The civil infrastructures needed to support the deployment and the operation of the ASTRI mini-array that is the foundations for telescopes and auxiliary instrumentation, the roads connecting the telescopes and the trenches for power and communication network.
- Office space to host the ASTRI personnel in charge of the coordination and the mini-array control room.
- A warehouse to store spare parts and handling tools.

- The power supply network needed to supply electric power to all the mini-array subsystems. In the network are also included power backup systems (UPS and emergency power generator).
- The communication network needed to connect the data centre to the telescopes and auxiliary instrumentation and the data centre to the outside world.
- The Control Room at the THEMIS Telescope.
- The infrastructure (power and data) necessary to host the onsite data centre.
- Service cabinets to interface the Telescope to the external world. In particular, they contain the power and communication networks interfaces. They also include part of the safety and security system (rain & humidity sensors, CCTV cameras).
- Facilities IAC La Laguna, including the infrastructure (power and data) necessary for the control room and the offices.

3.1.1.2 Safety and Security

The Safety and Security System is an independent system for the protection of people and site assets. It includes:

- The integrated safety system consists of all the hardware and software needed to prevent unintended accidents to people or elements of the mini-array during operations or maintenance activities. Typical elements of such a system are interlocks, emergency stops, fire alarms. This system is completely independent of any other system present at the site apart from power. The system implements safety functions to remotely stop the operations of all mini-array subsystems in case of danger.
- The Integrated Security and Alarm System that is intended to protect property and environment of the ASTRI mini-array assets from external “threats”. It will be composed of an access control system to prevent unauthorised people from accessing telescope areas or datacentre and closed-circuit television cameras (CCTV).

3.1.1.3 Software

The Mini-Array software system will provide a set of tools to the user from the preparation of an observing proposal to the execution of the observations, the analysis of the acquired data online and the retrieval of all the data products from the archive.

- **Supervisory Control and Data Acquisition (SCADA).** It is the software system devoted to control all the operations carried out at the MA site. It includes the Operator Human Machine Interface and the central control system which interfaces and communicates with all equipment and dedicated software installed at Teide and La Laguna.
- **Archive.** It provides the storage for all data, data products, and metadata generated for and by the MA, and defined in the MA Data Models.
- **Data Processing System**. It is the software system used to calibrate and reduce the data acquired. This software is also used to check the quality of the final data products. It is installed in the offsite ASTRI Data Centre.
- **Science Support System**. It provides the main point of access for the exchange of science-related data and information with the ASTRI Science

Users. It supports the whole science-related workflow, from the Observing Project submission to the access to the archived high-level MA science data products and the corresponding Science Tools to support data analysis.

- **Simulation**. It provides simulated data used by the event reconstruction algorithms for the reduction of scientific data.
- **Local Control Software**. It includes firmware and low-level software dedicated to the low-level hardware control operations.

3.1.1.4 Information and Communication Technology (ICT)

It includes:

- The system installed at Teide and La Laguna includes all computing/storage hardware, the overall networking infrastructure (including cabling and switches) and all system services (operating system, networking services, name services, etc.) to control the array and monitor its health status, perform online observation quality analysis, store temporarily data at the site and guarantee internal and external network communications.
- The offsite system is installed at ASTRI Data centre, located at the INAF Rome observatory, where all the data produced by the MA will be archived and analysed. It includes computing/storage hardware, overall networking infrastructure and all system services. Also, it hosts a gateway for the science users.
- The Time Synchronization System is designed to keep clocks synchronized to sub-ns precision for the Interferometry and Cherenkov time tagging of events. The system is based on the white-rabbit technology and is deployed at the mini-array observing site.

3.1.1.5 Monitoring Characterization and Calibration

This subsystem consists of:

- The **Environmental Monitoring System** is composed of all the hardware necessary to monitor the atmospheric and weather conditions at the Teide site. It includes:
- The **Atmospheric Characterisation System** is the set of devices necessary to measure the Night Sky Background (UVSiPM and SQM) and the atmospheric extinction (LIDAR) in the observing direction. The data obtained by these instruments are used in the Cherenkov and Interferometric data reduction and analysis process.
- The **Array Calibration System** is composed of an illuminator, an instrument used to uniformly illuminate the principal mirror of each telescope with monochromatic light of known intensity. It is used in the energy calibration procedure of the ASTRI MA Telescopes.

3.1.1.6 Logistic Support

The logistics support includes all the hardware & software necessary for the preventive, corrective and condition-based maintenance of the ASTRI Mini-Array. It is based on a commercial Compute Maintenance Management System that maintains a computer database of information to organize the Mini Array maintenance operations.

3.2 The ASTRI Min-Array Site Layout and Geographical Locations

The ASTRI Mini-Array will be installed at the Array Site location within the IAC Teide Observatory property. The ASTRI Mini-Array deployment at the Teide Observatory is illustrated in Figure 2.

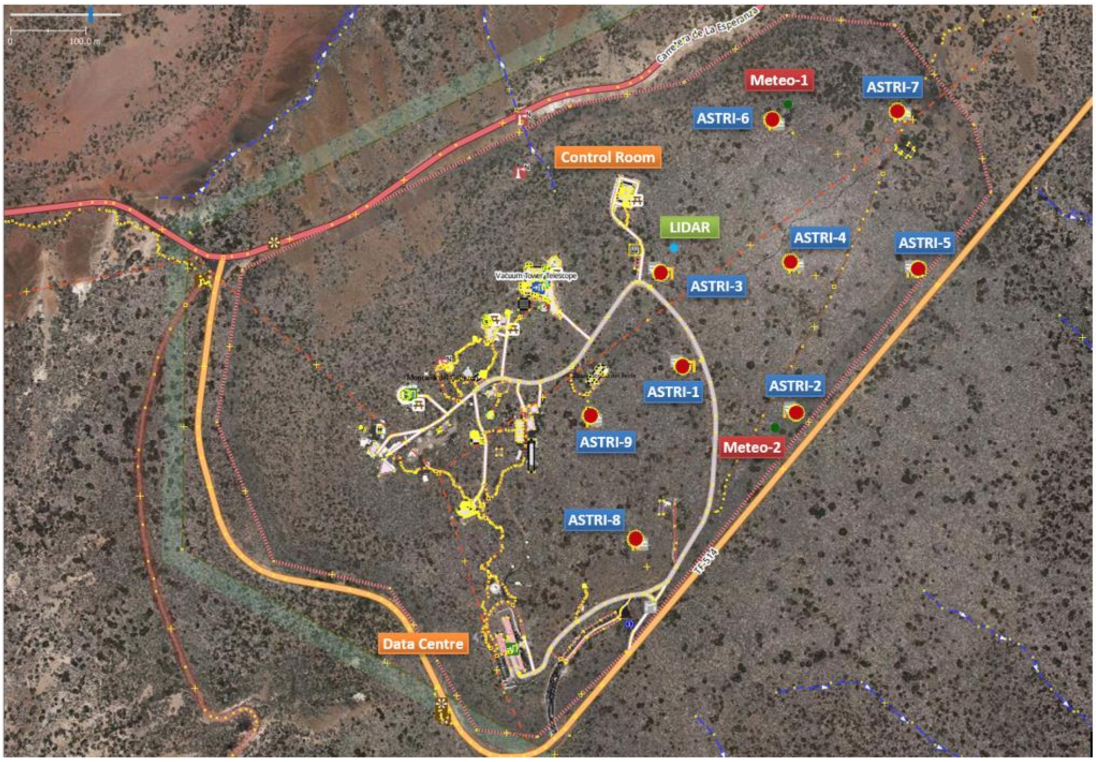

Figure 2. The ASTRI Mini Array Layout at Teide Observatory. The red dots indicate the positions of the ASTRI telescopes (ASTRI-1 to ASTRI-9).

Table 1. Geographical locations of the ASTRI Telescope Array at Teide

Telescope	Latitude	Longitude	Altitude (m)
ASTRI-1	28°18´3.69" N	16°30´28.69" W	2359.00
ASTRI-2	28°18´2.43" N	16°30´23.78" W	2348.00
ASTRI-3	28°18´8.53" N	16°30´29.82" W	2364.00
ASTRI-4	28°18´8.31" N	16°30´23.90" W	2356.00
ASTRI-5	28°18´8.73" N	16°30´17.63" W	2358.00
ASTRI-6	28°18´14.91" N	16°30´24.88" W	2351.00
ASTRI-7	28°18´15.56" N	16°30´18.56" W	2342.00
ASTRI-8	28°17´57.45" N	16°30´31.34" W	2359.00
ASTRI-9	28°18´2.75" N	16°30´33.98" W	2376.15

The nine ASTRI telescopes denominations and geographical latitudes, longitudes and altitudes are reported in Table 1.

3.2.1 Telescope Area at Teide

The logical deployment of the single Telescope at the Teide site is given in Figure 3 (the figure elements are just for illustration). The Service Cabinet represents the place where the Telescope is connected to the Site power, network and time distribution systems. The Local Security and Environmental Monitoring devices are the Local Camera of the Array Site CCTV system and local weather sensors (e.g. rain sensors). A safety fence is installed around the telescope area to keep persons and equipment safe.

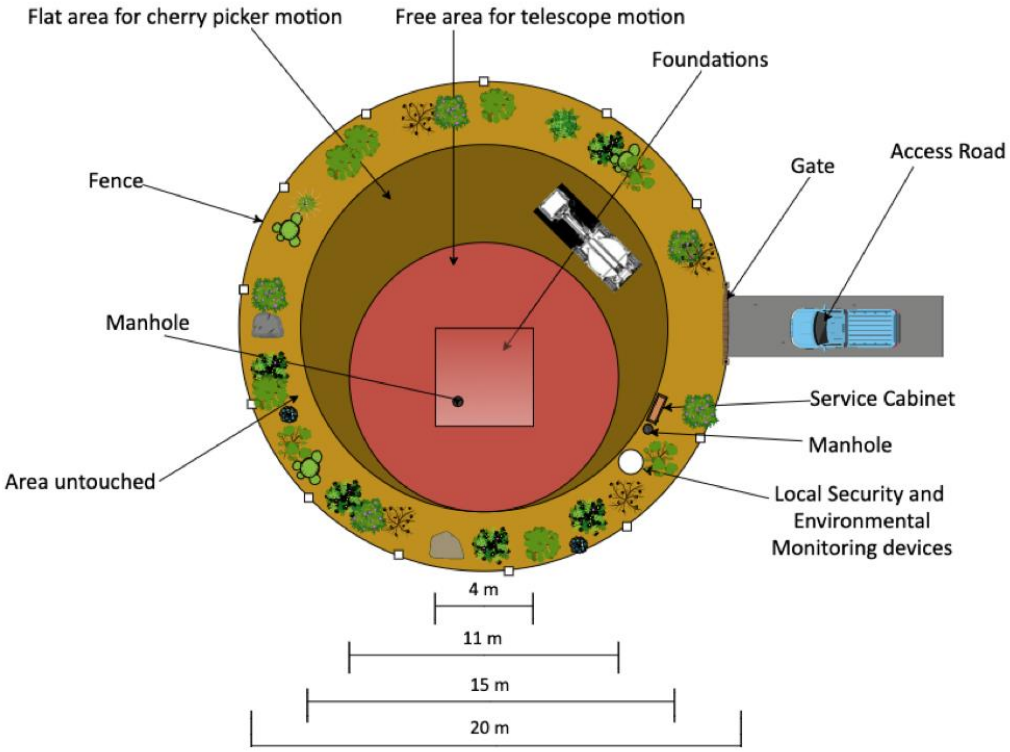

Figure 3. *Schematic diagram of the Telescope area at Teide.*

4 The ASTRI Mini-Array Telescope

4.1 Telescope functional description

The telescope has the following high-level functionalities: move automatically to any position in the sky; collect light (Cherenkov emitted by air shower, stars light, and artificial light from the calibration instrument); focus the light onto the focal plane photodetector (Cerenkov Camera, Intensity Interferometry Module or Optical Camera); acquire scientific and calibration images (i.e. to convert light into an electric signal, amplify, condition, digitize the signal and add a timestamp to each event); deliver the raw images to a local temporary storage for their transmission to the ASTRI Data Centre in Italy.

4.2 Telescope Context Diagram

The context diagram of the telescope is illustrated in Figure 4.

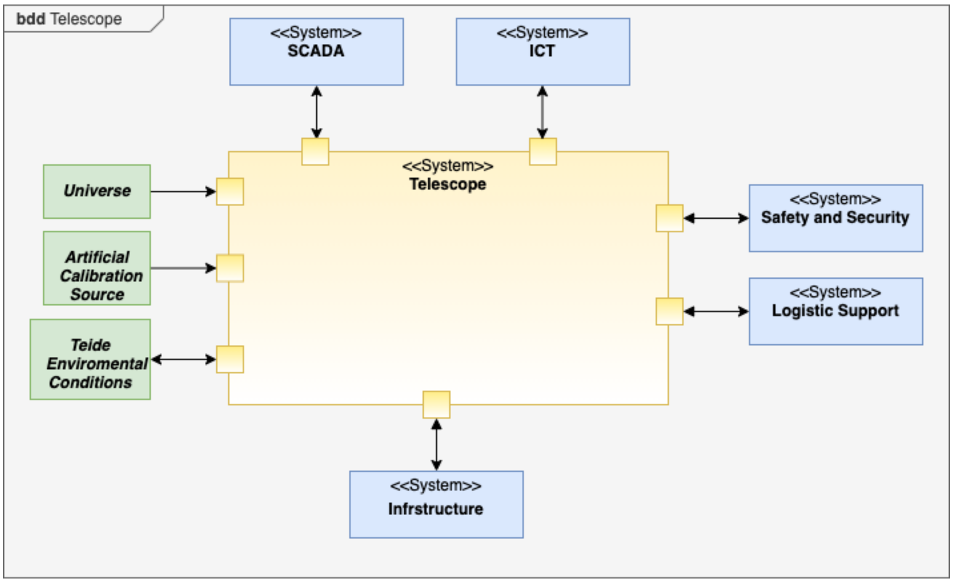

Figure 4. ASTRI Mini-Array Telescope Context Diagram

4.3 Telescope External Interfaces

The Telescope is connected to the Array site Power Distribution System provided by the Infrastructure. The Power Distribution System includes an emergency power generator that is able to provide the power needed to safely park all telescopes in case of a power grid outage.

As part of the ASTRI Mini-Array each telescope cooperates to obtain stereoscopic air shower and intensity interferometric observations and to the safety operation of the Array under supervision of SCADA and Safety and Security System. Therefore, the Telescope Local Control Systems receives commands from SCADA and from the Safety and Security System, providing them with status, monitoring data or alarm conditions.

In order to assign a timestamp to each detected light event, the Instruments mounted on the Telescope are connected to the data network and time distribution systems provided by the ASTRI Mini Array Information and Computing Technology (ICT) system.

4.4 The ASTRI Telescope Decomposition

The ASTRI telescope decomposition is given in figure 5. It includes the following subsystems:

- The Optical Assembly
- The Mechanical Structure Assembly.
- The Cherenkov Camera.
- The Stellar Intensity Interferometry Instrument (SI^3).
- The Auxiliary Assemblies.
- The Telescope Protection System.
- The telescope Control System.

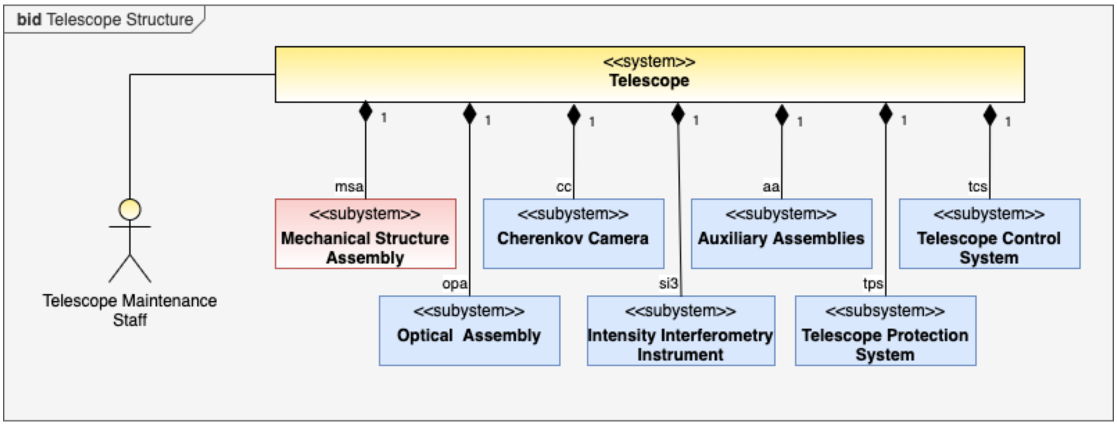

Figure 5. Telescope Decomposition

The description of the Telescope subsystems is given in the following subsections.

5 ASTRI Telescope description

5.1 Optical Assembly

The Optical Assembly includes all the systems needed to implement the telescope optical design.

5.1.1 The Telescope Optical Design

The optical system is a Schwarzschild-Couder configuration with a focal ratio F# of 0.5, see Figure 6. The design has a plate scale of 37.5 mm/°, the Cherenkov pixel is approximately 0.16°, over an equivalent focal length of 2150 mm. This delivers a usable field of view up to 9.6° in diameter.

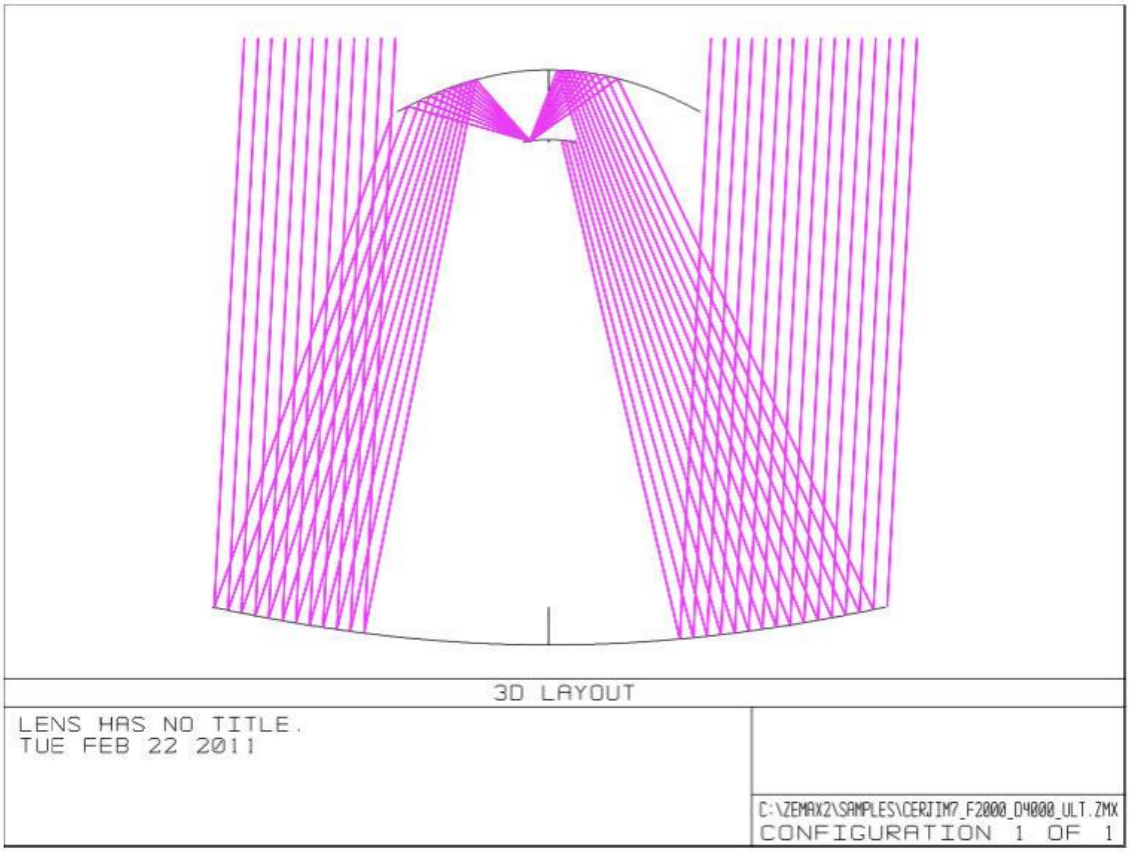

Figure 6. The Schwarzschild-Couder optical design adopted for ASTRI

Concerning the effective area (in m^2) it has to take into account:

- Segmentation of the primary mirror
- Obscuration of the secondary mirror
- Obscuration of the detector and of the SI3
- Reflectivity of M1 and M2
- A protection window for the detector
- Efficiency of the detector as function of the incident angles (25° to 72°)

The values in Table 2 do not consider the quantum efficiency of the detector and the absorption from the atmosphere, whilst they are calculated as function of the incoming wavelengths (λ1=320nm; λ2=350nm; λ3=400nm; λ4=450nm; λ5=500nm; λ6=550nm; λ7=600nm) for different field angles.

Table 2. Effective area of the entire optical system

	A(λ1)	A(λ2)	A(λ3)	A(λ4)	A(λ5)	A(λ6)	A(λ7)
0°	6.30	6.38	6.41	6.56	6.69	6.76	6.75
1°	6.26	6.38	6.39	6.56	6.67	6.77	6.76
2°	6.26	6.35	6.38	6.50	6.61	6.72	6.66
3°	6.15	6.22	6.31	6.39	6.57	6.69	6.60
4°	5.86	5.98	6.03	6.13	6.28	6.27	6.38
4.8°	5.87	5.86	5.90	6.04	6.16	6.21	6.22

The mirror surfaces can be described with the following polynomial equation:

$$z = \frac{cr^{2}}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{i=2}^{N} \alpha_{2i} r^{2i}$$

where z is the surface profile, r the surface radial coordinate, c the curvature (the reciprocal of the radius of curvature), k the conical constant, α_i the coefficients of the asphere. The main system dimensions are listed in tables for optical systems, M1 and M2 respectively.

Table 3. Optical System parameters

Item or Parameter	Value	Notes
Mont	Alt-Az	
Optical design	Schwarschild-Couder	
Distance M1-M2	3108.4 mm	
Distance M2-CAM	0.519 mm	
Equivalent focal length	2.15 m	
F-number, f/#	0.5	
Plate scale	37.5 mm/deg	
Average effective collecting area	5 m^2	
Point Spread Function, PSF, evaluated as D80 param.	< 0.19°	D80 parameter: diameter of the circle corresponding to an encircled energy of 80%.

Table 4. M1 Principal Characteristics

Item or Parameter	Value	Notes
Diameter	4.3 m	
Radius of Curvature, RoC	8.2 m	
Number of facets	18	distributed in 3 coronas
Number of facets coronas	3	
Radius of Curvature for each corona from the inner (1) to the outer (3)	(1) 8.52 m (2) 9.87 m (3) 12.54 m	
Facet type	hexagonal	
Facet side-by-side	0.85 m	
Coating	$Al+SiO_2+ZrO_2$	

Table 5. M2 Principal Characteristics

Item or Parameter	Value	Notes
Diameter	1.8 m	
Radius of Curvature, RoC	2.18 m	
Number of facets	1	
Facet type	Monolithic hemispherical	
Coating	$Al+SiO_2+ZrO_2$	

5.1.2 The Optical Assembly decomposition

The Optical Assembly includes the primary and secondary mirror and their control hardware. Its decomposition is shown in Figure 7. The primary mirror is decomposed in three coronas (corona 1, corona2, corona 3), the secondary mirror in mirror, pads and control hardware.

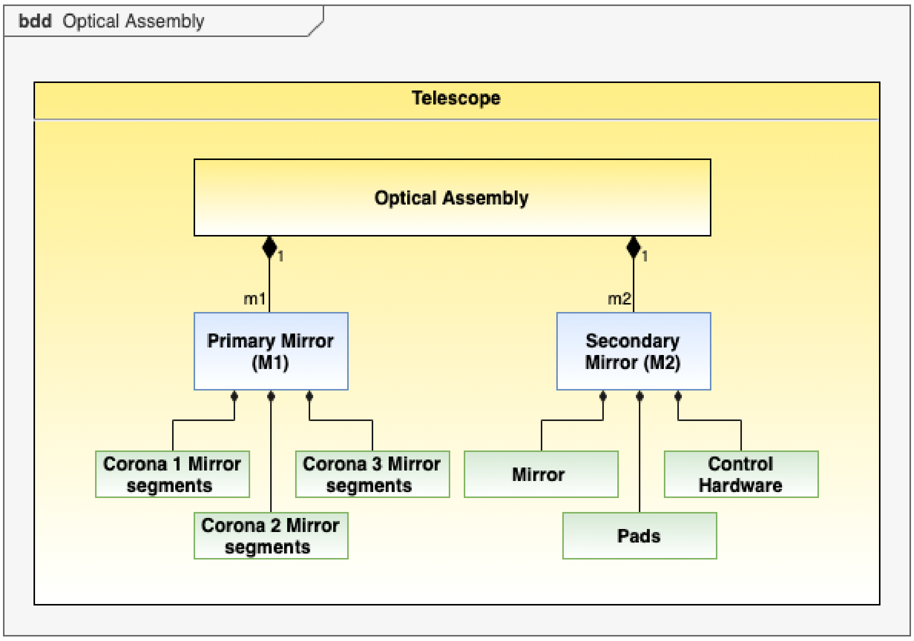

Figure 7. Optical Assembly Decomposition

5.1.2.1 The primary mirror M1

The primary mirror is segmented following the scheme reported in Figure 8. The full reflector is composed of 18 segments (the central one is not used). The segmentation requires three types of segments having different surface profiles:

- the green segments, inner corona: COR1;
- the blue segments, central corona: COR2;
- the yellow segments, outer corona: COR3.

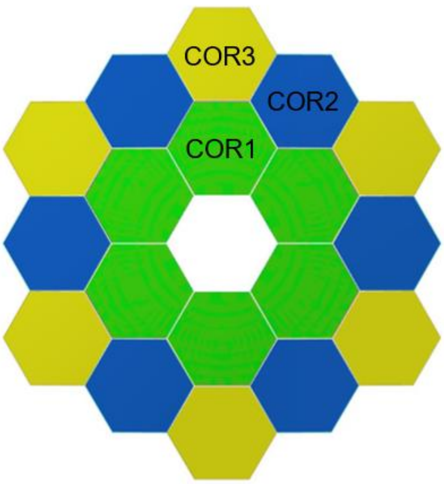

Figure 8. Tessellation of the primary mirror M1

The segments have hexagonal shape with aperture equal to 85 mm from face to face. Each segment has 9 mm of gap from the neighbours for mounting and alignment purposes. Each segment will be equipped with three actuators plus one fixed point for alignment. In this way Tip/tilt and piston misplacements of each segment can be corrected. The alignment system (actuators, controls etc) will be installed only during commissioning and maintenance activities.

Adopting the same mathematical notation introduced before we report in Table 6 the description of the surface profile of M1.

Table 6. Coefficient describing the aspherical terms in M1.

Coefficient	M1
α_1	0.00
α_2	9.61060E-13
α_3	-5.65501E-20
α_4	6.77984E-27
α_5	3.89588E-33
α_6	5.28038E-40
α_7	-2.99107E-47
α_8	-4.39153E-53
α_9	-6.17433E-60
α_{10}	2.73586E-66

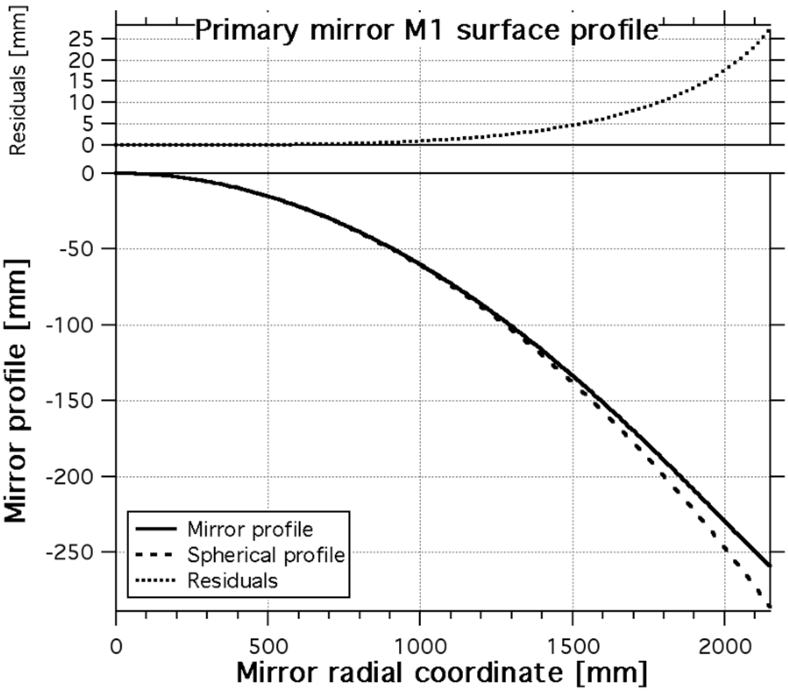

Figure 9. Profile of M1 as function of the radial coordinate

The M1 segments assemblies grant a positioning accuracy between each segment of:

- M1 segments in plane alignment error: ±2 mm along X'
- M1 segments in plane alignment error: ±2 mm along Y'
- M1 segment axial error: ±4 mm along Z'
- M1 segment tilt around X'-axis: 30 arcsec RMS
- M1 segment tilt around Y'-axis: 30 arcsec RMS
- M1 segment tilt around Z'-axis: 4 arcmin RMS

5.1.2.2 The secondary mirror M2

The secondary mirror is monolithic and equipped with three actuators. The implementation of the third actuator makes available also the piston/focus adjustment for the entire optical system.

Adopting the same mathematical notation introduced before we report in Table 7 the description of the surface profile of M2.

Table 7. Coefficient describing the aspherical terms in M2.

Coefficient	M2
α_1	0.0
α_2	1.62076E-11
α_3	-2.89584E-17
α_4	8.63372E-24
α_5	3.34856E-30
α_6	-1.03361E-36
α_7	-6.73524E-43
α_8	-3.06547E-49
α_9	3.17161E-55
α_{10}	-3.71183E-62

The displacement of M2 is:

- In plane error with respect to M1: ±3 mm along X'
- In plane error with respect to M1: ±3 mm along Y'
- Axial error with respect to M1: ±4 mm along Z'
- Axial error with respect to camera: ±1 mm along Z'

The maximum allowed rotation with respect to its nominal position shall be within 10 arcmin along all axes.

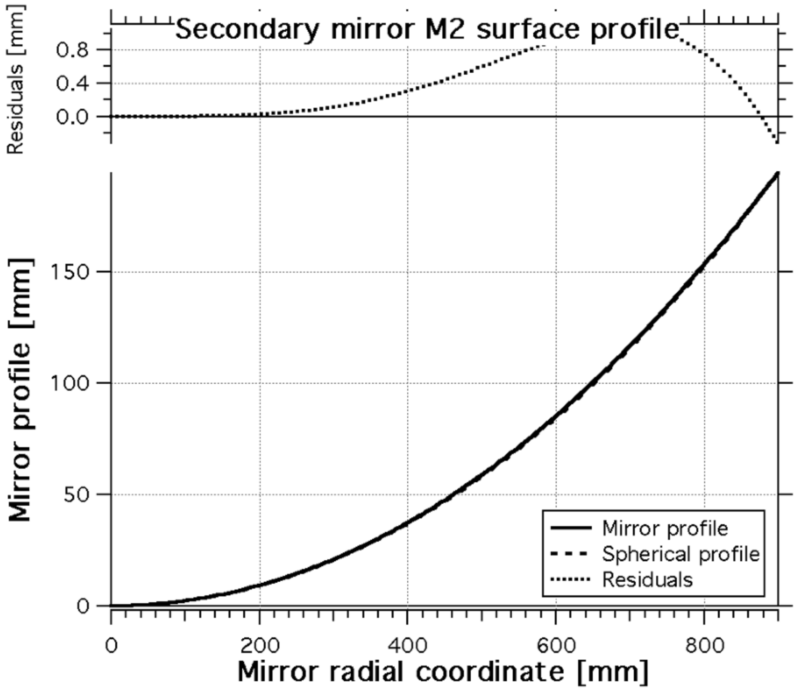

Figure 10. Profile of M2 as function of the radial coordinate

5.2 The Telescope Mechanical Structure Assembly (MSA)

The Telescope Mechanical Structure Assembly (MSA) includes all the hardware and software that allow the telescope to point to different parts of the sky with the required performances. All mechanical parts (structural elements, boltings, screws, bearings, gears, springs, bumpers, accessories) needed to support the telescope optics for collecting light are part of the MSA. A 3-D view of the telescope MSA is given in Figure 11.

The MSA provides the motion capabilities that allow the Telescope to point and track over its specified range. All the electromechanical parts of the MSA are provided with power and communication via dedicated supply lines.

The MSA is fixed to the concrete foundation by means of anchor bars.

5.2.1 The MSA decomposition

The MSA includes four main subsystems (see Figure 12):

- The Mount Assembly.
- The Optical Support Structure.
- The Electrical system.
- The Local Control system.

Each of these will be described in the following subsections.

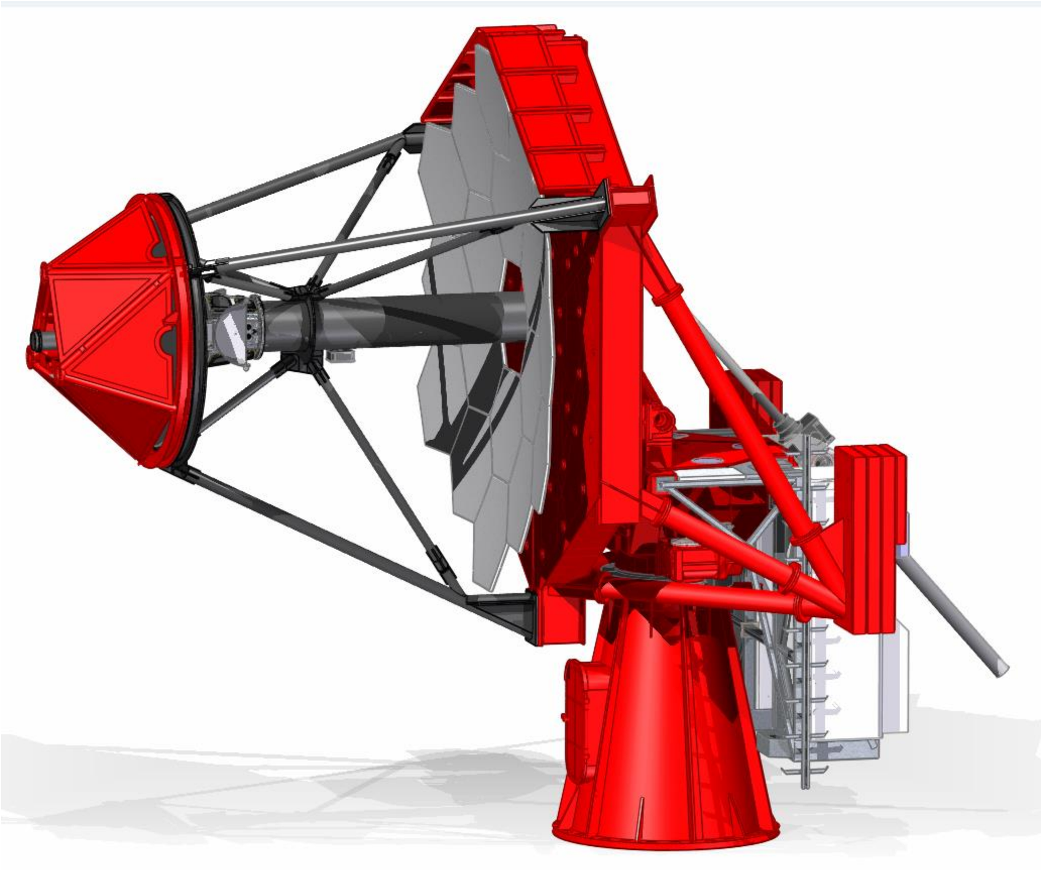

Figure 11. 3D view of the ASTRI telescope (courtesy of EIE)

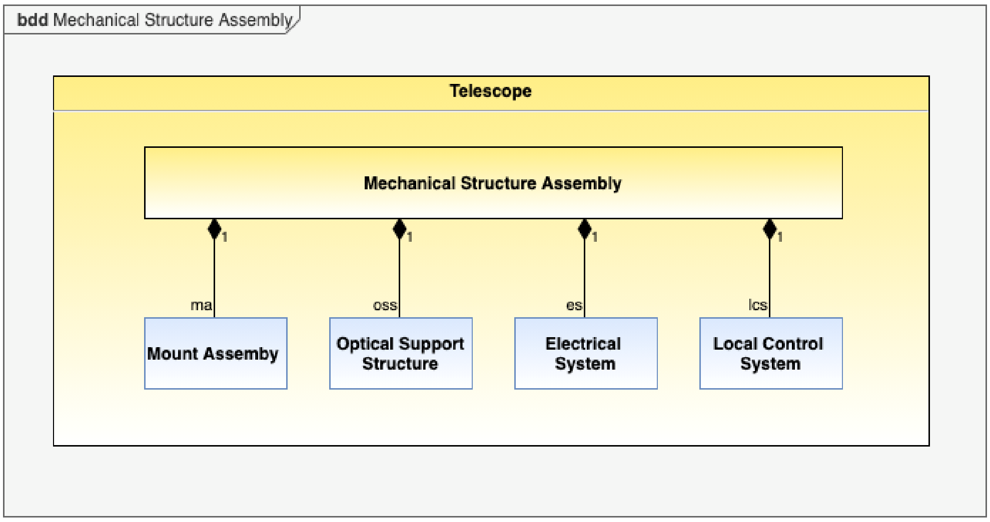

Figure 12. ASTRI Mechanical Structure Assembly Product tree

5.2.2 The Mount Assembly

The Telescope Mount Assembly provides the support for the optical support structure (OSS); it includes the mechanical structure and all the interfaces needed to install the telescope auxiliary systems as well as the interfaces with the Instruments (Camera and intensity Interferometry Module).

The Mount includes all the motors, encoders, drives, bearings, and electronics for the control of the main telescope axes.

The Mount Assembly includes the component devoted to anchor the whole MSA to the foundations. It also includes all the access equipment and handling tools needed to maintain the telescope and sub-systems.

The Mount Assembly decomposition is given in Figure 13; it includes four main logical sets:

- the Base;
- the Azimuth Fork Structure;
- the Elevation Structure;
- the Mount Drive mechanisms.

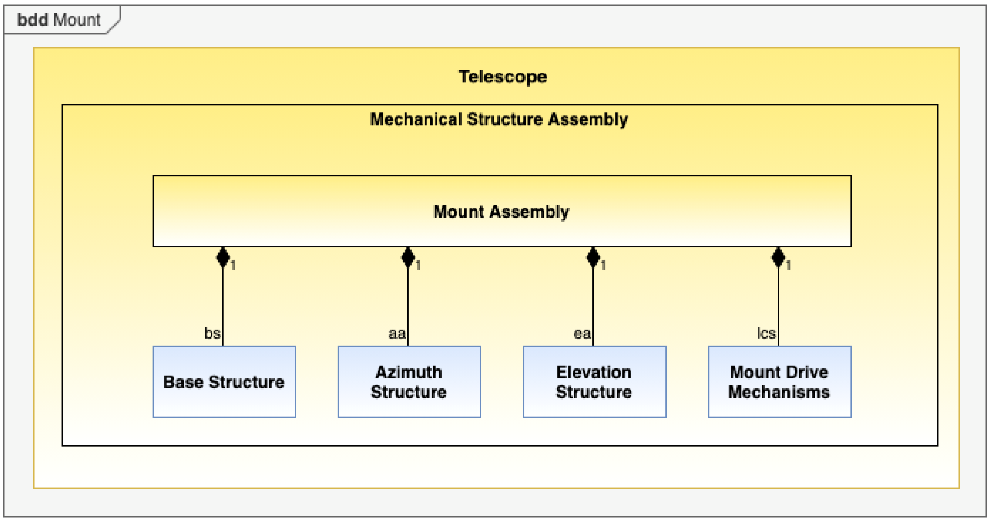

Figure 13. The Mount Assembly decomposition.

5.2.2.1 Base structure

This term indicates the fixed part of the Mount Assembly supporting the Azimuth Fork Structure (see Figure 14). It is fixed to the foundation by means of a set of anchor bolts.

The base structure has these tasks:

- to act as interface between the foundation and the Azimuth Fork, distributing the loads from the last;
- to provide safe access to the items installed inside the base, due to their sensitivity to weather agents (azimuth encoder, azimuth switches, cable wraps etc);

The conical shape, the ribs, the flange at the bottom, the material chosen (S355J0 steel) contribute to the complete satisfaction of the first task.

The second task instead is guaranteed by a hollow construction, whose internal volume is accessible by a door equipped with a safe switch connected to the interlock chain.

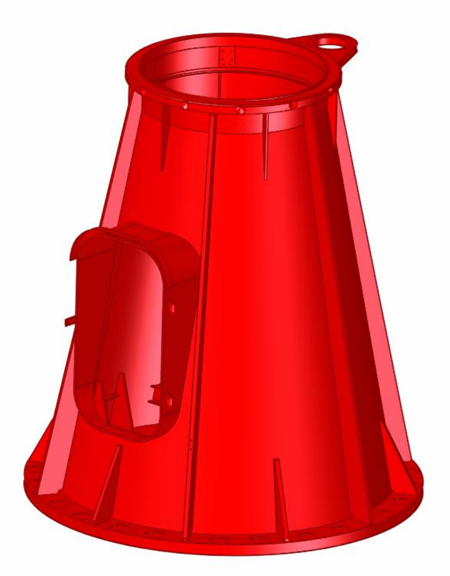

Figure 14. *The Base structure of the ASTRI Telescope* (courtesy of EIE).

Figure 15. The internal view of the Base structure (courtesy of EIE).

The Base bears the bush of the stow pin, located at an azimuth position angle of -90° and consisting in a sheet of metal properly shaped and dimensioned, welded to the structure.

5.2.2.2 Azimuth Structure

The Azimuth Structure rotates around the azimuth axis and connects the Elevation Structure to the Base. It provides support and interfaces for the following subsystems:

- azimuth and elevation switches;
- the support structure of the Telescope electrical and control cabinets;
- the elevation bearings;
- the azimuth bearings
- the support structure of the elevation drive system and encoder;
- the support structure of the azimuth drive system;
- the support structure of the azimuth and elevation stow pins;
- the Elevation and Azimuth cable wraps;
- the elevation bumpers.

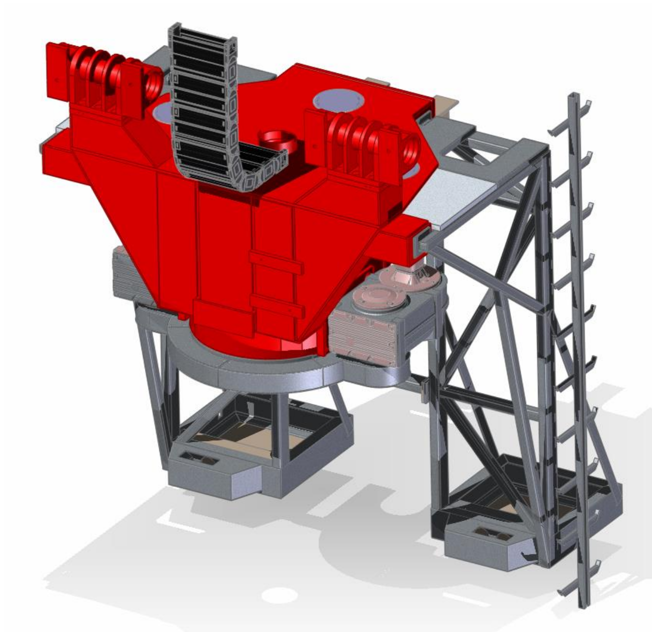

Figure 16. The Azimuth structure of the ASTRI Telescope (courtesy of EIE).

These items grant the motion of the telescope mount main axes as well as the telescope safety in survival conditions.

Elevation cable wraps are of high importance to guarantee power and data link for all the telescope's subsystems; in such a context the Azimuth Fork Structure plays a key role as its shape has been defined in order 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 grant the support for the cable trays and Elevation cable wraps.

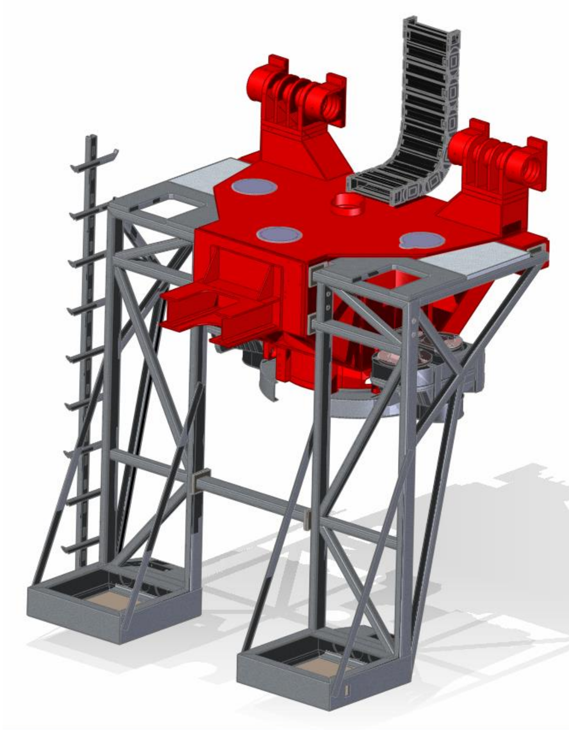

Figure 17. The Azimuth structure of the ASTRI Telescope (courtesy of EIE)

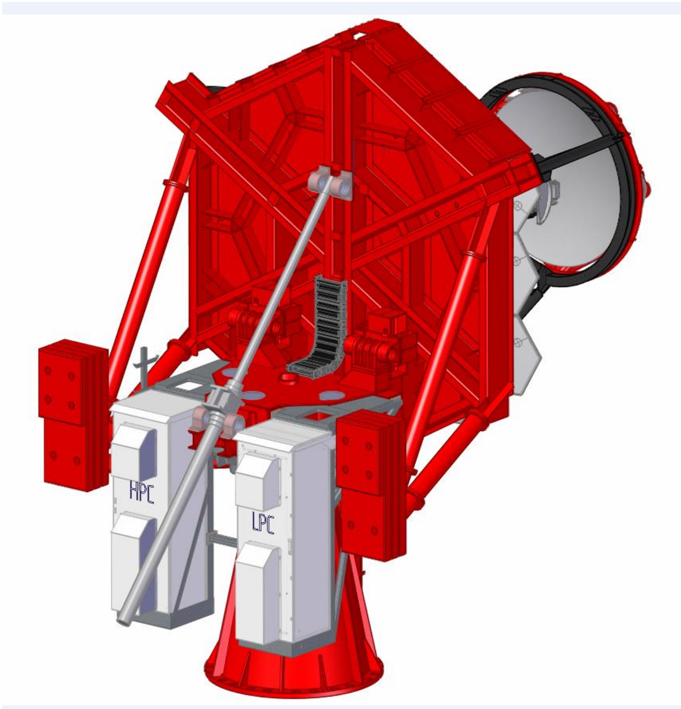

Figure 18. The Elevation structure mounted on the Azimuth structure of the ASTRI Telescope. The two electrical and Electronic cabinets are shown (courtesy of EIE).

5.2.2.3 Elevation structure

This term shall indicate the telescope element that includes:

- The M1 dish, the structure to which are anchored the OSS of the M1 mirror segment supports.
- The OSS Upper Structure,
- The M2 support structure which includes, as well, the Pointing Monitoring Camera support and the Intensity Interferometry Module support structure (TBC).
- The counterweights to balance the elevation structure around its axis of rotation.

Figure 19. The Elevation Structure of the ASTRI Telescope (courtesy of EIE)

5.2.2.3.1 Dish

It's the principal part of the subsystem; its main tasks are:

- bearing the triangles carrying the 18 mirrors of M1;
- supporting the counterweights;
- supporting the OSS Upper Structure.

It is a large, hexagon-shaped welded structure, where 3 principal beams (double C section) are recognizable: one vertical and the other two at 60° from the vertical one; such a structure provides support to the mast, while actuators interfaces have reinforcing ribs (organized in two concentric racks) to give stiff response and guarantee the adequate stability to keep the mirror segments in their position. An array of perforated aluminium sheets, located in the upper two sides of the hexagon, works as a shield, protecting the mirrors from the snow when the telescope is in the parking position.

Figure 20. The M1 Dish (courtesy of EIE)

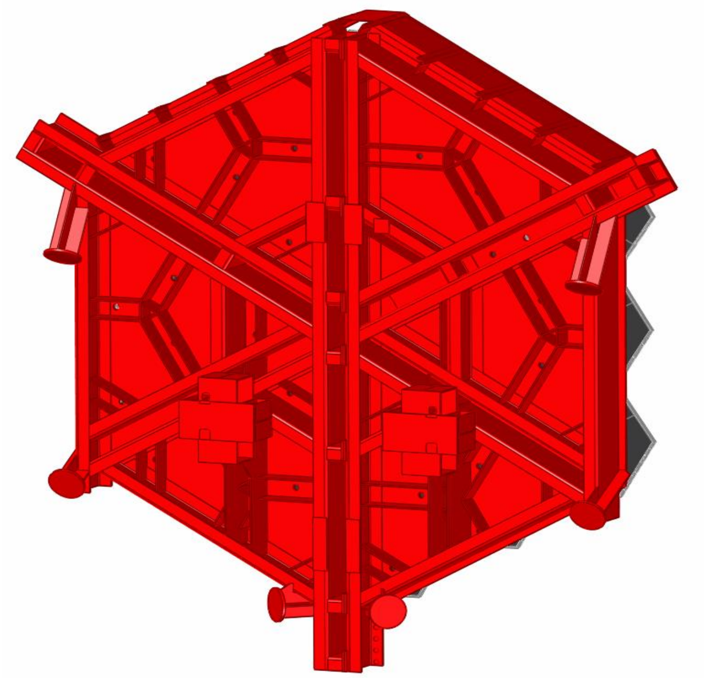

Figure 21. The M1 Dish views from the rear (courtesy of EIE).

5.2.2.3.2 M1 segment Support Assembly

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

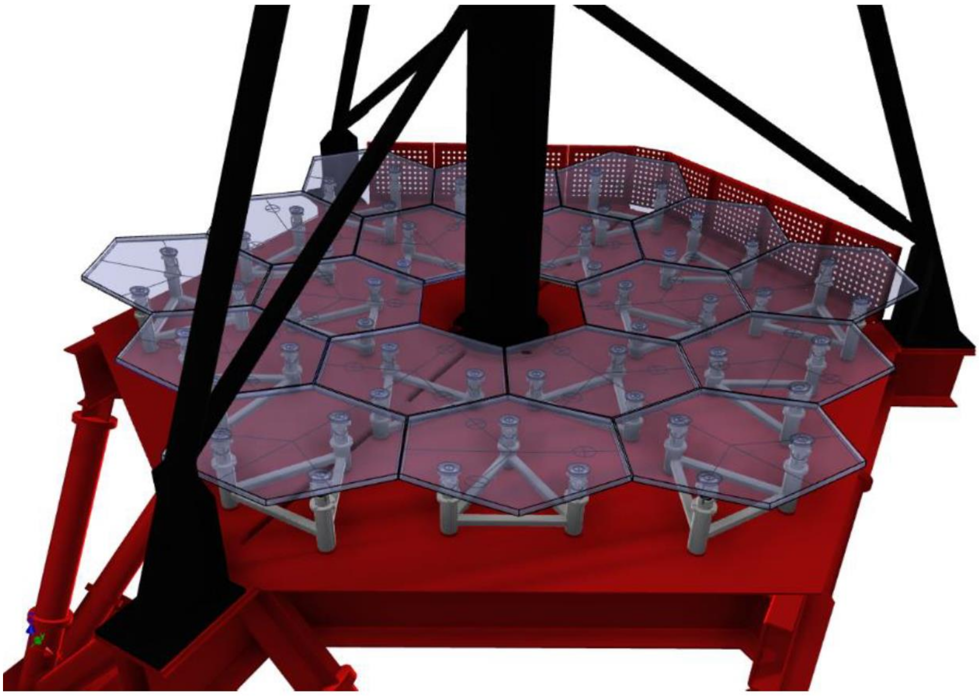

Figure 22. M1 segments support assembly view with transparent M1 (courtesy of EIE)

The handling of each segment is possible by removing, a single actuator per time, the locking device and the fixing screws. Each mirror segment can be detached from the actuators removing three fixing screws per pad. A sliding device is available for all three actuators, so that the segment can be slid out to permit the mirror removal.

5.2.2.3.3 Counterweights

The counterweights guarantee the proper balance of the movement of the whole Elevation Structure around the elevation axis; they consist in two sets of steel blocks each supported by 3 beams bolted to flanges welded to the M1 Dish structure.

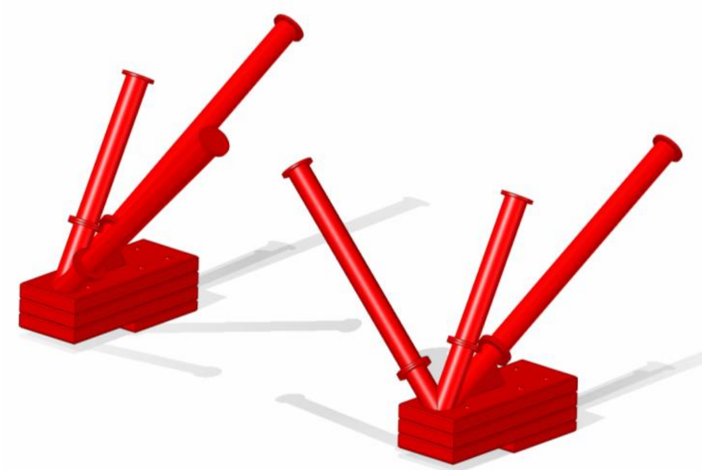

Figure 23. The Telescope Counterweights (courtesy of EIE)

Threaded rods permit to add small masses for fine tuning.

5.2.2.3.4 OSS Upper Structure

The OSS Upper Structure is the structure that support:

- the frame where the secondary mirror with its motors, drives and accessories, is mounted (M2 Support Structure);
- the main scientific instruments of the telescope: the Cherenkov Camera and the Intensity Interferometry Module.
- The Optical Camera used to align the mirrors during calibration and maintenance activities.

It consists of a central mast reinforced by three pipes spread at 120 degrees to each other. Both the mast and the pipes are bolted to the M1 Dish. Furthermore, a top ring connects together the end of the three pipes, to improve the structure's stiffness and to facilitate the operations of mounting/dismounting of the M2 Support Structure.

Figure 24. Left: the OSS Mast. Right: the mast with the Cherenkov Camera mounted (courtesy of EIE).

5.2.2.3.5 M2 Support Structure

The structure is designed to host the support suitable for M2.

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

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

Figure 25. *The M2 Support Structure* (courtesy of EIE)

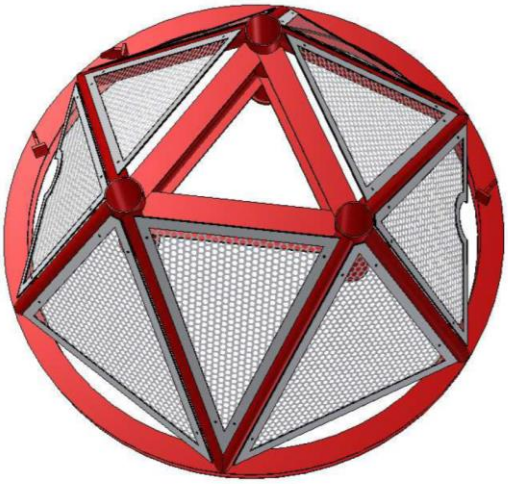

Figure 26. Top view of the M2 Support Structure (courtesy of EIE)

5.2.2.4 The Mount Drive Mechanisms

5.2.2.4.1 Azimuth Drive subsystem

The Azimuth axis motion is powered by two servo motors located at 180 to each other along the circumference of the azimuth bearings (a custom slewing bearing). Each motor shall be provided with two reduction stages and transmits motion to the mechanical axis through a pinion mounted on the second reduction gearbox that is coupled to the Azimuth slewing-bearing.

The two motors shall be coupled together in a master-slave configuration, controlled in differential torque mode in order to eliminate backlash and hence guarantee good motion accuracy under all operational conditions.

The master motors shall be equipped with a brake and a back shaft. In case of power failure or when the azimuth emergency switches are reached, the motor brake shall be able to be released manually to allow to move the azimuth axis with a battery powered emergency motor (e.g. a drill) coupled to the back-motor shaft.

The Azimuth axis encoder shall be the Heidenhain incremental tape encoder ERA7400C and four ERA7480 scanning heads, providing a resolution of 1.6”.

5.2.2.4.2 Elevation Drive subsystem

The Elevation axis motion (four hinges on slewing bearing) is powered by a servo motor (equipped with a brake to provide safe operations and avoid accidents to people and hardware) that drives a ball screw jack, fixed to the M1 Dish by means of hinges, one located on the top of the ball screw and the other installed on the ball screw jack body.

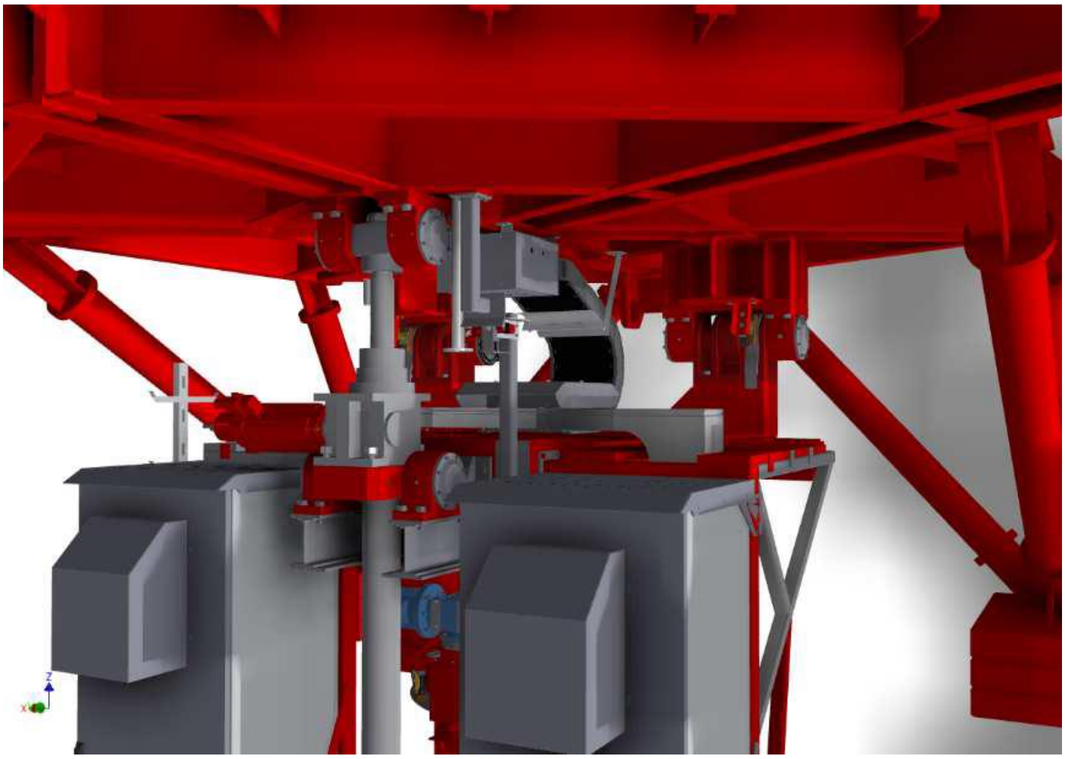

Figure 27. The Azimuth and Elevation Mechanisms (courtesy of EIE)

In case of power failure or when the elevation emergency switches are reached, the motor brake shall be able to be released manually to allow movement of the elevation axis with a battery powered emergency motor (e.g. a drill) coupled to the back-motor shaft.

The Elevation axis encoder shall be the Heidenhain RCN2580 absolute encoder, providing a resolution of ± 2.5”.

The telescope control hardware and electrical communication components are grouped following their functionality and they are contained in two electrical cabinets, supported by the Azimuth Fork: Telescope Power Cabinet (TPC) and the Telescope Control Cabinet (TCC).

5.2.3 The MSA Electrical System

The Telescope Electrical system includes all the means (cables, switchboards, cable trays, etc) for the distribution of electrical power inside the MSA.

A simple schematic diagram of the MSA electrical system is reported in Figure 28.

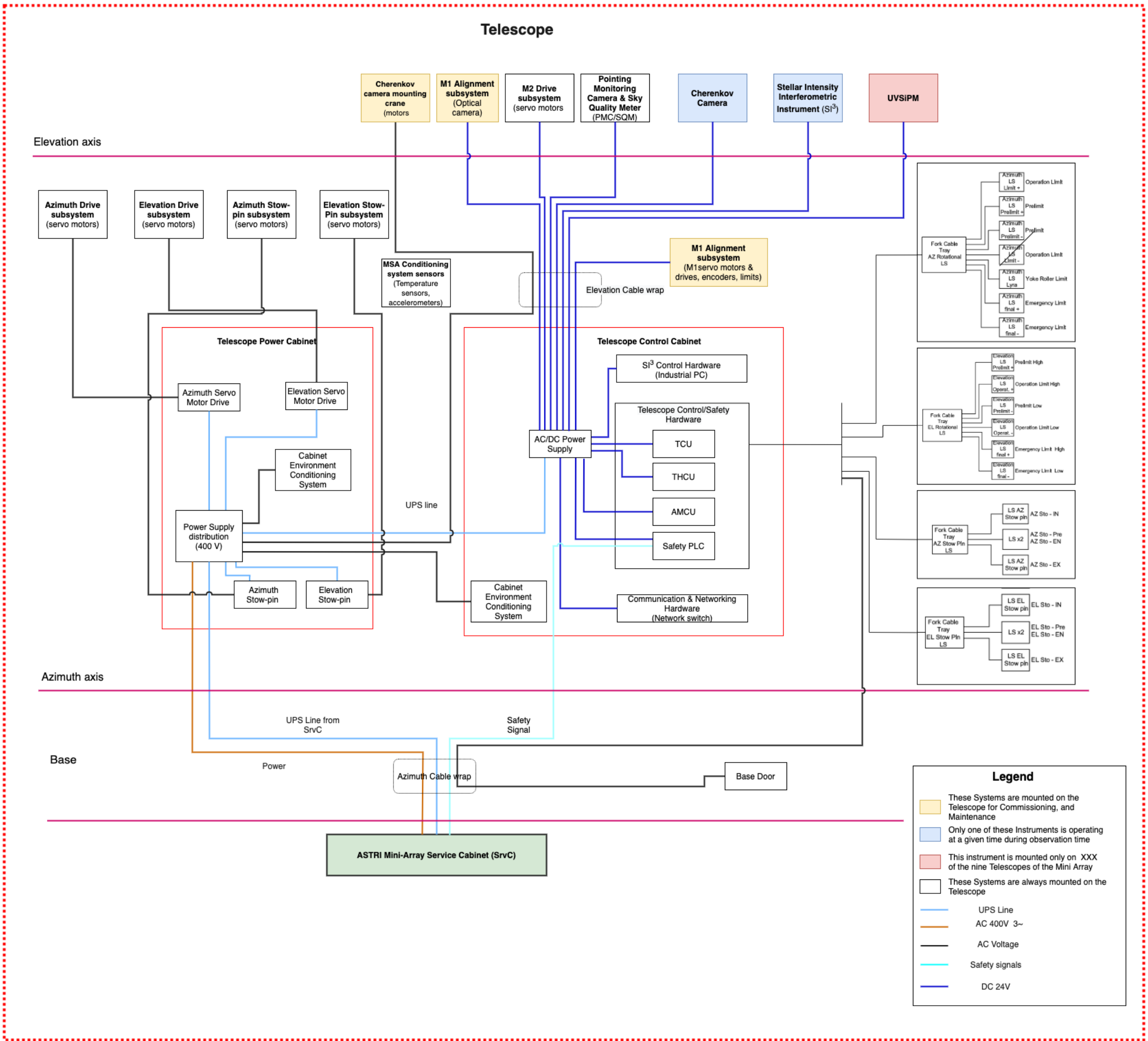

Figure 28. Schematic diagram of the ASTRI Telescope electrical system.

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

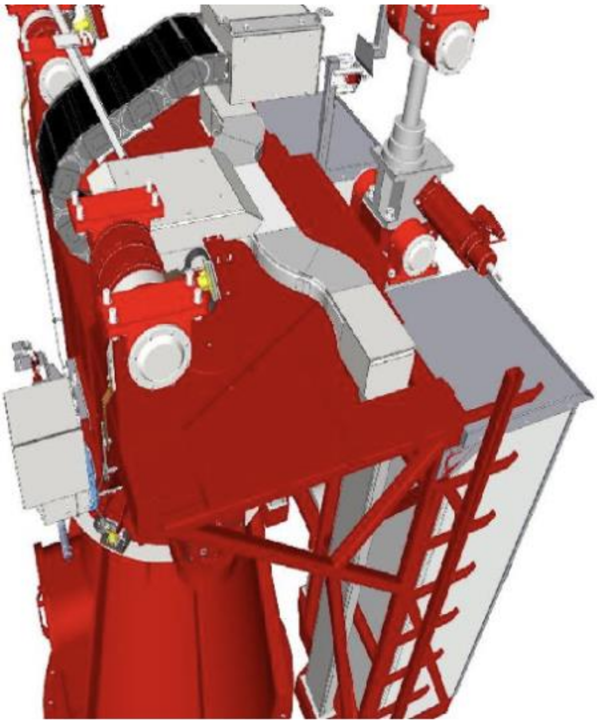

Figure 29. The Elevation cable distribution and cable wrap (courtesy of EIE).

From the Telescope Interface Infrastructure, the power and communication incoming lines enter into the telescope from the Base, pass through the azimuth cable wrap up the two electrical cabinets on the Azimuth structure (see Figure 29).
More in detail, the Telescope has four electrical interfaces incoming from the infrastructure:

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

All these cables are routed through the azimuth (AZ) cable wraps, considering also a spare length in order to allow the cables to follow the movement of the axis (see figure 5-1 right).

In the telescope's base are present these devices:

- AZ encoder heads;
- Base door limit switch.

At the top interface of the AZ cable drape there's a box (the "AZ structure cable box") which is the interface with the cable duct system: it allows the cables distribution towards the cabinets (Telescope control cabinet TCC and Telescope power cabinet TPC) and towards the elevation (EL) cable wraps. Furthermore, the cables which serve the various devices/equipment installed in this area exit from the cable duct by means of dedicated cable glands.

In the telescope AZ structure are present these devices:

- EL encoder;
- AZ and EL rotational limit switches;
- AZ and EL rotational motors;
- AZ and EL stow pins;
- Base light.

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 mast is used to distribute the cable towards the Cherenkov Camera while another set continues along the mast to reach the equipment of the M2 area. These last are:

- M2 actuators (with the relevant M2 box used as electrical interfaces and disconnection point);
- M2 actuators encoders;
- SQM/PCM equipment.
- The Optical Camera
- The SI^3
- UVSiPM
- The removable crane system for mounting the Cherenkov Camera.

6 Telescope Focal Plane Instruments

The ASTRI telescope will host two main scientific instruments:

- The Cherenkov Camera
- The Stellar Intensity Interferometry Instrument (SI^3)

The final design of both the instruments is still not completely finalized and then there could be differences with respect to the descriptions reported, at this time, in this document.

6.1 Cherenkov Camera

The description of the Cherenkov Camera reported in the following subsections is mainly based on the ASTRI-Horn Camera prototype. The final design of the Camera will include improvements derived from the analysis of the lesson learned in the use of the ASTRI Camera prototype.

6.1.1 The Cherenkov Camera Decomposition

The Cherenkov Camera includes all the hardware and software associated with Cherenkov image detection, digitisation, transmission and pre-processing. Figure 30 shows the camera decomposition down to the second level.

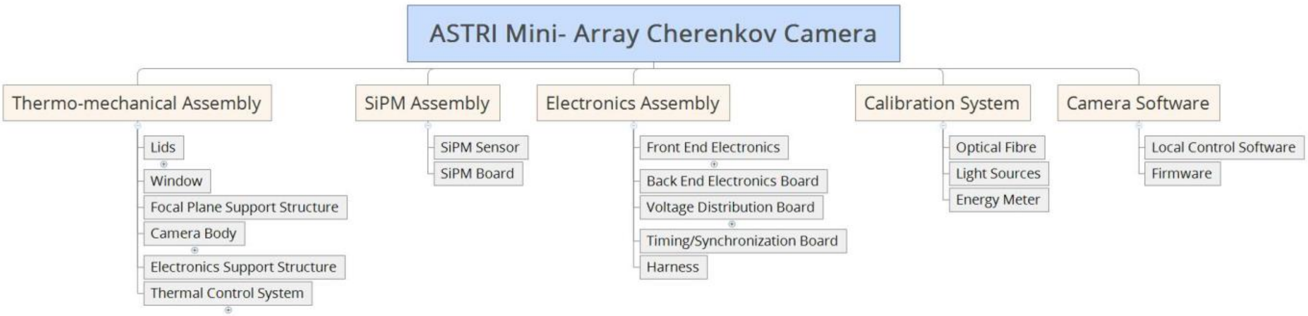

Figure 30. The ASTRI Camera Decomposition to the second level

Main assemblies of the camera are the following:

- **Thermo-Mechanical Subassembly**: The thermo-mechanical subassembly is made by two main sections: The Thermal Control System and the Mechanical System. The first one has in charge of temperature control the SiPMs of the focal plane independently on the thermal conditions of the working ambient of the Camera. It is essentially made by: Focal Plane Support Structure, Large Insulation, and a set composed by Peltier Cells, Spreader Heat Sink, Temperature sensors and Thermo-Electric-Controller.
  The Mechanical System is made is made by the set of structures that host or support the various sub-assemblies and parts of the camera (electronics boards and auxiliary devices), by the lids. Moreover, it provides also the mechanical interface to the telescope structure.
  It is important to note that the Focal Plane Support Structure fulfill both aspects: thermal and mechanical.
- **SiPM subassembly**: the SiPM subassembly is a board composed by the SiPM photodetectors themselves and by an electronic board, that interfaces the detectors to the front end electronics.

- **Electronics assembly**: the electronics subassembly comprises the Front End Electronics (FEE), the Back-End Electronics (BEE), the Voltage Distribution Board (VDB) and Timing/ Synchronization Board. The FEE Board is made by the ASIC board and by the FPGA Board. The former board is in charge to detect the signals from the SIPM, digitalize them, and send them to the latter board that runs the algorithm that detects a valid trigger on each PDM. The BEE controls and manages the overall system, including data management formats, lid mechanisms and fibre-optic calibration tool by means of a dual core ARM processor and two FPGAs. The BEE provides also the needed functions to process and transmit the data-images as processed by the FEE. The VDB has in charge to deliver power to all Front-End Electronics. The Timing/Synch board in the ASTRI Camera prototype is a White Rabbit board.
- **Calibration System:** The Calibration System embedded in the ASTRI Camera has in charge to perform to relative calibration of the Camera's components. It is made by: optic-fibre, light sources, energy meter.
- **Camera Software:** provides the management of the camera at low and high level up to the OPC-UA interface. It is also responsible for data acquisition and transmission from the BEE to the camera DAQ that is the hardware in the array control system and data acquisition that hosts the software which has in charge the camera data acquisition procedures.

Figure 31 shows the context diagram of the ASTRI camera. It defines the boundaries of hardware and software systems of the ASTRI camera and identifies the flows of information between the Camera and other external systems.

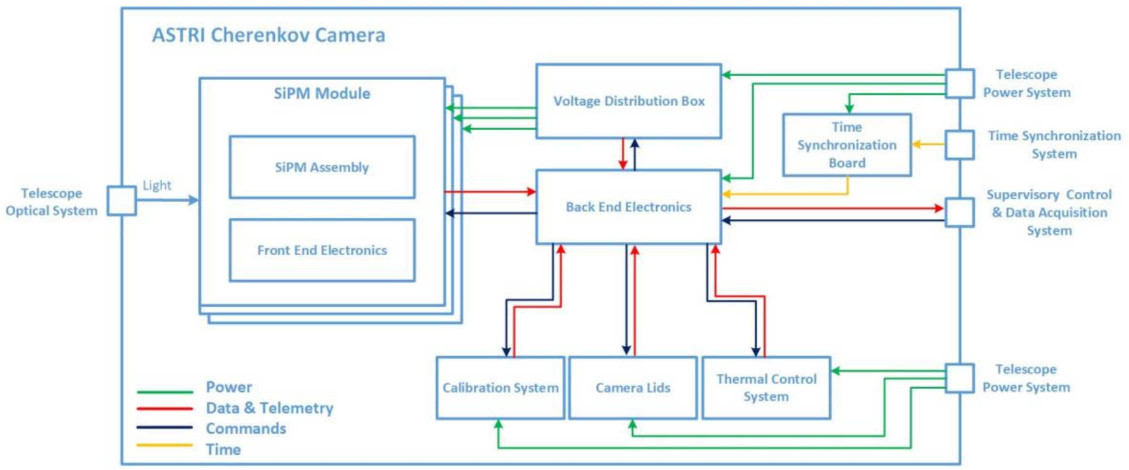

Figure 31. Context Diagram ASTRI Camera

In particular the ASTRI Cherenkov Camera is interfaced with:

- (optically) the Telescope Optical system from which it receives the Cherenkov light emitted by the interaction of ionizing particles with the Earth atmosphere but also the light emitted by star and by the sky background.
- The Telescope power system which deliver the power needed for its functions.
- The Time synchronization system that is a Timing Distribution System designed to keep clocks synchronized to sub-ns precision for Cherenkov Event Timing purposes. This system will allow to time tag any event recorded by every Cherenkov camera of the ASTRI array.

- The Supervisory Control and Data Acquisition System that is the software system devoted to control all the operations carried out at the ASTRI array site. SCADA is a central control system which interfaces and communicate with all equipment and dedicated software installed On-Site.

Figure 32 shows the logical view of the ASTRI Camera. It identifies the main hardware components of the camera that software must control and operate together with their internal and external connections.

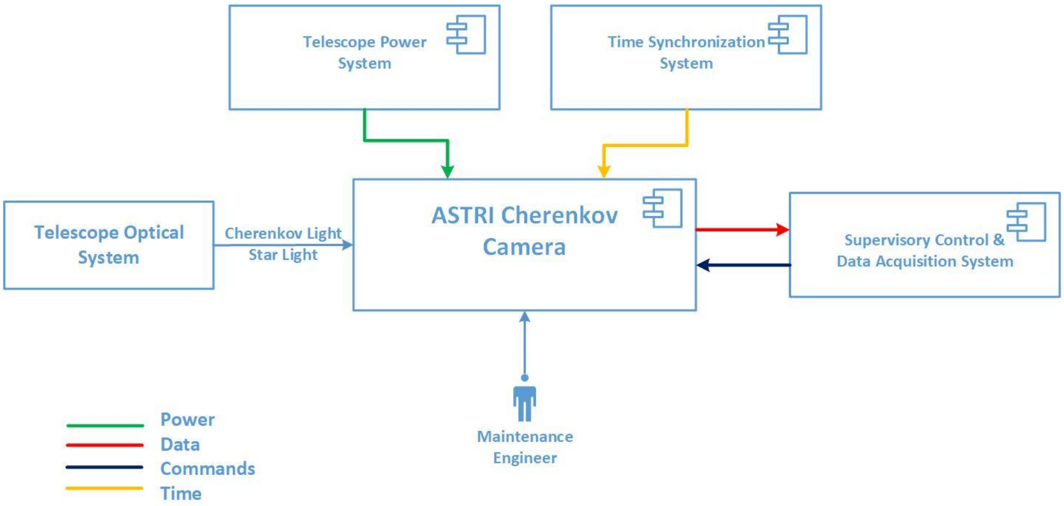

Figure 32. Logical view of ASTRI Camera showing SW internal and external connections. Auxiliary devices are lids, thermal control system and calibration system.

6.1.2 Camera thermo-mechanical subassembly

In Figure 33 the camera exploded view at the main components level is shown.
Camera mechanical assembly includes several components and it is referred, usually, as “camera body”. The camera body is, by definition, from a point of view of mechanical design, the complete deliverable object containing the controls, the detectors, the internal image processor, the thermal system and the associated circuitry. Moreover, the camera body includes the specific interface to the mechanical structure of the telescope.

The camera is equipped with a light-tight lid in order to prevent accidental sunlight exposure of the focal surface detectors, catastrophic in case of direct light reflected by the mirrors, and contemporary to perform detector relative calibration during day light.

The camera Thermal Control System has the main function to provide a thermal control of the SiPM sensors in the focal plane, stabilizing and equalizing the SiPMs temperature. This is accomplished by a mesh of heat pipes embedded in the support structure that facilitate the temperature equalization of the focal plane. Moreover, Peltier Cells are coupled to the heat pipes mesh to cool (or warm, depending on the environmental conditions) the whole focal plane support structure. The double Heat Sinks Fin Stacks blown by four fans, remove the heat from the hot side, allowing an optimal working of the Peltier Cells. The amount of power to the Cells are provided by four Thermoelectric Coolers, that sense the temperature of both hot and cold sides of the Peltier Cells in order to maintain the focal plane at the set temperature.

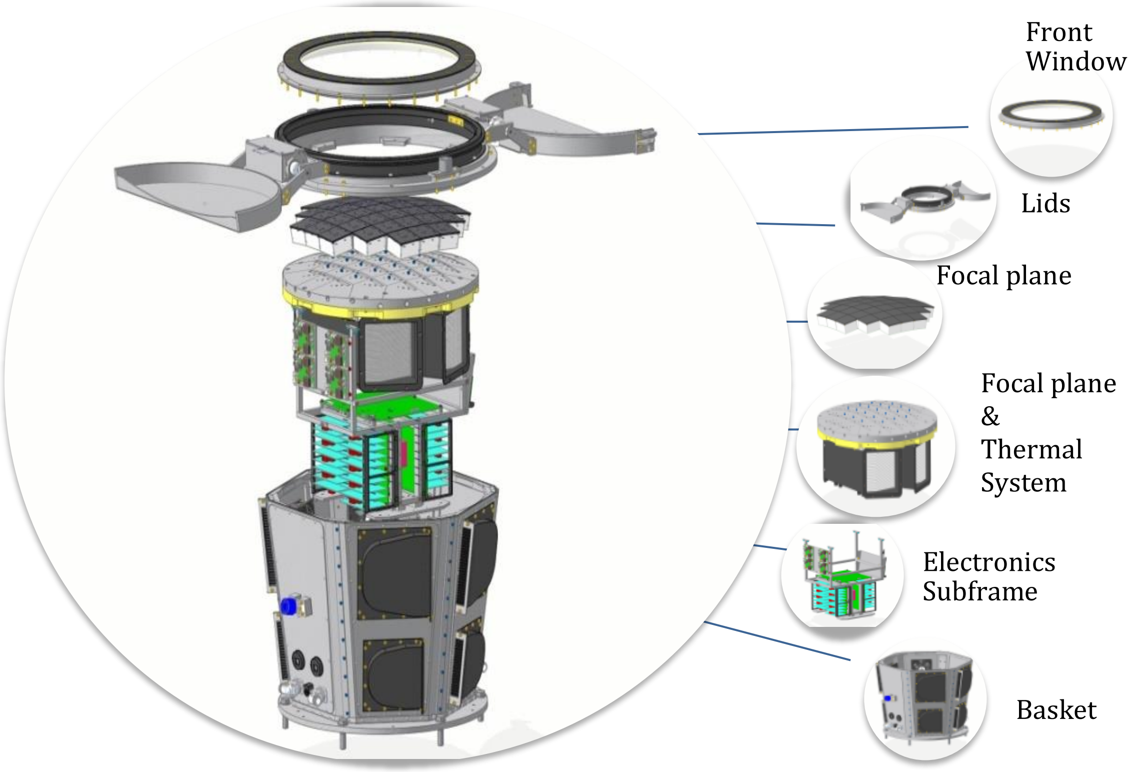

Figure 33. 3D rendering of the ASTRI camera prototype - Exploded view

6.1.3 SiPM subassembly

The baseline focal surface layout (FOV = 10.5°) consists of 37 SiPM matrices.

Figure 34. SiPM detectors' matrices.

Each SiPM matrix has 64 pixels for a total of 2368 for the entire FOV. SiPM of the LVR series produced by Hamamatsu are used for ASTRI camera (see Figure 34).

The SiPM subassembly is made by the sensors' matrix and a PCB board that contains electronics and connectors to interface the front end electronics.

6.1.4 Electronics subassembly

The **Front End Electronics** (FEE) or ASIC board is placed in the middle of the electronics boards stack, made by the SiPM and the FPGA boards (Figure 35). The assembly made by the boards and their container is named Photon Detection Module (PDM).

Figure 35. Camera Photo Detection Module. From top to bottom the SiPM board, the ASIC board and the FPGA board

The most important component installed on the board is the ASIC CITIROC-1A, produced by WEEROC. It performs the read-out of the charge produced by SiPMs when hit by photons. The CITIROC has the trigger circuitry composed by a "Bipolar Fast Shaper" that shapes the preamplifier pulse provided by preamplifier HG or LG, in order to obtain the channel digital trigger signal as output of operation of comparison between FSB and a threshold voltage level. The threshold voltage value is provided to the comparator by a 10 bit DAC and for more fine value by 4 bit DAC. The preamplified SiPM signal is formed by "Slow Shaper" circuit (SSH), "high gain" HG or "low gain" LG respectively, in order to change its shape and to delay the fast peak of the pulse.

The revealed incident photons are converted in equivalent analog pulses by SiPM detectors and sent to the FEE board. From the pulses that each CITIROC channel receives, the FEE board is able to generate digital triggers signals to be sent to FPGA board for successive elaboration.

The FPGA board hosts an FPGA to manage all the PDM functions. The FPGA is the heart of the PDM. It is composed of several firmware (F/W) modules that implement the logic functions required for the correct working of the PDM.

The **Back End Electronics** (BEE) is the main control unit of the ASTRI camera. It is hosted on a separate common board. The BEE is in charge of the complete data and commands management of the camera, interfacing the detectors to the external world. Its primary function is to collect all the data generated by the PDMs and make them available to the Camera Data Acquisition System and, to some extent, to the Camera Controller. At the same time the BEE is in charge of the health monitoring of the Camera Assembly and it controls all the auxiliary devices installed in the Camera.

The design of the BEE is based on a powerful FPGA.

In summary, the major tasks the Back-End Electronics System must perform are as follows:

- Receive commands from the Camera Controller and execute the relevant actions.
- Operating Modes management.
- Send commands to any of the PDMs of the focal plane.
- Receive data from the PDMs
- Generate Camera Trigger signal as result of the PDM triggers elaboration
- Routing of Camera Trigger to all PDMs
- Time Tag scientific data
- Arrange the data received by the PDMs into formatted packets
- Storage data packets in a local memory buffer.
- Send data packets to the Camera Server.
- Manage the communication stack with the Camera Controller by the OPC-UA framework
- Calibration System management
- Perform a limited number of additional processes upon user request.
- Monitor the health and functionality of the Camera Assembly
- Send command and receive housekeeping data from VDB
- Send command to lids motor drivers

The **Voltage Distribution Board** (VDB) has the function to generate and distribute the required operating voltages to the 37 PDMs starting from a single 24V power supply. This includes low voltages to power the FEE board and the FPGA control board plus the high voltage (30-60V) to bias the SiPM sensors.

The VDB is composed of two identical boards, called “mainboards” and 37 daughterboars connected to them. Each mainboard can host 19 daughterboards. The BEE is connected to just one of the two mainboards as master by SPI serial port. The mainboard directly connected to BEE is called “master”. The mainboard master is connected to the second mainboard, called “slave” by RS485 serial link. The mainboard master receives the commands from BEE but can redirect them to the second one. Each mainboard communicates with its own daughterboards by a multipoint RS485 network.

6.1.5 Calibration system

An Optical Calibration System is embedded in the camera in order to carry out relative calibration of all the pixels of the focal plane. The idea is to make use of a side glowing optical fibre placed all around the perimeter of the front window and illuminated by various light sources, coupled to one of the ends of the fibre. The light emitted by the illuminated optical fibre is partially reflected by the front window back to the focal plane, thus allowing the relative calibration of the pixels.

On the other end of the optic fibre is coupled a calibrated photodiode with its control module. This photodetector is in charge to monitor the difference of light between the amount of light injected by the light source and the sideways emitted light during the route in the fibre. This technique permits a stable light emission during monitoring.

6.1.6 Camera Software

The ASTRI Camera Control Software is organized as a client-server system. The server component run on the BEE board and the client component is deployed on a dedicated computer in the control room. The user interacts directly with the client component through dedicated GUIs and all the requested operations are dispatched to the server component and translated into commands for the camera instrumentations. The communication stack between these two components is managed by the industrial standard protocol OPC-UA and it is totally transparent for the user.

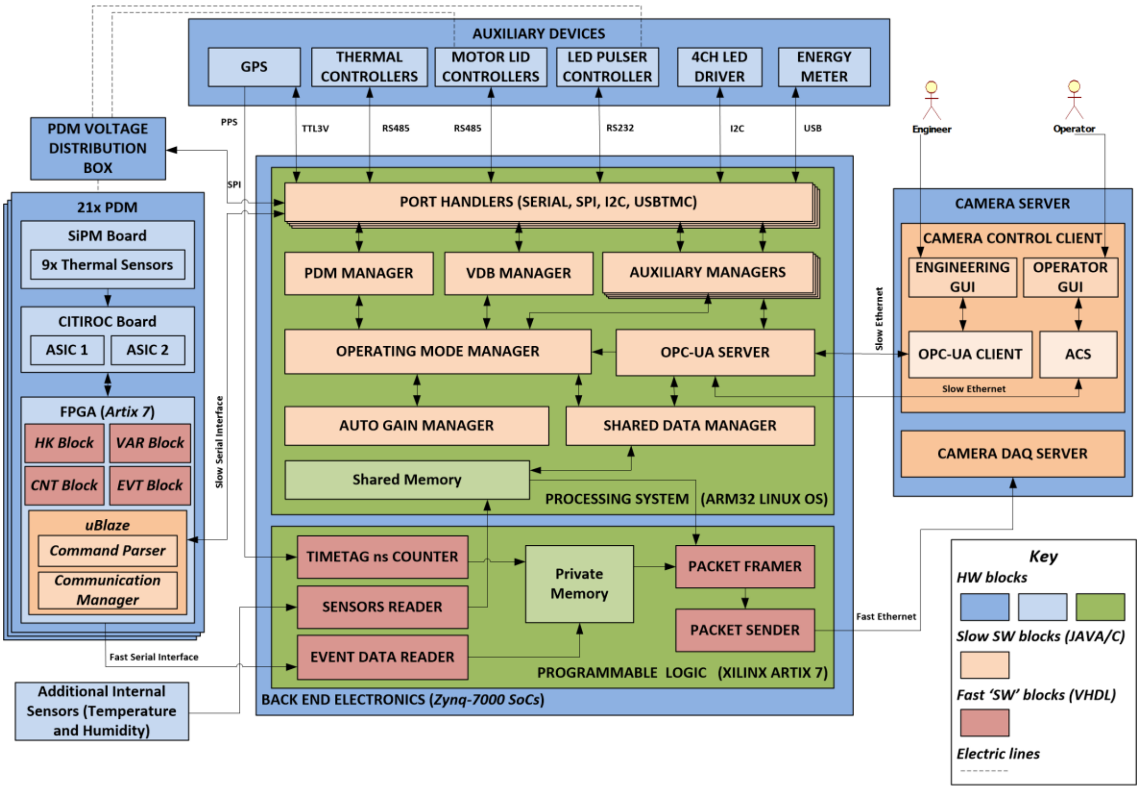

Figure 36. Local Camera Software Architecture (Camera Prototype)

The architecture depicted in Figure 36 where the functional blocks, their deployment and how they interact each other are represented was defined after identifying the functionalities of the camera to be implemented. These functionalities were grouped in terms of functional blocks according to the technique of modularization and modules decoupling of the software engineering. Once the functionalities were defined, due to requirements related to the elaboration speed and the hardware platform adopted for the BEE, two main classes of software components were identified: Slow and Fast. Slow software components are implemented in the Processing System of the BEE and run over ARM processors under Linux and Java Runtime environment installed on it. Fast software components do not implement particularly complex logic, but they are responsible for tasks that require high speed in their execution and for this reason they are realized in the Programmable Logic side of the BEE.

6.2 Stellar Intensity Interferometry Instrument

The Stellar Intensity Interferometry Instrument (SI^3) is a dedicated optical photon detection unit for intensity interferometry observations with the ASTRI telescopes of the mini-array. SI^3 is conceived to measure the second order discrete degree of spatial and temporal coherence (g2) of a star, performing the correlation off-line. To this end, accurate measurements (~1 ns) of single photon arrival times in a narrow optical wavelength range (~5 nm) are needed.

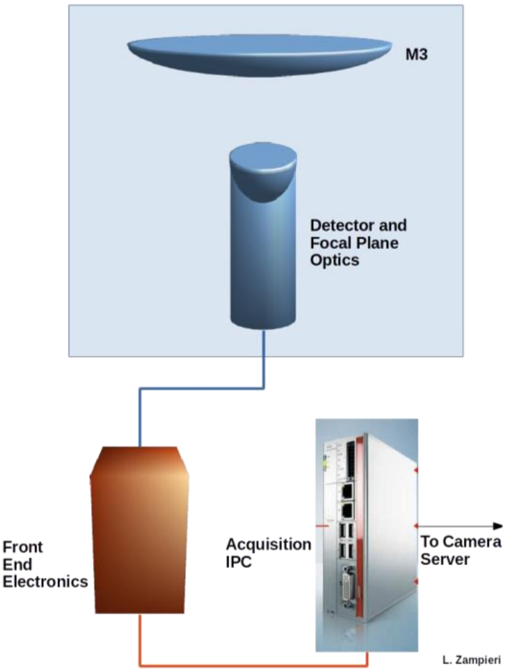

Figure 37. Detector and Focal plane optics of SI3 shown with M3 mirror

This module is mounted in front of the Cherenkov Camera through the use of a swing arm (TBC) and it is completely independent from it.
The SI^3 module consists of a single pixel and is accommodated in one of the free slots placed at the corners of the Cherenkov Camera, approximately 10 arcmin off-axis.
The module incorporates focal plane optics and dedicated front-end electronics as shown in Figure 37.

The decomposition of the SI^3 includes:

- Positioning sub assembly
  - mechanical support arm
  - motor control and power supply
  - cable casing
- Optics sub assembly
- Detector subassembly
- FEE subassembly
- VDB subassembly
- BEE subassembly
- Acquisition/control subassembly
- Science data production subassembly
- Assembly Integration and Verification tools

The SI^3 mirror M3 is designed as shown in Figure 38. The same figure shows M3 position respect to the other optical elements and the optical design of the optical module in front of the detector.

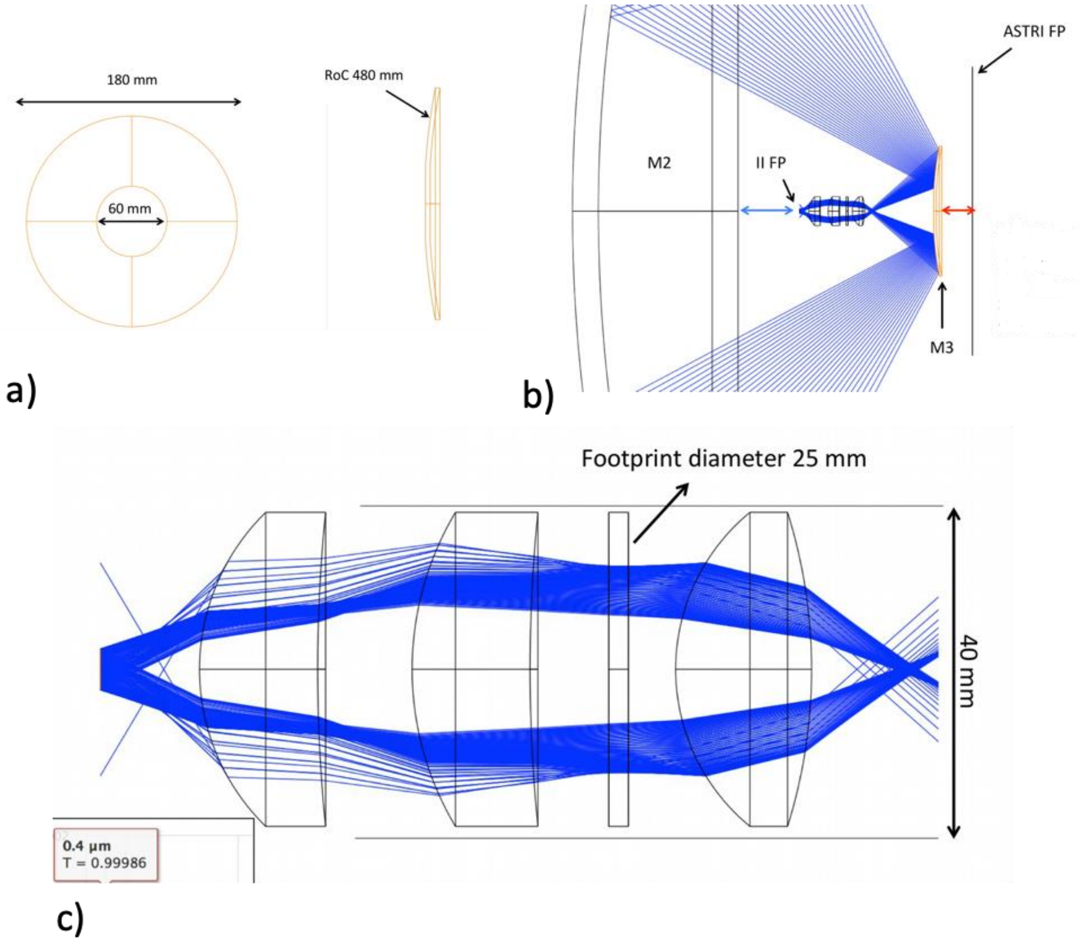

Figure 38. a) Design of M3 mirror: central and lateral view. b) position of SI3 and M3 in the ASTRI telescope. c) Optics of SI3

7 Auxiliary Assemblies

The auxiliary assemblies are those items that support the main function of the telescope during operations and maintenance. Not all those items are permanently present on the telescope but can be installed when needed. The Auxiliary assemblies include:

- The Pointing Monitor camera.
- The Telescope Conditioning Monitor System
- The Mirror Alignment system.
- The UVSiPM

7.1 The Pointing Monitoring Camera

This system is installed on the rear of the M2 support structure to obtain astrometric calibrated FoV of the region pointed to by the telescope. The system is based on a CCD camera and systems of lenses to assure a FoV of about 3x2 deg and a pixel sampling of about 7 arcsec, a sky coverage wide enough and sampled enough to obtain an astrometric accuracy of 5 arcsec over the full sky. The PMC with its astrometric calibration could be also used to implement a telescope-pointing model TPOINT-like with grid pointing directions over all the sky.

The PMC Assembly also includes a Sky Quality Meter (SQM) used to derive the sky brightness in the pointing direction of the telescope. There are only three of the nine PMC assembly equipped with the SQM.

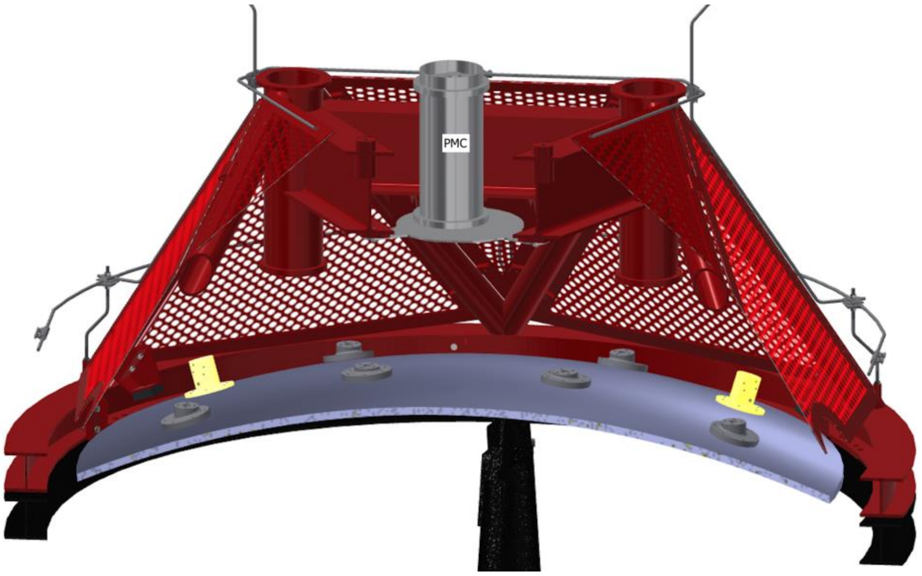

Figure 39. The Pointing Monitor Camera on the M2 Structure (courtesy of EIE).

7.2 The Telescope Conditioning Monitoring System

This system consists of accelerometers and temperature sensors mounted on the telescope drive system. The data provided by these sensors combined with the motor currents, voltage and speed will allow condition-based maintenance to limit system downtime and spare part stocks. The output signals of these sensors are read by dedicated Beckhoff modules connected to the Telescope Control Unit.

7.3 The Mirror Alignment system

The Mirror Alignment system is used to check and align the optical system of the telescope. This system will be used only during the commissioning of each telescope and, eventually, during maintenance/calibration activities.
The mirror alignment system decomposition is reported in Figure 40. In order to install this system, the Cherenkov camera has to be removed and replaced with the Optical Camera and a motorized system has to be mounted on the rear of each M1 mirror segment support actuator to allow the tip, tilt and piston movements of each mirror segment. The optical CCD camera is mounted on a rotary stage that is then mounted on a x-y linear stage to allow the positioning of the CCD, with right orientation, is several focal plane positions. This will allow to verify the correct alignment of the telescope optical surfaces measuring the optical Point Spread Function (PSF) of the system. The comparison of the measured PSF with that expected at the different position on the focal plane allows the correct repositioning of the M1 segments acting on their motorized support stage. After the completion of alignment, the Optical camera and the motorized support stage of the mirror stages are removed.
There is only one system for all the nine Telescopes.

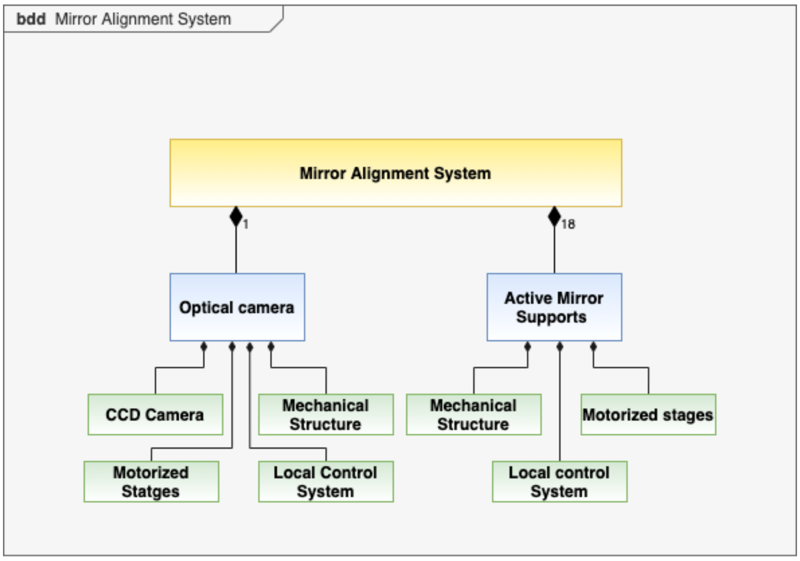

Figure 40. Mirror Alignment system decomposition

7.4 The UVSiPM

UVSiPM is a light detector that measures the intensity of electromagnetic radiation in the 300–900 nm wavelength range. The UVSiPM instrument, whose technical design is currently in progress, will be essentially composed of a multipixel Silicon Photo-Multiplier (SiPM) detector unit coupled to an electronic chain working in Single Photon Counting (SPC) mode, and the onboard computer devoted to the management of all functions and subsystems forming the instrument and to the communication with external actors.
Only one UVSiPM unit is currently foreseen for the entire Array. It will be mounted on the external structure of one of the nine ASTRI telescopes and centred with the related Cherenkov camera. The UVSiPM will acquire data contemporarily with the Cherenkov camera and with the SQM device installed on the same ASTRI telescope.

8 Telescope Protection System

All the hardware necessary to guarantee the safety of the telescope and of the people working on it during operations or maintenance activities. It includes the Telescope Safety and Fire protection systems.

9 The Telescope Local Control Architecture

In this section we will describe in more details the Local control system related to the Control of the Mechanical Structure Assembly (MSA).

The term Local Control System (LCS) indicates the control and safety units, control software, local communication infrastructure required to guarantee functional operation of a given equipment and all the other support elements needed for integration, verification and maintenance activities. The conceptual architecture of any ASTRI Local Control Systems is given in Figure 41:

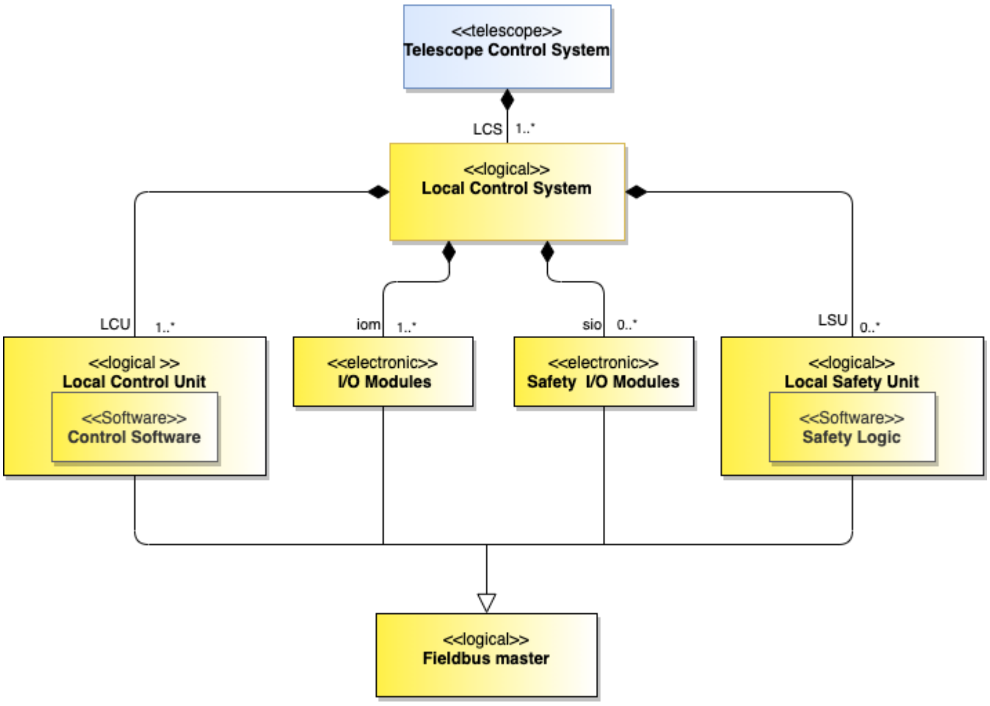

Figure 41. The logical Architecture the Telescope Local Control Systems

9.1 The MSA Local Control Systems

The complete block diagram of the Telescope local control system architecture is reported in Figure 42.

The MSA Local Control Systems (LCSs) include control software, control units, devices and local communication infrastructure (cabling, trays, patch panels, network equipment etc) needed to monitor and safely command the MSA and its subsystems. It does not include the actuators and sensors of the MSA.

The main MSA LCSs are:

- **The Mount LCS**, is the main control system of the telescope. It controls all the Telescope functionalities like pointing to and tracking any celestial object accessible from the Teide site.
- **The Telescope Health and Safety LCSs**, is in charge to monitor the health and safety of the MSA and of the entire Telescope. It is in charge of the power monitor a distribution management (switch-on/off) of all telescope subsystems,

including the Science Instruments and the Commissioning and Maintenance mechanisms that will be temporary mounted on the MSA.

- **The Optics LCS**, is in charge of the control of the M2 (focusing) and of the special mechanism that will be used to Align the M1 segment during the Telescope Commissioning and Maintenance.

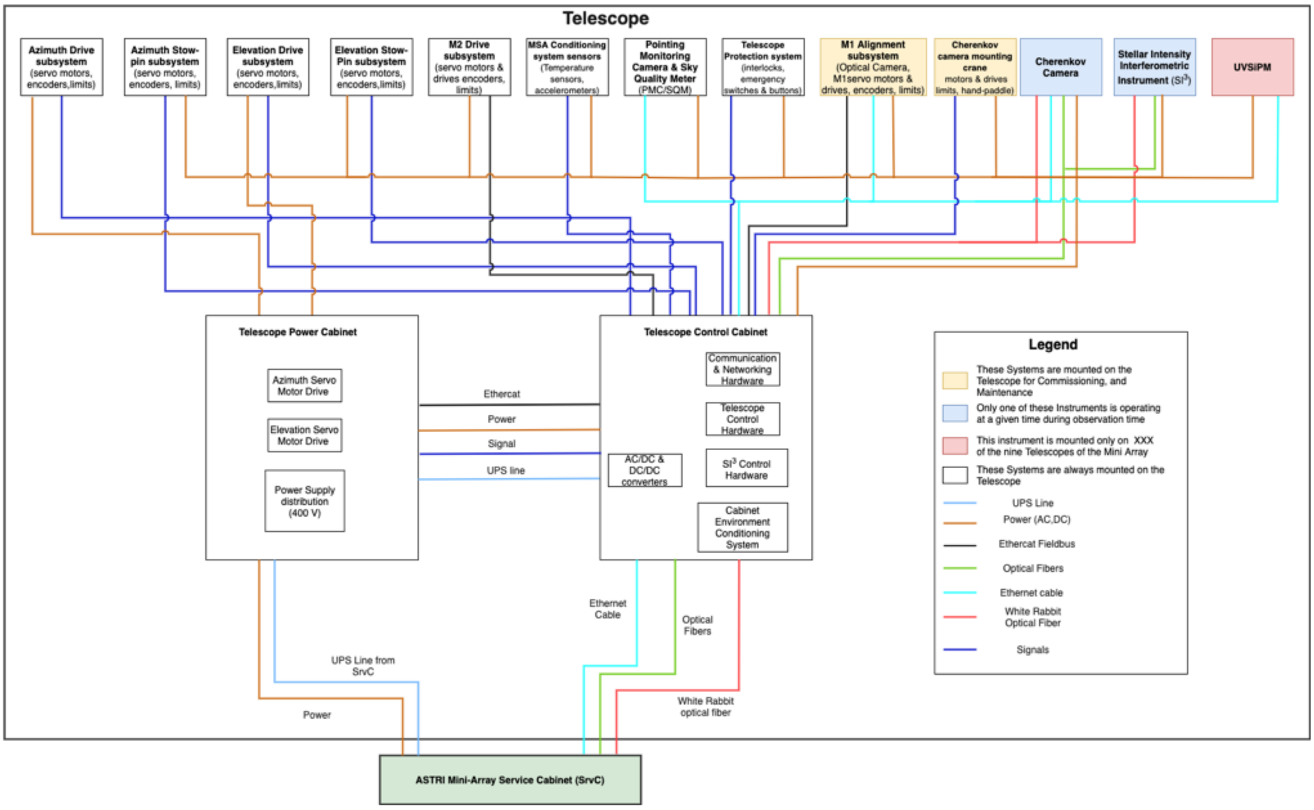

Figure 42. Overview of the Local control architecture of the Telescope

9.1.1 The MSA Local Control and safety System Units

Figure 43 shows the main components of the MSA Control Hardware. It includes all the electronics and hardware parts needed to drive the telescope to any accessible sky position during the commissioning, testing, observing phases and maintenance.

The main MSA Control Hardware components are:

- The Telescope Control Unit (TCU) is the IPC running the software which is in charge of the monitoring and control of the Elevation and Azimuth axes motion.
- The Telescope Health (THCU) and Safety Units (SU) runs the software and safety logic which are in charge of the interlock chain and power management of the telescope and of the monitoring of the health of all the Telescope subsystems.
- The Optics Control Unit (OCU) runs the software which is in charge of the control and monitoring of the M2 positioning system and of the control and monitoring of the M1 segment alignment system used during commissioning and maintenance.

- The Azimuth and Elevation Servo Drivers, which include the high-power electronics stage that deliver power to the and provide the main motor velocity and torque control loops.

The TCU, THCU and OSU are Beckhoff industrial PCs (IPCs) integrated in the Telescope control cabinet. These IPCs demonstrated their high reliability and reduced maintenance need during the last seven years of use in the ASTRI-Horn prototype.

TCU, THCU and OSU will run the Beckhoff TwinCAT software system which turns any MSA IPC into a real-time controller with a multi-PLC system.

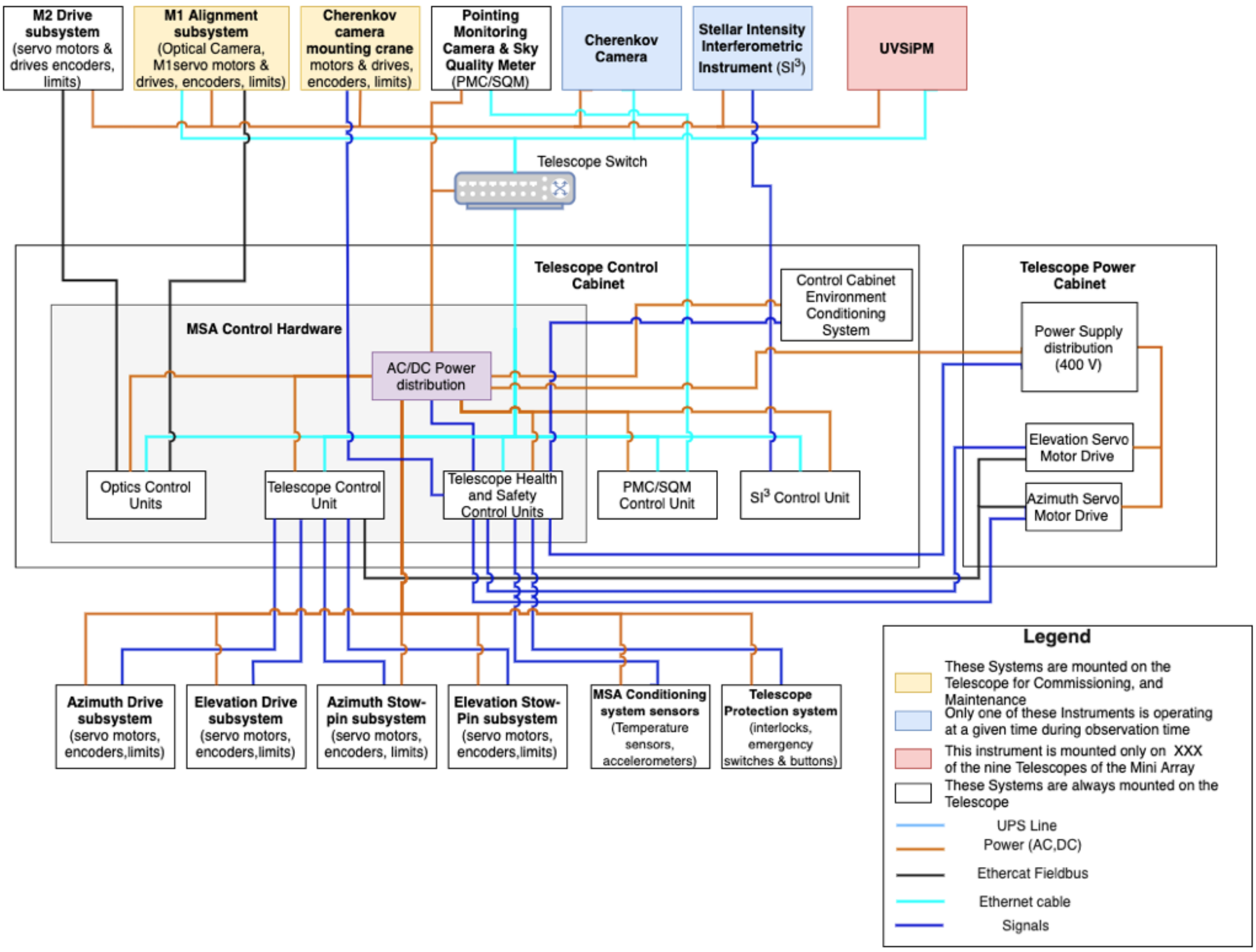

Figure 43. The MSA Control Hardware conceptual design

The Safety Unit is a Beckhoff safety PLC (IEC 61508 SIL 3). It is connected to the THCU via the Beckhoff E-BUS so it is considered as part of the THCU.

The Azimuth and Elevation servo drives are connected to the Local Control Units using EtherCAT (IEC 61158) fieldbus.

All digital and analog Beckhoff I/O modules used in the MSA Local Control Systems are connected to the Local control units using the EtherCAT (IEC 61158) fieldbus. The wiring of the Beckhoff I/O modules is via the special connectors provided by Beckhoff avoiding, when possible, the direct wires connections into the front clamps.

The TCU, THCU and OSU are connected to the electrical line under UPS provided by the ASTRI Mini Array site Infrastructure.

All Industrial PCs are equipped with a 24 V power supply unit and an integrated battery pack, to prevent sudden PC power off due the failure of the 24V Telescope power supplies. This allows data to be automatically saved and then the IPCs are shut down properly.

The THCU, the SU and the communication devices of the MSA should be always powered-on also during the day.

The TCU, THCU and OSU TwinCAT PLCs share internal variables through the Real-Time Ethernet protocol provided by Beckhoff and already available in the TwinCAT tool.

9.1.2 The MSA Local Control software

The MSA Local Control Software is running on the Local Control Units (TCU, THCU, OCU) and Safety Unit (SU). It runs as PLC programs under the Beckhoff TwinCAT software system which turn any MSA IPCs into a real-time controller with a multi-PLC system.

The MSA Local control system uses the OPC-UA communication protocol (IEC 62541) to exchange information with the TCS on the basis of a dedicated Interface Control Document.

The MSA Local Control Software main components are: (see Figure 50))

- The Mount Local Control Software running on the TCU, includes:
    - The Mount Axes Controller (MAC) software is running on a dedicated TwinCAT PLC (MAC PLC). The MAC uses the PLCopen Motion Control Library, available in TwinCAT, for implementing all servo control software necessary to safely operate the Azimuth and Elevation Drive subsystems. The Motor Axis Control is also able to control the movement of the MSA locally via a hand-paddle for diagnostic and maintenance purpose.

    - The Mount Control Software (MCS) running on a dedicated TwinCAT PLC (MC PLC). It provides the interface with the TCS and coordinate all functionalities needed to the science, calibration and maintenance operation of the MSA. The MCS is also able to handle position, velocity and time commands sent by the TCS.
    - The Astronomical Coordinate Transformation (ASTRO) running on a dedicated TwinCAT PLC (ASTRO PLC). It provides the needed Astronomical transformation and sky trajectory generation needed to point and track a celestial source.
    - A local Human Machine Interfaces should be provided to use locally the MCS functionalities.
- The Telescope Health Software (THS) that running on a dedicated TwinCAT PLC (THS PLC) of the THCU.

- The Safety Logic running on the Safety PLC.
- The Optics Local Control System running on the OSU, include
    - The M2 Control software (M2CS) running on a dedicated TwinCAT PLC (M2C PLC). The M2C uses the PLCopen Motion Control Library provided by TwinCAT for implementing all servo control software necessary to safely operate the Focusing system of M2.
    - The M1 Control software (M1CS) running on a dedicated TwinCAT PLC (M1C PLC). **This component is used only for the Alignment of the M1 segments during Commissioning or Maintenance activities**. *The M1CS is provided by a TwinCAT PLC program written in IEC61131-3 Structured Text language.*
    - A local Human Machine Interfaces should be provided to use locally the OSU functionalities.

10 Telescope Control System

The TCS is functionally part of the Telescope but it is a product that will be delivered by the ASTRI Mini-Array SCADA Work Package (see Figure 44). The TCS does not include direct control of any telescope mechanism and is not responsible for any time-critical operations. All real-time functions are performed by the Telescope Local Control systems (LCSs) provided by the Telescope and Instruments suppliers.

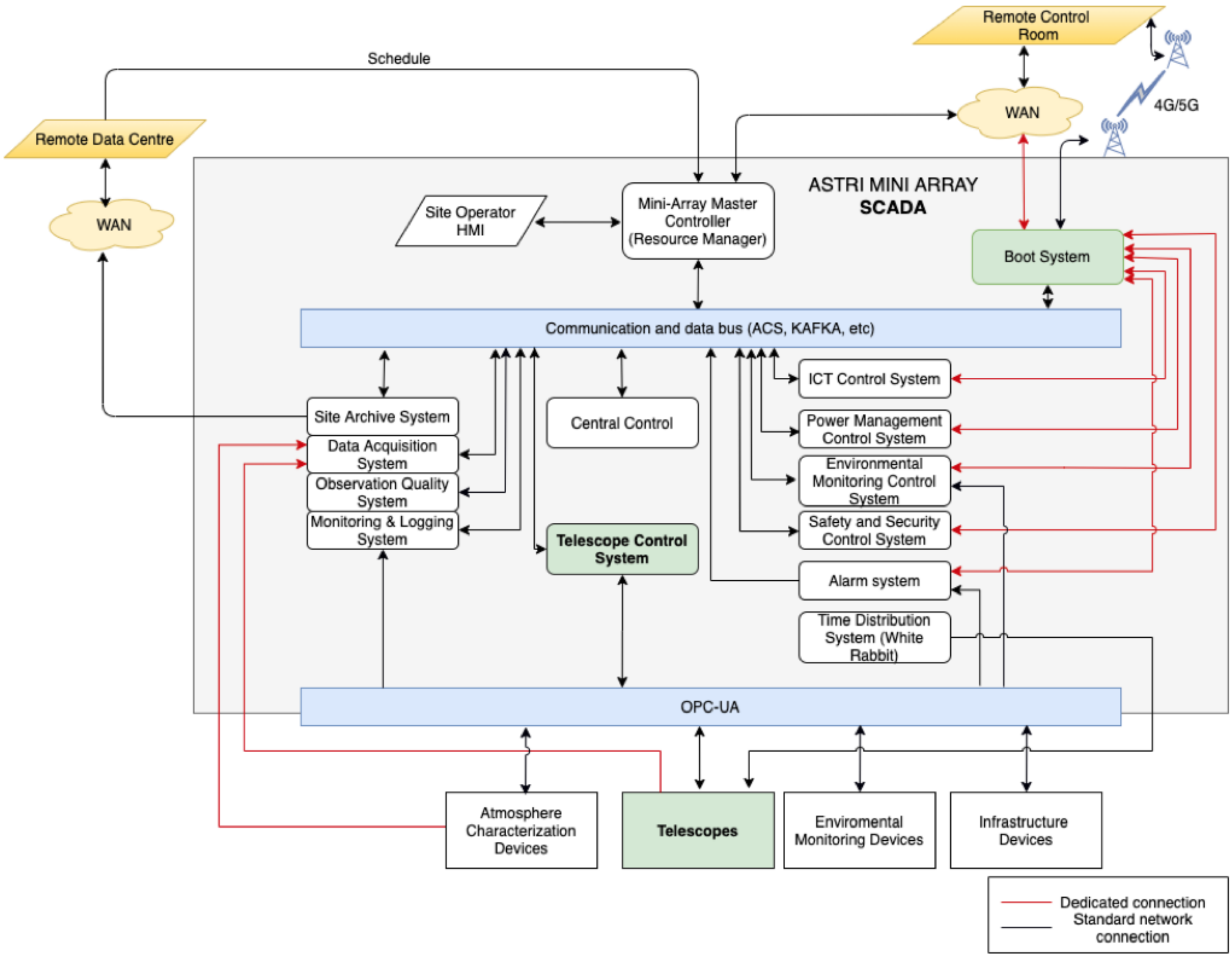

Figure 44. Logical Control Software Architecture of the ASTRI Mini-Array at the Teide site.

The Telescope Control System (TCS) implements the following functionalities: control of the telescope subsystems remotely; handling of human errors, hardware failures, and operational and environmental stresses to protect human, devices, and environment from unacceptable health risk of injury or damage.

The TCS communicate with the MSA, Optics, Cherenkov Camera and SI[3] Local control Systems via dedicated software connectors that implement OPC-UA Clients.

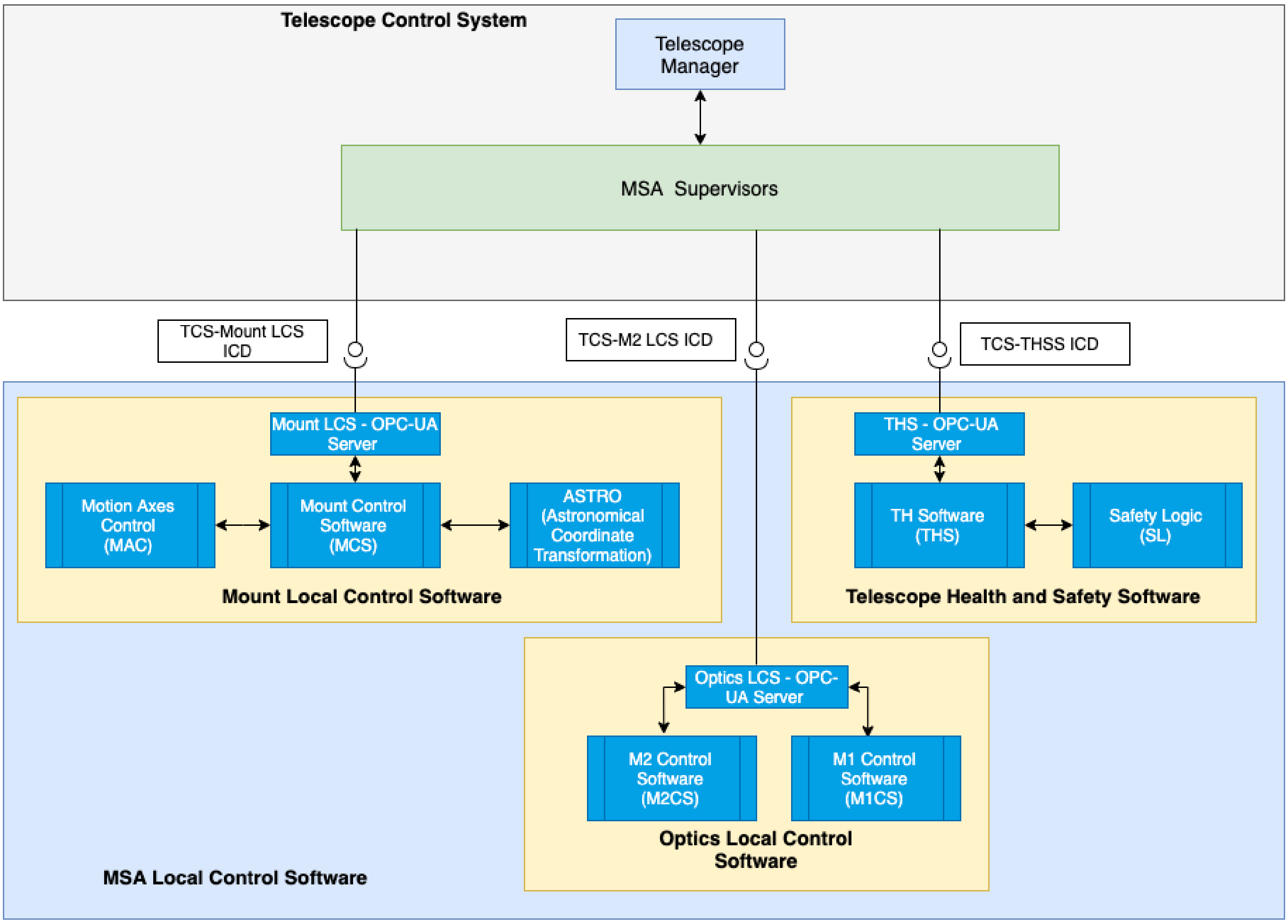

Figure 45. The MSA Local Control Software and their interfaces with the TCS

The TCS includes the MSA Supervisor that coordinates the logic of the Telescope Local controls systems. Also, the MSA Supervisor manage the MSA States through a software state machine.

10.1 Telescope MSA State machine

The MSA state machine is reported in Figure 46.

Off State: The MSA is entirely without electrical power.

On State: *The MSA* is powered-on, and available to operate under the sub-states described below:

- **Initialised State**: the state of the MSA after power on. All Local Control systems (LCSs) are powered-on. The LCS software is running, initialized and the communication with the MSA Local Supervisor is established. The MSA is in parking position, a configuration suitable for survival in extreme environmental conditions.
- **Standby State**: a state in which the MSA is still in safe configuration (but the MSA stow-pins are disengaged). All MSA LCSs are ready to receive

commands. MSA Drive system is powered-on. The MSA is ready to perform a transition to the operation State.

- **Operational State**: the MSA state associated with operations (e.g. pointing and tracking a sky object), with configuration dictated by performance requirements. Two Operational sub-states (not represented in the figure) could be present:
  - **nominal:** the MSA can be operated with full performances;
  - **degraded:** the MSA can be operated with reduced performances.

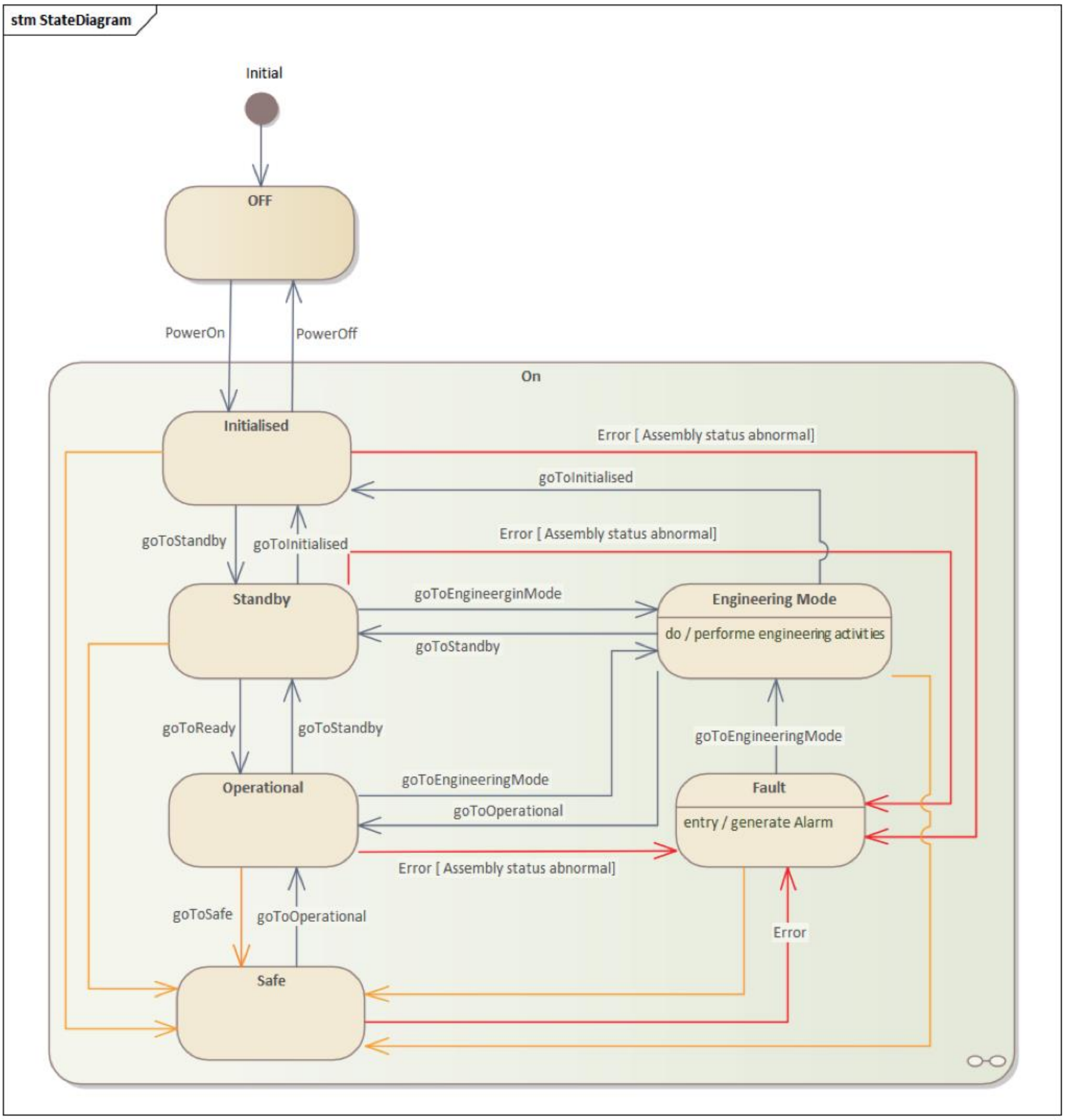

Figure 46. ASTRI Telescope Structure State Machine

- **Safe State**: if dangerous conditions are present, the MSA goes into a state where the MSA is considered exposed to "normal" risk for damage or loss. This is also the configuration designed for survival in extreme conditions, minimising the use of power. The MSA is in parking position and only some (TBC) MSA LCSs are still providing basic status and monitoring information to the MSA Local Supervisor.
- **Fault State**: the MSA has encountered a serious problem, which means it is currently unable to meet the requirements associated with one of the standard states. An alarm shall be generated by the MSA LCS before entering this state.
- **Engineering Mode State**: a logical state designed to facilitate MSA maintenance and engineering activities. This state is unavailable for routine operations and can be entered only upon request by MSA experts.